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James B. Pollack and NASA's Planetary Missions: A Tribute

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Cover: Portrait of James B. Pollack at NASA Ames

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DEDICATION

This document is dedicated to the planetary scientists whose efforts produce such amazing results for NASA, our country – and in particular, Ames Research Center. We look forward to their guidance to sustain a healthy planet Earth.

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In the words of T.S. Eliot:

“We shall never cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.
Through the unknown, remembered gate
When the last of earth left to discover
Is that which was the beginning”

‘Four Quartets’ 194

Preface

Near the time the New Horizons spacecraft started streaming images of Jupiter and its moons to Earth in 2007, I visited Jeff Moore, team lead of the mission at NASA's Ames Research Center, Moffett Field, Calif., in his office to talk about the media's interest in his work. Ames then was approaching its 70th anniversary and the conversation drifted to the Center's history of space science. He told me that one of the world's most extraordinary astrophysicists used to work at Ames, and his name was James B. Pollack.

During the next few months, I pursued Jeff's tip about Pollack by making inquiries among other space scientists at Ames. When brilliant people collectively agree on anything, it is remarkable; the consensus of opinion about Pollack's theoretical and practical achievements seemed true. He was an exceptional person who made exceptional contributions to space science. Later, in the "Reading Room" of the Space Science building, I found the complete set of Pollack's publications beautifully archived as leather- bound volumes. It was the beginning of my fascination with the man and this period of NASA history.

Jim Pollack was a theoretical astrophysicist whose career covered that Golden Age of Planetary Exploration, when NASA started launching small, ambitious, inconspicuous spacecraft into space, travelling millions and millions of miles to make detailed scientific observations and take thousands of photographs. It was an era when, for the first time ever, close-up remote sensing data were available and beginning to answer centuries-old questions about the planets and our Solar System. Some of these spacecraft, managed by Ames, are legend. Perhaps the most glorious of which were the Pioneer spacecraft. With a mission to fly by Jupiter, a 500-pound spacecraft, named Pioneer 10, was the first to encounter and race through the asteroid belt at 50,000 mph, the first man-made object to use a "gravity assist" maneuver from a planet to escape the Solar System, and the first NASA spacecraft powered exclusively by nuclear energy.

This was Jim Pollack's time. He was a masterful planetary scientist, who was considered preeminent in his field by many knowledgeable people. What better way to commemorate him than to follow his investigative journey through the Solar System and beyond during these "first" unmanned space exploration missions.

A brief history is written about Pollack's life and career to pay tribute to him as one of our country's most distinguished theoretical astrophysicists and planetary scientists. He worked on almost all of the NASA unmanned missions in his lifetime, including the Mariner, Viking, Voyager, Pioneer Venus, Galileo, Mars Observer and Cassini expeditions. Early in his career, Pollack was modeling theories of planetary processes, planning and designing experiments, and interpreting observations. As part of this work, he wrote elaborate numerical codes for computer models that captured the unique character of each planet and tied them to spacecraft observations.

Profoundly interested in observational work, he also acted as an interdisciplinary scientist. To answer specific questions, he needed specific data. As a result, he cultivated strong working relationships with the research observers who flew his science experiments on NASA's aircraft, including the NASA Ames Convair 990 "Galileo" Observatory, Learjet Observatory, high-altitude U-2 aircraft and Gerard P. Kuiper Airborne Observatory, a modified Lockheed C-141A "Starlifter" four-engine cargo plane. He made similar relationships with experimental scientists and engineers, who built specialized, state-of-the-art instruments and launched them on NASA's spacecraft missions. In many ways, his insights and inspiration helped guide the planetary science work and spacecraft development at Ames.

Examples of his extraordinary work, accomplished in collaboration with talented scientists he recruited for his research teams, are the Mars Global Climate Model (GCM), and the "first ever" models developed to validate the theory of the "origin and evolution" of the giant planets. The Mars GCM was used during the Viking mission to interpret its data and explain the winds and pressure patterns on Mars. Today, it is considered the world's most complete model of the red planet's atmospheric circulation. In the early 1970s, cosmogony (the "origin and evolution" of the planets and Solar System) was regarded by many scientists as speculative, or unapproachable. Pollack, however, was thinking of the "big picture" and how these many observations might fit together. He led two research teams that constructed models of this area of research that were the first fully, self-consistent, realistic, quantitative models of the epoch. His approach to studying the "origin" of planets and the solar system inspired NASA to start an "Origins" program, according to many scientists.

For this work, he was honored with the Space Science Award from the American Institute of Aeronautics and Astronautics, the most prestigious award in aerospace. Between 1978 and 1982, he was a member of NASA's Space Science Advisory Committee, formed by NASA Headquarters and the National Academy of Sciences.

Applying similar methods to study the atmosphere of Earth, he was cited "for making major contributions to our understanding of planetary atmospheres, surfaces and climates, and for making major contributions to the theory of aerosols and the climatic influence of stratospheric aerosols." He was a member of the executive council for the Planetary Division, and was the chief scientist for the Ames Climate Office. His research on volcanic eruptions and climate changes led to his interest in the extinction of the dinosaurs, and later to an imaginative application of theory that captured the public's attention with "nuclear winter." He was a member of the TTAPS (Richard P. Turco, Brian O. Toon, Thomas P. Ackerman, James B. Pollack and Carl Sagan) group. Their provocative publication on "nuclear winter" created a "firestorm" of political and social controversy, but nevertheless they were granted the Leo Szilard Award from the American Physical Society "in recognition for outstanding accomplishments by physicists in promoting the use of physics for the benefit of society in such areas as the environment, arms control, and science policy."

Throughout his NASA career, Pollack recruited, mentored and orchestrated immense talent in the Earth and planetary sciences, helping many of them start their careers. Several young researchers felt it was an honor and a privilege to publish a paper with Jim Pollack. "When a researcher published a paper with Jim, the researcher knew it would be an important paper and would be cited a great deal. Hence, a career would be enhanced," said Richard Young, chief of the Theoretical Astrophysics Division at Ames, and Pollack's supervisor.[1] Many of his papers are considered classics, laying the foundation for the next generation of researchers, and are still heavily cited by researchers today. According to the Web of Science, Jim's career publication profile shows 315 peer-reviewed papers listed, over 15,000 citations, and an h-index of 62. The h-index measures research impact: any number over 50 is outstanding, 62 is phenomenal.

At 50 years old, Pollack was awarded the prestigious Gerard P. Kuiper Prize, a lifetime achievement award by the Division for Planetary Science of the American Astronomical Society. A Mars crater is named James B. Pollack to commemorate his many contributions to Mars science. He received the NASA medal for exceptional scientific achievement twice, and he received the Arthur S. Fleming Award in recognition of his outstanding federal service. He was a Fellow of the American Geophysical Union, American Association for the Advancement of Science, American Astronautical Society and NASA Ames Research Center.

Carl Sagan referred to Pollack's planetary research in his book, *The Pale Blue Dot*.[2] He wrote, "…James B. Pollack made important contributions in every area in planetary science. He was my first graduate student and a colleague ever since. He converted NASA's Ames Research Center into a world leader in planetary research and the post-doctoral training of planetary scientists. His gentleness was as extraordinary as his scientific abilities. He died in 1994 at the height of his powers…"

The purpose of this paper is to provide a historical record of Pollack's NASA career and his many professional accomplishments for the NASA History Office. This paper reviews Pollack's career as one of America's most prestigious scientists and recognized authority on both the terrestrial (Mercury, Venus, Mars and Earth) and Jovian (Jupiter, Saturn, Uranus and Neptune) planets in our Solar System. The reader will be introduced to Pollack by describing first his formative years, followed by his early career as a senior research physicist at the Smithsonian Astrophysical Observatory at Harvard University, his federal career as a NASA planetary scientist at Ames, and parts of his life-long, professional relationship with Carl Sagan. To encompass the many concurrent achievements that make up Pollack's career, major events are traced separately in eight relatively independent sections. All sections represent unmanned NASA missions, including our nation's call to "study Earth." These sections necessarily overlap historically. The focus is on a few select incidents that reflect the start and progressive work of the Golden Age of Planetary Exploration.

1 Email from Richard Young 1 February 2008.
2 Sagan. *Pale Blue Dot*, 145.

I am conscious of my inability to tell Jim Pollack's "entire" story. The science requires a technical text, which is not my intention. I find Pollack's story intrinsically interesting and important. It is a useful illustration of the scientific process and the incredible amount of time, patience and persistence required to find definitive answers. Many pieces of the story are lost due to undocumented telephone conversations, face-to-face conversations and unpreserved correspondence. In short, this document is meant to be a practical historical document about the people and research facilities that contributed their best to NASA's Golden Age of Planetary Exploration.

Acknowledgement

The author wishes to acknowledge and thank the many scientists and colleagues who either helped with the manuscript, or took a moment to share their experiences, when asked "what was it like?" to work with Jim Pollack: Thomas Ackerman, Astrid Albaugh, David Atkinson, Jim Bell, David Black, Peter Bodenheimer, Jack Boyd, Ginny Pollack Breslauer, Clark Chapman, Larry Colin, Dale Cruikshank, John Keay Davidson, Steven Dick, Francois Forget, April Gage, Hal Graboske, David Grinspoon, Al Grossman, Robert Haberle, James E. Hansen, Olenka Hubickyj, Andrew Ingersoll, Jim Kasting, Timothy Lee, Conway Leovy, Jack Lissauer, Justin Marlaire, Michael L. Marlaire, Mark Marley, Chris McKay, Eugene Miya, David Morrison, Julie Moses, Jim Murphy, Boris Ragent, Kathy Rages, Raymond Reynolds, Ted Roush, Phil Russell, Bradford A. Smith, Ann Sullivan, Fred Witteborn, Richard Young, and Brian Toon. I also am especially grateful to Jeff Moore for introducing me to Pollack, Michael Bicay for supporting its publication, Donald James for allowing me time to finish this story, Yvonne Pendleton and Mary Walsh for editing and restructuring this complicated paper, Lynn Albaugh for retrieving many of the images from the Ames photo archive, and to Jeff Cuzzi, who showed enormous amounts of patience and kindness when answering my many, many questions.

Author's Note

It has been my honor and privilege to have worked at two of the world's greatest institutions: The Library of Congress and the National Aeronautics and Space Administration, but especially NASA's Ames Research Center, Moffett Field, Calif. For such a tiny place, it has produced extraordinary successes in science and technology. It has been, and is the home to many brilliant minds. Jim Pollack was one of those talented people. His life was his work; he expressed himself through his work. It was how people knew him. Although Pollack's life was cut short at age 56, he was fortunate to have had a career full of opportunity and intellectual challenge. I believe James B. Pollack had found his place in the world.

The Early Years

James Barney Pollack was born July 9, 1938. He started life in Woodmere, a town on Long Island, New York, "a very affluent and successful Jewish community," according to some people. Both parents were American born, native New Yorkers. His maternal grandparents were of English and Irish descent, but American born. The Pollack grandparents were first-generation immigrants from Russia and Poland. Grandfather Pollack started the family business, a clothing store named "Pollack's," near the turn of the century. When he died, Jim's father dropped out of college to continue the business. Perhaps this is the reason his father told his children that they could do whatever they wanted in life. Jim was the first born of two children. His younger sister was named Virginia, but called Ginny. As a child, Jim had a speech impediment that caused his elementary school teacher to think he was mentally retarded. "He didn't really start talking until he was three or four years old," recalled his sister Ginny Pollack Breslauer.[3] When the school wanted to hold him back in sixth grade, his family insisted that his intelligence be tested, and the results revealed his genius potential. It seemed his cognitive abilities were so lightning fast that he had trouble verbalizing his thoughts. Once the problem was diagnosed, he was sent to speech therapists who taught him to speak slowly and carefully, a habit he maintained throughout life, according to Breslauer.

Seeking a better environment for their son, his parents transferred Jim to a new school where he flourished and excelled in his academic studies. By eighth grade, he was rated top in his class, and later became valedictorian of Lawrence High School, class of '56. In high school, Jim enjoyed normal activities, including reading the comics and collecting baseball cards. He was a varsity track star, and showed an earnest interest in science by building a "space rocket laboratory" in the basement of the family home. There are no family stories of explosions, however. While Jim helped with the bookkeeping at "Pollack's," there was never any expectation he would go into the family business.

Leaving Home

Jim was headed to college. He was accepted into a number of prestigious colleges, including Harvard and Brown universities. He chose Princeton University, New Jersey, because Albert Einstein, "the pope of physics," had worked there. Following Einstein's example, he studied physics in college, but also found time to participate in the camaraderie and spirit of Princeton by joining the staff of the school's mascot humor magazine, "The Princeton Tiger." He graduated in 1960 magna cum laude in physics and Phi Beta Kappa.[4]

While Pollack was at Princeton, the Soviet Union successfully launched Sputnik I, the world's first satellite to orbit Earth. Although a single event, it is attributed to the start of the space age. As a technical achievement, it caught the world's attention and the United States by surprise. The United States, concerned now with its status in the world, soon responded by launching Explorer I on 31 January 1958. These events ushered in new political, military, scientific and technological developments.

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3 Jeff Cuzzi, e-mail to author, 1 December 2008.
4 Toon, Cuzzi, and Sagan, "In Memoriam," 227.

As part of its response, the United States established the National Aeronautics and Space Administration (NASA). On 29 July 1958, the U.S. Congress signed the National Aeronautics and Space Act, from which the National Aeronautics and Space Council was formed to advise the president on matters relating to space policy and the administration of its space program. The Act terminated the National Advisory Committee for Aeronautics (NACA) and transferred all its assets, duties and powers to NASA,[5] an agency that later became very important to Jim and his career.

As a young man, Jim Pollack was as much a product of his environment as any young American. Space was America's new frontier, but an old frontier had yet to be explored. At twenty-two years old, Jim was ready to strike out on his own and go West to experience new places, a different culture, and a young man's independence. Soon after he graduated from college, he headed for California and the University of California at Berkeley, where he earned a Master of Arts degree in physics in two years. While at Berkeley, he also met Carl Sagan, a postdoctoral researcher from the University of Chicago. This relationship would both change his life and continue throughout his life. Sagan studied Venus and its microwave radiation as part of his Ph.D. thesis, which later became the focus of study for Pollack. By 1962, Sagan had accepted a position at the Smithsonian Astophysical Observatory in Cambridge, Mass., a part of the Harvard-Smithsonian Center for Astrophysics.

Once Sagan accepted the position, Jim followed him to Harvard as a doctoral student in astronomy; he was Carl Sagan's first graduate student. Influenced by his mentor, he

Carl Sagan at Cornell in 1974 with former students (left to right): David Morrison, Joseph Veverka and James Pollack. Photo credit: David Morrison

chose the greenhouse effect of Venus as his doctoral thesis, building off of Sagan's own thesis topic. In three years, Jim graduated from Harvard and joined Sagan as a research physicist at the Observatory.

5 Garber, "Sputnik: the Fiftieth Anniversary" http://history.nasa.gov/sputnik/ (accessed 21 May 2014).

These two men, similar in so many ways, were also dissimilar in many other: Both came from New York Jewish families with loving parents in the garment industry. Like Pollack's paternal grandfather, Sagan's father also was a first-generation immigrant from Russia. Each was the first born of one other sibling, a sister.

Pollack was the quiet introvert who was detail-oriented, cautious and meticulous. Sagan was the glib extrovert who loved publicity and fanciful ideas.[6] Their relationship was so complementary that some compared it to the right and left sides of the brain.[7] For the next thirty years, they would become one of the great duos of modern space science.[8]

A New Life

Pollack enjoyed working with Carl Sagan.[9] When Sagan accepted a professorship at Cornell University in 1968, Jim also moved to Ithaca, New York as a senior research associate at the Center for Radiophysics and Space Research at Cornell. During this time, big things were starting to happen in space science outside of academia. While the largest television audience in history watched live, Neil Armstrong became the first person to walk on the moon. The date was 20 July 1969. "That summer, at a huge family party, Jim dragged the TV set out onto the lawn, so he and everyone else could watch the first human landing on the moon," recalled Breslauer.[10]

Jim Pollack at Cornell, Ithaca Photo credit: David Morrison 1969

By 1970, Jim moved back to California to start his career as a space scientist at NASA's Ames Research Center in Moffett Field. Raymond Reynolds, the chief of the Theoretical Studies Branch, hired Pollack. "Jim and I were interested in greenhouse effects and the atmosphere of Jupiter," said Reynolds, who originally met Pollack at the Gordon Conference on the Physics and Chemistry of Space in New Hampshire. "We continued to talk over time and began a joint study of the atmosphere of Jupiter. Jim really wanted to work for NASA. He loved the culture of northern California, so Ames was the perfect place for him."[11]

That culture was another reason why Pollack wanted to return to northern California; San Francisco was more accepting of alternative life styles than any other place in the

6 Davidson, *Carl Sagan*, 190.
7 Poundstone, *Carl Sagan*, 137.
8 Davidson, *Carl Sagan*, 168.
9 Ibid, 173.
10 Jeff Cuzzi, e-mail to author, 1 December 2007.
11 Ray Reynolds, e-mail to author, 26 November 2007.

country.[12] He was a brilliant, young man who had difficulty communicating with others; a quiet, gentle person, who was socially awkward and at times a misfit. While generally taciturn about his private life, Pollack started a more open lifestyle in the 1970s.[13]

Away from work, Jim enjoyed sports, science fiction and the opera. As an opera fan, he liked operas of every style and period, but was particularly fond of those new or rarely performed. According to Jim's longtime friend Bruce Hassell, Jim was especially fond of Wagner. But his favorite opera was Turandot, a story of suitors and riddles set in China. Susan Mead, another Ames opera buff, recalls that Jim would radiate sheer delight for days after seeing a good performance — which led some of his coworkers to name a local workstation "Tosca."[14]

Jim Pollack's move to northern California, served him well. He remained a resident, while working at Ames, for the rest of his life. He was proud to be a NASA scientist, a leading member of an elite group that shared his passion for science.

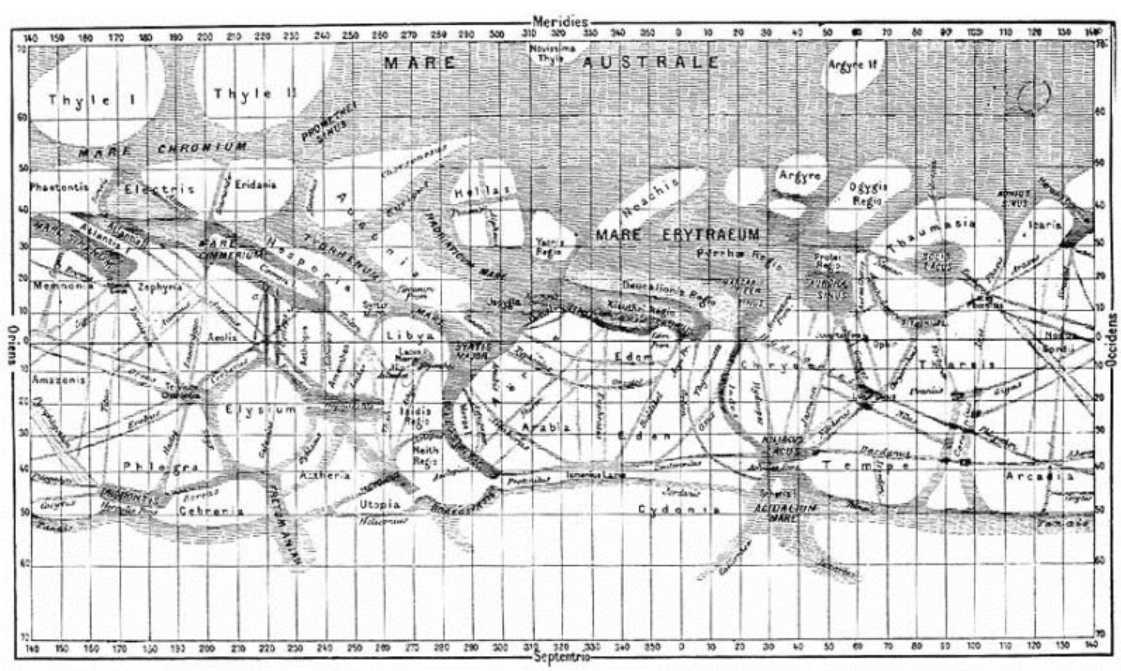
12 Davidson, *Carl Sagan*, 245.
13 Poundstone, *Carl Sagan*, 88.
14 American Astronomical Society obituaries http://aas.org/obituaries/james-b-pollack-1938-1994 (accessed 7 May 2014).

The Search For Life On Mars – Mariner Mars (1964, 1969, 1971), Viking(1975) And Mars Observer (1992) Missions

Long before the 20th century, the public held a fascination with life on Mars. Popular books promoting the idea of life on Mars started to appear in 1895. But what was the origin of this interest in Mars? Why Mars?

By the 1800s, observatories were being built with larger and larger telescopes around the world. In 1877, an Italian astronomer and science historian named Giovanni Schiaparelli, started to map and name areas on Mars. He named the dark areas “seas” and light areas “continents,” using names from historic and mythological sources. Among Schiaparelli’s contributions are his telescopic observations of Mars. He observed channels on Mars and called them “canali.” In Italian, the term canali means channels, which suggests the observed features were natural configurations of the planetary surface. But the word was mistranslated into “canals,” indicating an artificial construction, and implying intelligent life on Mars

During this time, about 1869, the Suez Canal was recently completed and was considered the engineering wonder of the era. The misinterpretation of the word “canali” was taken to mean that large-scale artificial structures had been discovered on Mars. The importance of canals



Giovanni Schiaparelli’s map of Mars used names still in use today.

for worldwide commerce at that time, without a doubt, influenced the popular interest in “canals” on Mars. The misinterpretation of the term “canals,” more than anything else, seemed responsible for assumptions made about life on Mars. These assumptions popularized the idea of artificial "canals" on Mars, which gave rise to waves of hypotheses, speculation, and folklore about the possibility of intelligent life on Mars.[15]

Among the most fervent supporters of the artificial-canal hypothesis was the American astronomer Percival Lowell, a wealthy man from Boston. He made his first observations of Mars from his own private observatory in Flagstaff, Ariz. Lowell decided that the canals were legitimate and ultimately mapped hundreds of them. He believed that the straight lines were artificial canals created by intelligent Martians, with the purpose of carrying water from the polar caps to the equatorial regions. In 1895, he published his first book about Mars with many illustrations, and over the next two decades, published two more popular books promoting his ideas.

Lowell spent much of his life trying to prove the existence of intelligent life on the red planet. After his death in 1916, astronomers developed a consensus against the canal hypothesis, but the popular[16] concept of Martian canals excavated by intelligent Martians remained popular. For the first half of the 20th century, his books supported a new category of literature called science fiction. The most famous Martians in the history of sci-fi and popular culture may be the invaders in H.G. Wells' 1898 novel "War of the Worlds."[17]

The National Academy of Sciences

By 1958, soon after the U.S. launched the Explorer I spacecraft, the National Academy of Sciences (NAS) formed a Space Science Board to help establish national goals in space science. The Board's mission was to assess the scientific aspects of human exploration in space.[18] Since then, it has been NASA's primary adviser on planetary protection.

In 1961, the Space Science Board produced "Man's Role in the National Space Program," which says that "space exploration of the Moon and planets should be clearly stated as the ultimate objective of the U.S. space program for the foreseeable future…"[19] In 1964, NASA requested a study "to recommend to the government ...whether or not a biological exploration of Mars should be included in the nation's space program … and further, to outline what that program, if any, should be." The NAS committee concluded that such an exploration merited "the highest scientific priority," increasing the urgency to develop an unmanned spacecraft that can detect life on Mars.[20] Scientists generally agreed that the evolution of organisms, or "prebiotic materials," was most likely to have occurred on Mars. By 1968, the NAS Space Science Board recommended the key experiments for the Viking lander and its search for life on Mars.[21]

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15 NASA Aerospace Scholars *http://www.nasa.gov/audience/forstudents/postsecondary/features/F_Canali_and_First_Martians.html* (accessed 12 May 2014).
16 Percival Lowell http://en.wikipedia.org/wiki/Percival_Lowell (accessed 12 May 2014).
17 NASA Aerospace Scholars http://www.nasa.gov/audience/forstudents/postsecondary/features/F_Canali_and_First_Martians.html (accessed 12 May 2014).
18 National Academies: Advisers to the Nation on Science, Engineering and Medicine. *Space Science Board, 1958 – 1974*. http://www.nasonline.org/about-nas/history/archives/collections/ssb-1958-1974.html (accessed 11 March 2014).
19 National Academy. *Review of Space Research*, 17 June – 10 August 1962.
20 Pittendrigh, *Biology and the Exploration of Mars*.
21 National Academy. *Review of Space Research*, iii, 47, 486-493.

One Dead Planet

Meanwhile, NASA was moving forward with its initial phases of planetary exploration. Between 1962 and 1973 [22], NASA designed and built ten spacecraft named Mariner to explore the inner Solar System. When the Mariner 4 flyby mission launched in November 1964, Pollack was still working at the Smithsonian Astrophysical Observatory. He and his colleagues waited eight months before receiving photographs of the surface of Mars. As the spacecraft flew by Mars' equator, it took 22 photographs at a distance of approximately 9,000 miles. To more efficiently disseminate the Mariner 4 satellite data, Pollack, Sagan and Clark Chapman published a special report that catalogued over 300 craters and crater-like objects. The report was published three years later on 14 February 1968.[23]

Mariner 4 captured the first images ever seen of Mars and its surface; they depicted a cratered, lifeless world with "the absence of any sign of running water as river valleys." Although the photographs were considered poor quality, they were recommended by Pollack and his co-authors to study the origin, age and history of the craters. They decided that snapshots of a particular region did not provide enough evidence to determine the habitability of the red planet; after all, "surface features smaller than ten kilometers would not have been detected by the Mariner 4." Thus, they recommended to NASA that an orbiter be sent to Mars.

Although the Mariner 4 photographs were poor quality, they were recommended by Pollack and his co-authors to study the origin, age and history of the craters. These images were the first ever of another planet returned from deep space. *At left is an analog image (S-66-52439) taken at the closest approach of 6,118 miles. This photo was enhanced from the raw data received from the spacecraft. Photo credit: NASA 1966*

"When I graduated from high school in 1962, I began working at the Gerard Kuiper Lunar and Planetary Laboratory at the University of Arizona, Tucson. I worked on the Lunar Lab's lunar crater catalogs," recalled Clark Chapman, a scientist at the Southwest Research Institute, Boulder, Colo.[24]

"Somehow, Carl and Jim heard that I had experience working on lunar craters, and I was asked to measure the Martian craters. The three of us spent a number of sessions, always in Carl's office, looking at the pictures and talking about processes that might have shaped the eroded forms of the craters. My working relationship with Jim and Carl was egalitarian, even

22 NASA JPL Past Missions http://www.jpl.nasa.gov/missions/?type=past (accessed 12 May 2014).
23 Chapman, Pollack and Sagan, "An Analysis of Mariner 4," 2.
24 Clark Chapman, e-mail to author, 1 November 2007.

if I had the least experience. I guess I was first author of the paper because I did most of the work," said Chapman.

Unfortunately, Mariner 4's boring pictures of a barren planet undermined support for later Mars missions. In 1967, NASA canceled the Voyager Mars Program, a planned series of unmanned NASA probes to the planet Mars. Funding for the program was cut in 1968, and the mission itself was cancelled entirely in 1971. To save future NASA missions, space scientists needed a salesman. NASA needed someone who could capture and hold the imagination of the public. That someone was Carl Sagan. By the 1960s, Sagan started appearing on television talk shows to interest the public in NASA's space program, and became one of America's most successful science celebrities.[25]

Seeing Is Believing

Mariners 6 and 7 were the next missions to Mars, both flyby missions launched in 1969. As the spacecraft flew by the equator and the south pole, remote sensors analyzed the Martian atmosphere and surface. This time the spacecraft were able to take 50 and 93 pictures of the planet, respectively. These photographs, however, showed no traces of the canals that were believed to be present. Dark spots, or a "wave of darkening," were seen on the surface, but project scientists couldn't agree on their cause or nature. Some scientists believed they were optical illusions caused by the atmosphere. Others believed they were the result of dust storms whipped by high winds. The photographs gave little hope that Mars could have vegetation, but the snapshots were, after all, from quick flybys.

"The Mariner pictures were extremely low resolution and quality, and could hardly be used to rule out life (on Mars). The low atmospheric pressure was a stronger constraint. Nevertheless, the idea that the 'wave of darkening' might be due to some algae-like micro-organisms responding to seasonal changes did not die with the Mariner flyby observations," recalled Conway Leovy, emeritus professor in atmospheric sciences and geophysics at the University of Washington, Seattle.[26]

According to a paper coauthored by Pollack, the photos of the Martian environment suggested that life, if any, "…operates on a bare subsistence level in a marginally possible habitat, at least measured by Earthly standards…High-resolution photography could provide evidence of anomalies such as top heaviness of tree trunks (oriented in the gravity field)…. an isolated oasis is a possible model for a habitat. The Mars temperatures are far below freezing, and whatever moisture has been retained by the planet must be in the form of water of hydration and permafrost. An oasis would be an area where the crust would be broken and the subsurface warmed sufficiently to release the moisture to the surface, where it is available to organisms and released into an arid atmosphere... Another possibility is that Martian life has evolved a specific adaptation to separate its water acquisition mechanism from the solar flux at the surface and to filter the photochemically destructive ultraviolet. On this model, the Martian 'plant' would have leaves, encrusted with ultraviolet filter material (iron oxide or carbonate would serve), and a tough barrier to evaporation. These plants would be joined to the bound-water or ice-harvesting mechanisms below by a deep tap root. A community of different organisms that collectively serve the same functions is also imaginable. Chemically

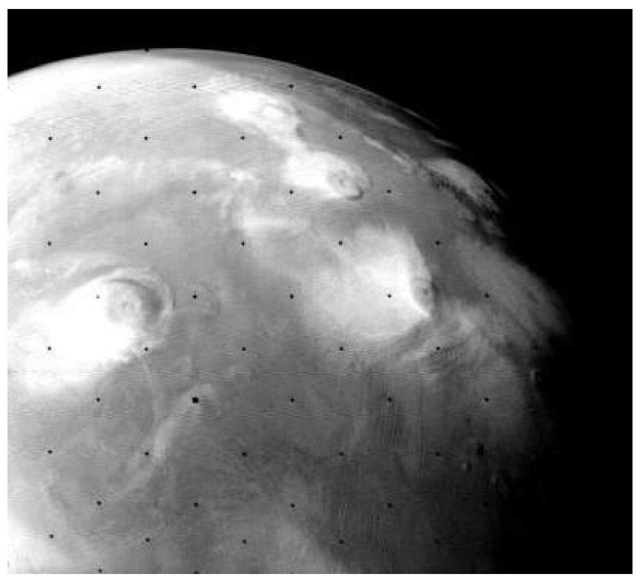
25 Davidson, *Carl Sagan*, 181.
26 Conway Leovy, e-mail to author, 31 October 2007.

bound water may be tappable by Martian organisms…Many other models are conceivable." One model, at most, may survive criticism.[27]

Dust Everywhere

Three years later, NASA launched Mariner 9, its first satellite to orbit Mars. It photographed and mapped almost 70 percent of the planet. For nearly a year, it orbited the red planet and took nearly 5,000 photographs from as close as 750 miles. Jim was one of 26 experimenters from 11 institutions on the experiment's television team, led by Harold Masursky of the U.S. Geological Survey, Flagstaff, Ariz. He also played leading roles on two sub-teams: the "Variable Features," which studied the atmosphere and surface, and the "Atmosphere," which analyzed and interpreted characteristics of the great dust storms. "For the Atmosphere team, Jim came up with a nice way of inferring the basic optical parameters of dust," recalled Leovy. "He, Rich Zurek and I published a paper[28] on the mechanisms of the great dust storms which, I believe, has stood the test of time."[29]

The primary purpose of the experiment was to collect photographs. Researchers used these images to map crater shapes, sizes and distribution, to measure the planet's slopes and elevations, and to determine the changes in surface brightness and the planet's albedo (reflected light). This experiment provided information about the red planet's atmospheric structure and circulation, details of daytime and seasonal changes, and clues regarding the possibility of life on Mars.[30]



The Mariner 9 television experiment team was at NASA JPL when pictures (above) were received, showing a global dust storm. As the storm subsided, volcano summits were the first surface features to appear. Photo credit: NASA

Jim and the others agreed that although the experiment was not expected to provide direct information regarding the possibility of life, it was expected to provide indirect evidence on the suitability of Mars as a habitat for life. "Like a lot of Mars scientists of the day, Jim had a keen interest in the question of life (on Mars)," said Leovy. "He was a pretty hard-nosed scientist and went about the problem by trying to use the data to infer the history of the planet from current observations plus some theory."[31]

As chance would have it, when Mariner 9 arrived at Mars, an enormous dust storm made it impossible to begin mapping operations. It took six weeks for the dust storm to subside. "I don't remember whether we (experimenters) were all in a

27 Masursky et al., "Television Experiment," 40.
28 Leovy, Zurek and Pollack, "Mechanisms for Mars," 749-762.
29 Conway Leovy, e-mail to author, 31 October 2007.
30 Masursky et al., "Television Experiment," 42.
31 Conway Leovy, e-mail to author, 31 October 2007.

room awaiting the first pictures, but I believe that all or most were. We knew from ground-based data that a planet-wide dust storm of exceptional intensity was underway, but were not prepared for the almost complete obscuration of the surface," Leovy continued. As the storm ended, "the gradual unveiling of Mars was a little bit delicious. Each day a tiny bit more could be seen, starting with the great volcanoes whose summits were the only surface features seen in the beginning, and were gradually revealed to be immense calderas. This discovery of powerful and relatively recent volcanism resembling the Hawaiian style was one of the first to move people's thinking away from the moon-like Mariner 4 Mars."[32]

Sagan, too, was a member of the television experiment team, and was at NASA's Jet Propulsion Laboratory (JPL), Pasadena, Calif., when the pictures were received. He said that the television pictures radioed back to Earth showed a planet engulfed in a dust storm, and were about as interesting as "… a tennis ball, but without the seams…"[33] Although the images from the spacecraft were a disappointment, other scientific instruments were sending back surprising information. The infrared spectroscopy experiment measured large diurnal temperature changes at various altitudes in the planet's atmosphere, both during and after the planet-wide dust storm. It showed that where the dust was blocking sunlight, the atmosphere of Mars was warmer than expected, and the surface was colder than expected. Carl and Jim tried to calculate these temperature anomalies, but when the dust storm cleared, they put aside their calculations.[34] This unsolved mystery started them down a path to unexpected future findings.

While the storm forced the postponement of mapping objectives, it provided an unparalleled opportunity to examine at close range a storm phenomenon on the surface of Mars. The only features clearly visible were the south polar cap, and dark spots in Nix Olympica and the Tharsis region. Since spacecraft observations were obliterated by the storm, Mariner 9 turned its attention to the Martian satellites, Phobos and Deimos.[35] Jim later identified his responsibility as being "in charge of obtaining the first close-up photographs of the Martian satellites."

NASA held a news conference at JPL to discuss the dust storms that had covered the planet and the origin of the Martian craters. Bradford Smith of New Mexico State University, Las Cruces, explained that the mission's primary objective was to "map 70 percent of the planet in high resolution." He said that if the storm did not clear up immediately, it would not be possible to do that within the nominal mission, and they may have had to focus on the dust storm. The Viking Mars landing mission would not be significantly affected by a failure to complete mapping because "Viking has the capability to keep its landers in orbit for as long as two months while it does the mapping."

Pollack also participated in this conference. He described Mars moons Deimos and Phobos: "Deimos was approximately 12 by 13.5 km (7.5 by 8.5 miles) and Phobos was 21 by 26 km (13 by 16 miles)." The moons were "among the darkest objects in the Solar System, reflecting only about five percent of the sunlight that fell on them. The moons' darkness could be attributed to basalts or carbonaceous chondrites. If scientists could determine a reason for

32 Ibid.
33 Sagan and Turco, *Path Where*, 456.
34 Ibid.
35 Masursky et al., "Mariner 9 Television Reconnaissance," 294.

their darkness, they would soon be able to determine whether the moons were captured asteroids, or remnants of material from which they formed."[36]

Mariner 9 made it possible to determine more accurate orbits of the moons, their rotation periods, sizes and shapes, and to study their surface textures and morphologies. It was now possible to estimate the ages of their surfaces; it was certain that Phobos and Deimos are at least two billion years old. "Both satellites appear to be remnants of a larger body (bodies) evolved through a complex collisional natural selection…"[37] As possibilities were contemplated, Jim, Carl and Joseph Veverka agreed that Phobos and Deimos were not artificial satellites launched by an ancient Martian civilization as had once been suggested.[38] According to Pollack, final determination of any sort of life on Mars would depend on a future landed system.

A Mars General Climate Model

To explain the unknown, theorists sometimes engage nature by first imagining a phenomenon and then creating simulations, or computer models, to work out the consequences of its physical principles. Astrophysicists build models that represent an aspect of the universe, then manipulate the model to show phenomena predicted by that model. If the model is faulty, or calculations show errors, the observers or experimentalists will detect a mismatch between the model's predictions and real occurrences in the universe. That's the first clue to try again, by either adjusting the old model, or creating a new one.[39] Jim Pollack was one such theoretical astrophysicist, although with a special gift of intuitive insight and a remarkable imagination.

During the planning and execution phases of the Mariner missions, Yale Mintz and Akio Arakawa, both University of California, Los Angeles researchers in the field of atmospheric general circulation models (GCM), were working on a model that caught Jim's attention. They had developed a general circulation model to study the underlying mechanisms of Earth's atmosphere. GCMs can predict atmospheric properties without actual data, and can be used with certain parameters (such as the axial tilt of the planet) to simulate planetary climates. This type of modeling helps assess changes in a global environment throughout geological time. A modified GCM could help scientists understand the few observations they had of the Martian atmosphere. According to Conway Leovy, Mintz wanted to apply these simulation models to all planets **---** again with the purpose of understanding how atmospheric circulation and its climate systems work. Mintz invited Leovy to help them adapt the GCM to Mars. They later published the first paper on a GCM simulation of another planetary atmosphere. "It was a pretty primitive study," recalled Leovy.[40]

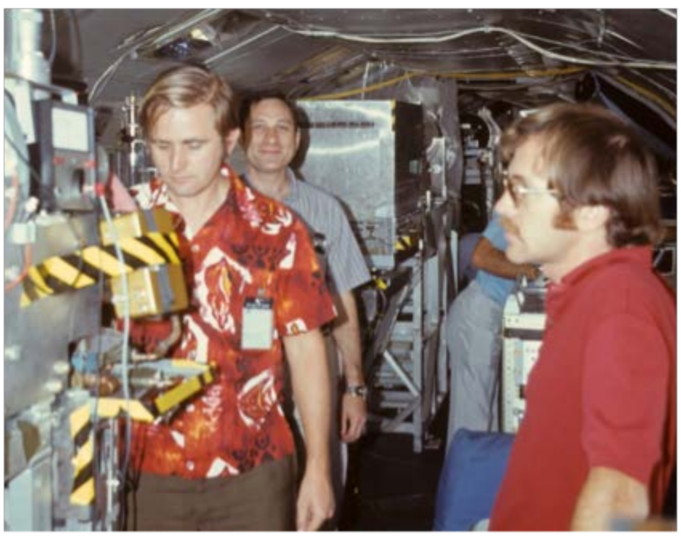
Pollack noticed their publication. By the early 1970s, he started working with Mintz and Leovy to further develop the Mars GCM. "Our motivation at the time was…very sizable elevation differences on Mars," Pollack said. Using data obtained from the Mariner 9 mission, they updated the model's topography by adding the appropriate physics for a predominately carbon dioxide atmosphere and seasonal cycle. Once modified to Mars

36 NASA Historical Office, *Astronautics and Aeronautics*, 1971, 339-340.
37 Pollack et al., "Mariner 9 Television Observations," 394, 406.
38 Shklovskii and Sagan, *Intelligent Life*, 908.
39 Neil DeGrasse Tyson, "Gravity in Reverse," 54.
40 Conway Leovy, e-mail to author, November 28, 2007.

specifications, their research group was ready to test its value. Jim enthusiastically wrote: “The two Viking spacecraft now en route to Mars are carrying instruments designed to measure wind, temperature and pressure at the planetary surface. If successful…such measurements will be of great interest as a direct check on our ability to extrapolate terrestrial meteorological theory.”[41]

Most impressively, their Mars-modified model was the first to predict winds at the potential Viking landing sites.[42] “To our relief, the landers did descend in places where the winds were mild, as we predicted,” said Jim.[43]

“I have never met anyone quite like Jim,” said Robert Haberle, a planetary scientist at Ames and Pollack’s long-time collaborator on the Mars GCM. “Jim didn’t actually do the coding, but he would write notes to programmers that were incredibly detailed and accurate. The notes were hand written without many mistakes. I still have many of them. He was just so good about seeing all the complexities and figuring out how to deal with them correctly, right from the beginning. This was truly an amazing skill.” Haberle started his NASA career working for Pollack as a postdoctoral researcher from the University of Washington (UW), Seattle. Pollack recommended Haberle to UW’s planetary scientist Conway Leovy, another giant in the field of space sciences.[44]



In August 1971, Ames research scientists (left to right) Dale Cruikshank, Jim Pollack and Terry Z. Martin were part of a Mars experiment on the Galileo Observatory, a converted Convair 990 (N711NA). In 1974, Galileo was replaced by the Gerard P. Kuiper Airborne Observatory (KAO). Photo credit: David Morrison

Jim and his colleagues made many changes and refinements to the Mars GCM; in particular, the model was used to investigate the effects of large scale, large amplitude topography on atmospheric winds[45], and the effects of dust on the heat balance and stability of the seasonal carbon dioxide ice deposits in the polar regions.[46] These measurements showed a strong coupling between the dust and carbon dioxide condensation during the winter season. The Mars GCM successfully simulated a number of observations obtained from the Mariner 9 and Viking spacecraft missions, including key characteristics of traveling weather systems (baroclinic eddies), the three dimensional (altitude, latitude, longitude) temperature fields, and the seasonal pressure variations.

41 Pollack, “Kuiper Prize Lecture,” 180.
42 Pollack, “Winds on Mars During the Viking Season.”
43 Pollack, “Kuiper Prize Lecture,” 180.
44 Robert Haberle, e-mail to author, 28 November 2007.
45 Pollack, “A Martian General Circulation.”
46 Pollack, “Simulations of the General Circulation.”

Always questioning and refining his data, he also employed the NASA Gerard P. Kuiper Airborne Observatory (KAO), a converted Lockheed C-141 military cargo plane carrying a 36-inch reflecting telescope. It was capable of conducting infrared astronomy, which he used to test the reliability of Mars' thermal infrared spectra. During one experiment, he tested the reliability of the Mariner infrared data by comparing them to KAO results. He also used these findings to develop theories of surface composition on Mars, particularly the occurrence of sulfate and carbonates on Mars.[47]

Throughout the years, new data revealed the importance of applied physics to their model. As discoveries were made of Mars' always-changing surface features, such as its reflectivity and wind streaks behind craters, scientists better understood the profound effect atmospheric dust made on its circulation patterns. They found that dust particles strongly absorb solar and infrared radiation. This absorption of the sun's rays changes the intensity of the heat near the Mars surface and in its dusty atmosphere, and subsequently its weather patterns. To include these effects in the model, an entirely new radiation scheme needed to be developed and tested. "Jim led this effort which took place throughout the 1980s. Ultimately this work contributed to our general understanding of how aerosols affect the climate system," continued Haberle.[48]

For a long time, NASA was the only agency willing to invest in such a model. But the Mars GCM predictions eventually inspired the development of more models, which started to appear in the 1990s. First, at the Geophysical Fluid Dynamics Laboratory at Princeton, then at the Laboratoire de Météorologie Dynamique in Paris, then at CalTech, and, today, there are Mars GCMs being developed in Germany, Canada, and Japan. "All of these groups acknowledge the pioneering efforts of Leovy, Mintz and Jim Pollack," concluded Haberle.[49]

Scientists now use GCMs to predict changes in temperature, humidity and winds, anywhere in the atmosphere and in three dimensions (altitude, latitude, longitude). To simulate planetary atmospheres, these models require thousands of equations that run on supercomputers. Mathematical equations written for GCMs can be identified as three separate but linked categories: the atmospheric forces (called 'dynamics'); the climate system physics; and other factors, such as topography and soil and orbital properties, such as the tilt of poles to sun which changes throughout time. GCM equations are based on known physical laws such as the conservation of energy and mass, as well as relationships based on observations, such as those between temperature and humidity changes in cloud formation.[50]

As mindboggling as computer modeling may be for most researchers, it's the minor things that sometimes most confound us. In the early 90s, Ames used VAX and UNIX computers for its email program that was basically ascii text files. Julie Moses, an NRC post doctoral researcher back then, remembers a funny story about Jim. She was meeting with Jim to go over a complicated algorithm, and was impressed by Jim's knowledge of the physics and even numerical methods used in the algorithm. Before the meeting ended, an information technology person had entered the room to explain the problem Jim was having with his VAX VMS computer account. Jim had filled his entire computer disk with undeleted email messages, who seemed astonished that (a) email messages could be deleted, (b) email

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47 NASA Ames History Office, PP05.03, Acq. 009-2005.
48 Robert Haberle, e-mail to author, 28 November 2007.
49 Ibid.
50 NASA Ames Mars Climate Modeling Group. http://spacescience.arc.nasa.gov/mars-climate-modeling-group/ (accessed 12 March 2014).

messages were stored at all, and (c) he would be expected to know how to delete email messages. The problem was Jim had years and years of email messages clogging his machine. "I came to realize that although he was well versed in computer algorithms and numerical methods, he didn't actually touch the computer much himself, at least when I knew him," said Moses.[51]

What? No Life Forms?

More than four years lapsed between the Mariner 9 launch in May 1971 and the first Viking launch in August 1975. A few weeks later, on September 9th, NASA also successfully launched Viking 2. Both spacecraft consisted of an orbiter and a lander, and both were designed to take high-resolution images of the Martian surface, characterize the structure and composition of the atmosphere and surface, and search for evidence of life. On 20 July 1976, Viking 1 touched down at Chryse Planitia. Viking 2 touched down at Utopia Planitia two months later.

The Viking mission performed the first successful entry, descent and landing on Mars. The landers accumulated 4,500 images of the Martian surface, while the orbiters provided more than 50,000 images, mapping 97 percent of the planet. The results from the Viking experiments gave the most complete view of Mars for that time. Volcanoes, lava plains, immense canyons, cratered areas, wind-formed features, and evidence of surface water were apparent in the orbiter images. The planet appeared to be divided into two main regions, northern low plains and southern cratered highlands. Images showed surface features of these regions that included the Tharsis and Elysium bulges, which are high-standing volcanic areas, and Valles Marineris, a system of giant canyons near the equator. The surface material at both landing sites was characterized as iron-rich clay. Temperatures at the landing sites ranged from 150 to 250 K (-190 degrees to -10 degrees Fahrenheit), with a daily variation of 35 to 50 K (about 30 degrees F). Observations included seasonal dust storms, pressure changes and tracking of atmospheric gases as they travelled between polar caps. There was no evidence of life at either landing site. The data also suggested that early Mars was very different from the present planet. Originally designed to function 90 days, the Viking space probes continued collecting data for more than six years.

The success of the Viking mission represented the work of thousands of people whose signatures were contained in a microdot attached to each of the Viking Landers. Jim participated on the Viking 1 and Viking 2 Lander imaging science team by recommending imaging sequences for the Viking lander cameras.[52] Pollack's sequences included instructions for timing of the shots, phase angles, and various width of angles, use of filters and calibrated exposures. He used these results to further understand the properties of the atmospheric dust[53] and its profound impact on the atmospheric temperatures and winds.[54]

The first color image of Mars was eagerly awaited, as Viking 1's camera scanned its surroundings through filters of red, green and blue. On Earth the data were converted into images by exposing a sheet of color film to red, green, and blue laser beams, reproducing

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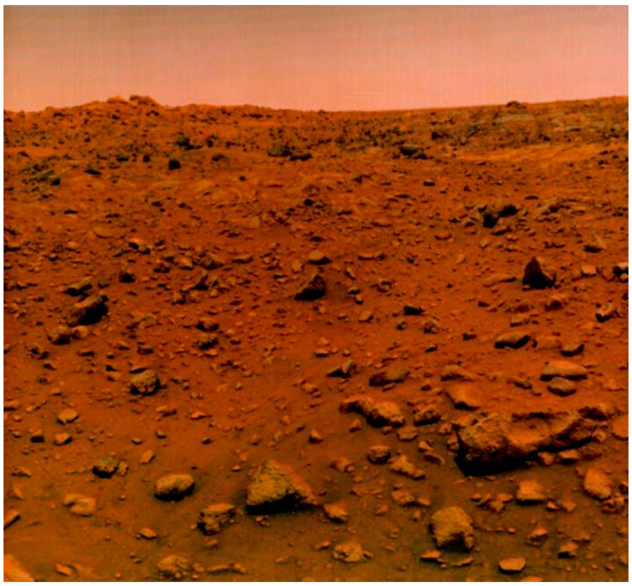
51 Email from Julie Moses, 11 July 2014.
52 NASA Ames History Office, PP05.03, Acq. 009-2005.
53 Pollack, "Properties and Effects of Dust Particles," 1979.
54 Haberle, "Some Effects of Global Dust Storms," 1982.

the scans of the Viking imager. But the cameras started to relay unexpected data, and there was difficulty matching the color filters on the Viking with the laser beams used to produce the photos on Earth. The color imaging had to be recalibrated with techniques used in the test shots on Earth. People were astonished by the first color picture that revealed a brick red ground and a salmon pink sky. The pictures were viewed with skepticism. The imaging team sensed people's mistrust of the colored pictures, and corrected the images to reveal a more appealing brick red ground with bluish shadows and muted gray skies. The correction was broadcast on TV, and a hard copy was released to the media.



Viking was equipped with color calibration swatches to gauge the accuracy of the color images. When the color images were checked, Mars really had a brick red surface and a pink sky. Pollack announced the error the following day and was heckled by those who viewed the new image. But his assertion proved accurate. Sagan said that people were not ready for Mars to be different than Earth.[55]

The first Viking image (left) of Mars revealed a brick red ground and a salmon pink sky. Sagan said that the public wasn't ready for Mars to be different from Earth. Photo credit: NASA

On November 9, a press conference was held at NASA JPL, where Viking project scientists said that the $100 million spent by the U.S. on the search for life on Mars had produced only disagreement over findings. Four of six Viking scientists said they did not know whether life existed on Mars; one denied that Viking had found life; the sixth said he felt Viking had found "primitive microbes" in the Mars soil samples. All six agreed that Viking had found nothing at either the Chryse or the Utopia landing sites representing fossils that would have confirmed a previous existence of life on Mars, reported Thomas O'Toole of the *Washington Post*. Harold P. Klein of Ames said the Viking results "do not rigorously prove there is life on Mars, nor do they rigorously disprove it."[56]

"The Viking mission focused on the search for live microbes in Mars' soil. The biology experiments on Viking were looking for active metabolism," said Chris McKay, a NASA authority on Mars and space scientist at Ames. "The Viking results were pretty discouraging in terms of active life on the surface. At the same time, the Viking results (and Mariner 9 before that) found fluvial channels which indicated that in the past the climate on Mars was much different than today. Gradually the consensus of scientific opinion turned away from a Viking-like search for active life, to a search for early climate and early fossil evidence of life."[57]

55 Poundstone, *Carl Sagan*, 207-208.
56 Ritchie, *Astronautics and Aeronautics*, 1976, 274.
57 Chris McKay, e-mail to author, 15 December 2007.

Pollack and then post-doctoral researcher Jim Kasting, now Distinguished Professor of Geosciences and Meteorology at Pennsylvania State University, University Park, published a provocative paper titled "The Case for a Wet, Warm Climate on Early Mars," in which they make the case for a warm, early Mars, due to a dense carbon dioxide atmosphere. "Some researchers believe that Mars was never warm and Earth-like and that the fluvial features formed under much colder conditions. Today, thirty years after Viking, we are still arguing about these same issues," said Kasting. "People are once again interested in the possibility of subsurface life. There are (unsubstantiated) reports of methane in Mars' atmosphere, which could conceivably be biological. So, the question of whether there is extant life on Mars has not gone away."[58]

The next opportunity to make close-up, remote sensing observations of Mars arrived when the Mars Observer spacecraft launched in 1992.[59] It was the first of the Observer series of planetary missions, designed to study geoscience and climate. In preparation for the launch, NASA named its interdisciplinary scientists in 1986. Pollack was selected as the interdisciplinary scientist for the Atmosphere and Climatology investigation. This experiment investigated the influence of dust on atmospheric circulation, the factors that control the life cycle of dust storms, the seasonal water cycle, the transport of dust, and an early dense carbon dioxide atmosphere.[60] The Mars Observer was one of NASA's first low-cost planetary missions, of which Jim was an early advocate.[61]

A very large crater in the Sinus Sabaeus quadrangle was named for Pollack by the International Astronomical Union in 1995. Photo shows the Pollack Crater and the White Rock. Photo credit: NASA

Pollack made numerous extraordinary contributions to Mars research. Throughout his career, Jim was an author or co-author of more than 86 publications on Mars. Soon after Mariner 9 arrived at Mars, he and his colleagues published papers on Mars' atmosphere and surface, estimated erosion rates and moons Phobos and Deimos. While still new to NASA Ames and its research facilities, he used the Ames wind tunnels to simulate first the light and dark streaks on Mars, and later the threshold wind speeds for sand on Mars. His research included the properties and effects of aerosols in the Martian atmosphere, estimates of wind friction speeds for dust particle movement and the Martian twilight. He also played an important role in studies of possible climate changes in the planet's past.[62] For instance, he was the first to suggest that a much more massive carbon dioxide-rich atmosphere than the present one could have raised the surface temperature on early Mars to the freezing point of water, setting the conditions for the formation of valley

58 Jim Kasting, e-mail to author, 11 January 2008.
59 Bowker, "American Men and Women," 1124, NASA NSSDC, http://nssdc.gsfc.nasa.gov/nmc/experimentSearch.do (accessed 19 March 2014).
60 NASA NSSDC, "Mars Atmosphere and Climatology (IDS)," http://nssdc.gsfc.nasa.gov/nmc/experimentDisplay.do?id=1992-063A-14 (19 March 2014).
61 NASA Ames History Office, PP05-03, Acq. 009-2005.
62 Pollack, "Climate Changes on the Terrestrial Planets," 1979.

networks on the ancient cratered uplands. He used the Ames supercomputers to construct numerical models of Mars physics, simulating its polar cap winds, the abrasion of windblown particles, and the violent dust storms. One of his last simulations studied the formation and evolution of water ice clouds in the Martian atmosphere.

"…Mars was his first love; I believe his first computer password was 'martian,'" said Jeff Cuzzi, a space scientist at Ames.[63] Bradford A. Smith, deputy leader for the Mariner 9 Imaging Science Team and leader of the Voyager Imaging Science Team, agrees, "Jim's overall contributions to our knowledge of Mars are recognized in crater Pollack on Mars."[64]

Pollack was known in the Mars research community for his atmospheric research. In his honor, a very large crater in the Sinus Sabaeus quadrangle of Mars was named for him by the International Astronomical Union in 1995. The Pollack Crater contains "White Rock," an identifying mark of the crater. "I think this was the first crater observed to have obvious sedimentary deposits on the floor, and its relatively light color attracted a lot of interest at the time. We know now that many of the large ancient craters on Mars have eroded sedimentary deposits on the floor, and that many of these deposits are rich in gypsum and other salts," said Leovy.[65]

As engaged and productive Pollack was studying Mars, like so many other planetary scientists, he also was looking beyond Mars and the asteroid belt.

63 Jeff Cuzzi, e-mail to author, 31 August 2008.
64 Bradford A. Smith, email to author, 22 June 2008.
65 Conway Leovy, email to author, 3 November 2008.

Above photo shows Tom Gehrels, an astronomer at the Lunar and Planetary Laboratory *at the University of Arizona, Tucson, and James Pollack during the 1974 Pioneer press conference at Ames. Photo credit: NASA*

In 1963, NASA's Lunar and Planetary Programs Office commissioned a series of studies, conducted by the Astro Sciences Center of the Illinois Institute of Technology Research Institute (ASC/IIT), to investigate the feasibility of a deep space mission. Jupiter was of special interest to the science community because it is the closest planet of a "separate" planetary group from Earth. Jupiter is by far the largest planet in the solar system, with a predictable orbit that made it a promising target. Its size and low density are characteristics of the Jovian group of planets, as opposed to the small, high-density terrestrial planets. After more than 300 years of observation, no one knew what lay beneath its dense atmosphere and cloud coverage. The ASC research group started its investigation from the beginning, by discussing theories of Jupiter's origin and its physical properties.[66]

In the 1950s, Gerard P. Kuiper and others theorized that the Solar System was formed by condensation from a massive stellar cloud using only mechanical forces and dynamics.[67] The planets were formed from very large protoplanets, reduced in size by evaporation. Kuiper suggested that Jupiter's size may have been 20 times larger than its present size. The protoplanets continued to condense and shrink in size, some localized condensations may have escaped to form the planets' satellites.[68] The other basic theory of origin was postulated by Hannes Alfven and Gustav Arrhenius, which agreed that the planets were formed by

66 Roberts, "Scientific Objectives," 1.
67 Kuiper, Astrophysics, 1951.
68 Kuiper, Vistas in Astronomy, 1956.

condensation from a stellar cloud, but their theory required the stellar cloud to consist of a hot, ionized gas that resisted the sun's gravitational pull by the strength of the condensing planet's magnetic field and the type of ions condensing. They also postulated that the terrestrial planets were formed from a different cloud than the giant gas planets.[69]

The ASC group reviewed the known physical properties of Jupiter and defined the scientific objectives for a mission to this planet. They said that past observations of Jupiter were limited by the planet's atmosphere and cloud layer. They knew that Jupiter was the most massive planet in the Solar System, 318 times greater than Earth. Its size is one tenth of the sun's, and its measured albedo (reflectivity) is 0.44, which is less than the planet Venus. Jupiter's visible surface shows grays, browns, reds and blues, but no one knew the reasons for these colors. Some scientists thought that they may be due to the sodium in ammonia, others thought that organics, oxides, nitrogen or hydrogen may be the reason. Scientists agreed that the main constituent of the Jovian atmosphere was hydrogen with less helium and impurities of argon, ammonia, and methane. The more striking features of the atmosphere were the light and dark cloud belts that suggested high winds and severe turbulence. Whether the deep "surface" of Jupiter was liquid or solid was completely unknown, since it was not visible from Earth. It was generally accepted that Jupiter had a solid metallic hydrogen core, and radio emissions from the planet implied it had a magnetic field.[70]

The many deductions made about Jupiter's physical properties needed to be verified or disproved. Questions pertinent to the understanding of Jupiter were identified and considered for experimental purposes.

The ASC report[71]also proposed experiments and their measurements for a Jupiter mission. Convinced that the future "state-of-the-art" technology would meet the challenge, ASC recommended a flyby spacecraft, but favored an orbiting space probe, one that landed on one of Jupiter's satellites and thus always faced the planet. Although crossing the asteroid belt was recognized as risky, the report recommended using simple probes as trailblazers to map a course through the asteroid belt to prevent collisions for the primary spacecraft. The second phase of investigation would include entry into Jupiter's atmosphere and possibly landing on the planet. Biological measurements in and below the atmosphere was another consideration, as was gathering interplanetary data between Earth and Jupiter.

In a second report,[72] minimum experimental payloads were selected for a three-spacecraft mission. The ASC group felt confident that by using state-of-the-art technology, the next-generation launch vehicles would be capable of such a mission. The report concluded that both flyby and orbiter configurations seemed "feasible" and further NASA effort was needed to estimate costs for the next stage. NASA was going to Jupiter.

Pioneering the Way

When Pollack joined NASA in 1970, Ames was managing the Pioneer Program, a series of unmanned space missions designed for planetary exploration. Pioneer 10 and 11 were low-cost exploratory missions that would fly by Jupiter. Although engrossed with studies of Mars

69 Alfven, *On the Origin*, 1954.
70 Roberts, "Scientific Objectives," 7-9.
71 Roberts, "Scientific Objectives," iv-12.
72 Roberts, "Survey of a Jovian Mission," 1-36.

and Venus, and with support of his supervisor Ray Reynolds, then chief of the Theoretical Studies Branch, Jim broadened his field of study to include the primitive gas giants.

Pioneer 10 (Pioneer-F) was launched on 3 March 1972. With a mission to travel through the asteroid belt and fly by Jupiter, it was the first spacecraft to obtain close-up photographs of Jupiter and measure its twilight side, never before seen from Earth. It was also the first spacecraft to observe the asteroid belt between the orbits of Mars and Jupiter, the first man-made object to use a "gravity assist" maneuver from a planet to escape the Solar System, and the first NASA spacecraft powered exclusively by nuclear energy. It carried 11 scientific experiments that successfully provided new information on Jupiter, the Solar System and the Milky Way.[73]

By September 1972, Pioneer 10 had traveled almost half of the 620-million-mile distance to Jupiter. Racing through the asteroid belt at 50,000 mph, the spacecraft successfully transmitted data at the speed of light to the Deep Space Network, with a round trip communication time of three minutes.

According to the *Washington Post*, anxious scientists had assembled at the Ames Mission Control Center on 3 December 1973 to await the fate of their tiny, 500-pound spacecraft as it approached the harsh radiation of Jupiter, radiation that was increasing ten-fold every two hours. The mood was tense as Pioneer 10 raced past Jupiter at an altitude of 81,000 miles, and at a record-breaking 96,400 mph, the fastest speed ever achieved by a man-made object.

Image is an artist's concept of NASA's Pioneer 10 spacecraft flying by planet Jupiter. Image Credit: NASA

After a flight of 641 days and 513 million miles, the spacecraft's 11 instruments transmitted readings and pictures that came in loud and clear, taking 46 minutes to reach an ecstatic team on Earth. "Needless to say, we're elated," said John Wolfe, the Pioneer project scientist, to an applauding group of reporters. "So deluged were Pioneer scientists with transmissions of the spacecraft's instruments, they were literally changing their minds about Jupiter's physics and chemistry every hour." NASA Administrator James C. Fletcher said, "Some of us have been looking through telescopes at Jupiter since our early teens. This is more than we ever dreamed of."[74]

Pioneer 10 was expected to transmit data until 1980, but continued sending information about solar winds until 2003. The mission was officially declared a success 9 January 1974.[75]

73 Science, *Astronautics and Aeronautics*, 1972, 81.
74 Science, *Astronautics and Aeronautics*, 1973, 310.
75 Ibid., 311.

Preliminary findings included Jupiter's moon Io surrounded by an ionosphere (an electrically charged outer region of the atmosphere), indicating it had an atmosphere; helium present in Jupiter's atmosphere; new density measurements of the planet; and similar temperature readings for both average day- and nighttime temperatures; all of which changed then current theories of the formation of the universe.

NASA's second Jupiter probe, Pioneer 11 (Pioneer-G), was successfully launched on 6 April 1973. The primary objective was the same as the Pioneer 10 spacecraft, to return scientific information about the asteroid belt and Jupiter. Its secondary objective was to advance the technology for long-term flights to the outer Solar System. On April 11, the midcourse correction moved the target point at Jupiter to allow more mission options: to fly by one or more of its moons, to fly by the planet's flattened pole, to fly on to Saturn in 1980, or to leave the Solar System like Pioneer 10. As it happened, Pioneer 10's successful flyby of Jupiter in December determined the new course.

During this time, Pollack wrote and published (1975) in *Space Science Reviews* a 90-page, comprehensive review, titled "The Rings of Saturn,"[76] which summarized the current status of the observational data and critically examined the analyses that had been made of them. He assessed observations of the rings of Saturn at visual, infrared and radio wavelengths, and evaluated past attempts at deriving the physical characteristics of the rings from these measurements. His review included a discussion of the origin and evolution of the rings, including the early science history of the Saturn system. Before Pioneer 11 reached mid-course, a decision was made by the spacecraft team to re-target the spacecraft for Saturn. This new path would be used for the Voyager spacecraft mission. Pioneer 11 was scheduled to reach Jupiter in December 1974. It would be the first spacecraft to explore the planet Saturn and its main rings, passing by the planet on 1 September 1979.[77]

The Evolution of Jupiter

During this time, few planetary scientists (except A. G.W. Cameron from Harvard University and Victor Safronov from the Soviet Union) seemed interested in explaining the evolution and formation of the planets; most seemed focused specifically on the observed properties of the planets. Pollack, however, was already thinking deeply about the "big picture." As a NASA employee, he now had access to impressive resources, talent and research facilities to study the outer planets and their satellites in the Solar System. He had theories, and now needed a team of experts to test and validate these theories using real observations. At this time, this area of research had previously been regarded as speculative and/ or unapproachable, according to Jeff Cuzzi, an Ames space scientist and world authority on the rings of Saturn.

Pollack theorized that since hydrogen and helium are the most abundant elements in the atmospheres of the outer planets, but not for the inner terrestrial planets, the outer planets are unique in that they were able to retain significant amounts of the gases most abundant in the primordial solar nebula. Therefore, he reasoned, the origin and evolution of the atmospheres of the outer planets are intimately tied to the origin and evolution of the giant planets and the Solar System as a whole.[78] In the early 1970s, he started thinking about building models that

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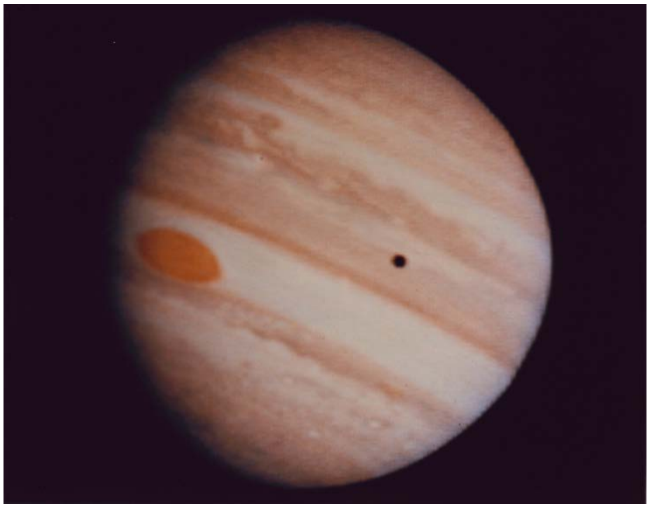
76 Pollack, "The Rings of Saturn."
77 Science, *Astronautics and Aeronautics*, 1973, 106-107.
78 Pollack and Bodenheimer, "Theories of the Origin," 564.

would represent the “evolution and origin” of the gas giants and Solar System, by showing predicted phenomena. Jim and a select group of researchers would prove that looking outward into space would be like looking backward into time.



Using data collected during NASA missions, Pollack and his team constructed a Jupiter model, composed of hydrogen, which gave the correct energy output, at approximately the correct radius, and at the correct age of the Solar System. Pioneer 10 spacecraft, managed by Ames, was first to obtain close-up photographs (left) of Jupiter, and collect data on the Jovian aurorae, Jovian radio waves, the atmosphere of Jupiter and some of its satellites. Photo credit: NASA

Jim’s daily routine consisted of setting aside mornings to read and write, and concentrate on his work. Afternoons were for discussions, problem-solving and the other demands of the day. He was a voracious reader, and took an interest in what other scientists were publishing in the field. If a publication caught his attention, he contacted the author for discussion, or possible collaboration. “It was part of Jim’s genius to see the big picture, and how it all could fit together to solve a problem, and how that problem related to even bigger questions. He had a talent for bringing people together, creating the appropriate mix of expertise to make progress,” said Cuzzi. As a young scientist, Cuzzi knew of Jim’s genius and came to Ames to work with him; he was Pollack’s first postdoctoral researcher.[79] He also knew that Pollack’s leadership brought recognition and insightful perspective to projects.

Two scientists who caught his attention at this time were Allen Grossman, an astronomer from Iowa State University, Ames, and Harold (Hal) Graboske, a physicist from Lawrence Livermore National Laboratories, Calif. They were developing a computer model of the evolutionary histories of very-low-mass stellar objects. As a graduate student at Indiana University, Bloomington, in the late 1960s, Grossman started developing a computer model to simulate the internal structure and time evolution of low-mass stars. “Prior theoretical work, by several authors during the 1950s, seemed to suggest that Jupiter may have undergone such an evolutionary process,” said Grossman.[80] To study these evolutionary histories, he joined forces with Graboske, an expert on the properties of hydrogen and helium gases at densities and temperatures that occur at the centers of these stellar objects.

Pollack hypothesized that the process used to study the evolution of very-low-mass stars also could be used to study the evolution of Jupiter. To test his theory, he needed the supercomputers, Grossman’s star code, Graboske’s data set of thermodynamic properties for the hydrogen-helium mixture in Jupiter, and his own “radiative transfer” code (equations

79 Jeff Cuzzi, e-mail to author, 31 March 2008.
80 Al Grossman, e-mail to author, 3 November 2007.

that measure how thermal energy redistributes itself by infrared radiation being absorbed, re-emitted, and scattered by gas molecules and small particles, while visible light from the sun enters the upper atmosphere) to define the boundary of their model. To support this work, Grossman came to Ames in 1972 as a summer NASA research associate. According to Grossman, that summer is when they started to include Jupiter-mass objects in their modeling.[81]

Pollack was aware that infrared observations of Jupiter showed that it was radiating about two and a half times more energy than it was receiving from the sun. These observations confirmed the earlier suspicions that Jupiter might have undergone stellar-like behavior. "Thus, the problem became clear!" said Grossman. "Could we construct a computer model of Jupiter that started from a large cloud, contracted to the size of Jupiter, and have the same excess energy emission as when the solar system began? Is Jupiter a real stellar object, a so-called 'brown dwarf' star?"[82] (A brown dwarf star is a cold, dark star that is too small to initiate the nuclear reactions that generate heat and light.)

As their work progressed, Pollack theorized that Jupiter's atmosphere regulates the rate at which internal energy escapes from the planet's surface, and indirectly regulated the rate of contraction by the proto-Jupiter cloud, an early stage of Jupiter's birth. This theory posed a numerical problem that was complicated by the fact that, in addition to energy flowing from the surface, solar energy was flowing into the surface. Another complication was the nature of the molecules absorbing the radiation in the atmosphere; such "absorbers" include hydrogen, ammonia, water vapor and methane. To calculate the energy flow of the atmosphere, they needed to know the molecular composition at each point in the atmosphere. Each point of molecular matter was defined by its temperature, pressure and chemical composition. For Jupiter and Saturn, they used a temperature range of approximately 100 to 5000 K (-279 to 8540 degrees Fahrenheit) to cover the thermal properties used in the modeling.[83]

Pollack solved the planets' "atmospheric heat transfer" problem by using the same methodology he developed early in his career for the greenhouse model of Venus.[84] "This area was where Jim had expertise and was able to provide me (the star modeler) with a temperature-pressure point for each time in the evolution calculation. We showed that our Jupiter model, composed of hydrogen, could give the correct energy output, at approximately the correct radius, and at the correct age of the Solar System. This calculation seemed to validate earlier speculation that Jupiter lies close to the star-planet interface," said Grossman.[85]

For many years, Pollack and his modeling team continued to collaborate and publish their findings about the "evolution" of the giant planets.[86] According to Graboske, now an emeritus professor in the Atmospheric Sciences and Geophysics Division at Lawrence Livermore, the success of their findings was based partially on Grossman's "star code," which was the framework of their research; Graboske's application of the interior physical properties of planetary materials, using an ultrahigh pressure, and high-temperature fluid mixtures of light elements up to argon; and Pollack's radiative transfer codes that measured the heat exchanges

81 Ibid.
82 Ibid.
83 Al Grossman, e-mail to author, 5 November 2007.
84 Pollack, "A Non-Gray Carbon Dioxide."
85 Al Grossman, e-mail to author, 3 November 2007.
86 Grossman et al., "Evolutionary Calculation;" Graboske et al. "Structure and Evolution."

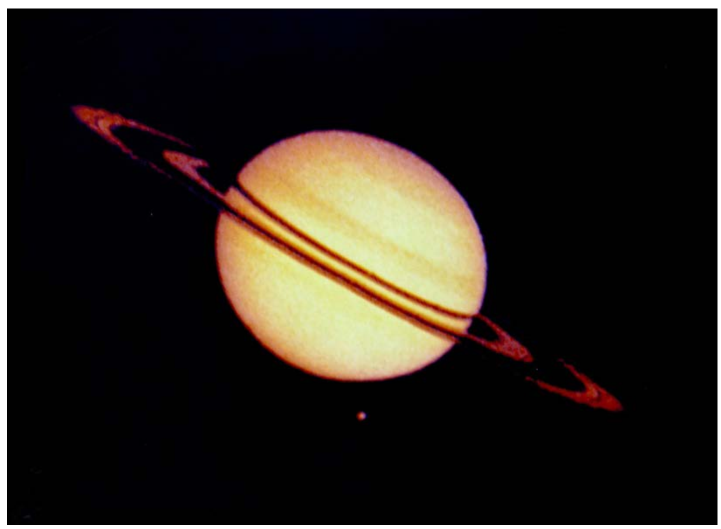
in Jupiter's atmosphere. "Jim was the world's expert, I believe, on the atmosphere of the 'outer giant' planets. The role of the atmosphere in controlling thermal energy release from the interior was critical in getting a good picture of how the interior approached, and then receded from 'stellar ignition.' At the time, the composition was not tightly quantified," said Graboske.[87]

The Evolution of Saturn

Flushed with success, the same team tried a similar calculation for Saturn, which was also observed to be radiating more energy than it was receiving from the sun. The Saturn results seemed to show that gravitational contraction could not produce enough energy to agree with the observations at the current age of the Solar System. Scientists thought that the settling effect of Saturn's helium toward its core provided the additional energy that powers this excess emission. However, at the time, their research showed that a dense rocky core made of very heavy elements was needed to bring their evolutionary models into agreement with the correct values for radiation, size and age of Saturn. The value of this core was about three Earth masses (it's now thought to be between 10 and 15 Earth masses). "This was interesting because other researchers had shown that both Uranus and Neptune also seemed to have similar mass rocky cores," said Grossman.[88]

Pollack also thought that the strength of Jupiter and Saturn's radiated energy, during the early evolution phase, might have played an important role in their moons' densities and distances from their mother planets. A study [89] showed this to be the case, and also suggested why Saturn had a massive ring system and Jupiter did not. At the time, Saturn's rings were discovered to be strong radar reflectors, but weak emitters of radio waves. Their weak emission suggested small particles in the rings, but the strong reflection excluded this possibility. Scientists could only speculate what this new oddity might mean. Some thought spheres of solid metal in the rings were causing the strong bounce-backs. Pollack, however,

The weak emission but strong reflection of microwaves by the rings was a major puzzle. Scientists could only speculate what this new oddity might mean. Pollack, however, correctly proposed that normal water ice particles of the proper size could explain this phenomenon. Photo at right was taken by Pioneer 11 at a range of 1,601,274 miles, and enhanced to provide more detail in rings. Photo credit: NASA 1979



87 Harold Graboske, e-mail to author, 30 October 2007.
88 Al Grossman, e-mail to author, 3 November 2007.
89 Bodenheimer et al., "Calculations of the Evolution." 1980.

correctly proposed that normal water ice particles of the proper size could explain this phenomenon, a property that later tied together the origin of the rings and their parent planet. "Jim's proposal was very controversial," said Cuzzi. "In 1973, I was a postdoctoral researcher and a radio interferometer specialist at the University of Massachusetts. I tried to prove him wrong, and ended up proving him right. Jim's insight was both creative and profound."

With this new discovery, Pollack continued to study the origin of the moons of Jupiter and Saturn. He, Joseph Burns and Michael Tauber published a paper[90] in 1979 that discussed the satellites of the outer solar planets. They wrote that these satellites can be divided into two groups based on their orbital characteristics: regular and irregular satellites. Regular satellites orbit very close to the equatorial plane of their parent planet, in almost circular orbits, and move in the direction of their parent planet's rotation. These characteristics suggested that regular satellites formed as part of the same process as their parent planet. Conversely, the irregular satellites have eccentric orbits inclined to the equatorial plane and travel both with and against the rotation of their parent planets. They are always located much farther from the parent planet than the regular satellites and are much smaller. These characteristics strongly suggest that irregular satellites were formed outside the zone of their parent planet, and were subsequently captured. To validate their assumptions, these scientists used the "evolution" models to explain the origin of the irregular satellites, as they were captured by the drag of a planet gripping the gases surrounding it.[91] According to Grossman, these studies showed that giant planets, or small stars, fit into a normal stellar evolution pattern. It became clear that our Solar System was not a freak of nature, but a normal outgrowth of diverse physical processes. Today, most stars are known to have planetary systems, where these processes are surely occurring.[92]

As NASA's unmanned missions continued to provide new sets of data, Jim and his research teams were busy assimilating them into new concepts and models, and modern paradigms of the origin of planets. With a consistent scenario of the early evolution of gas giants successfully modeled, Pollack next sought to study the path by which they achieved their massive initial state. He had already reviewed aspects of the origin of the Solar System based on his modeling of the evolution of the giant planets.[93]

The Origin of Jupiter

When Pollack was attending Berkeley in the 1960s, he met Peter Bodenheimer, who was a graduate student in astronomy there. Bodenheimer later became an expert in stellar-evolution modeling, which caught Jim's attention. Pollack was aware that Bodenheimer was collaborating with David Black, another space scientist at Ames, on a project studying the collapse of protostellar clouds. These clouds are composed of interstellar gas and dust grains that eventually collapse, forming a hot, dense core, which evolves into a star. Bodenheimer had modified an original code, designed by Louis G. Henyey at Berkeley, to study early evolutionary phases of star formation before the star stabilizes. His basic methods were similar to those of Grossman and Graboske, but the details and physics included in the code

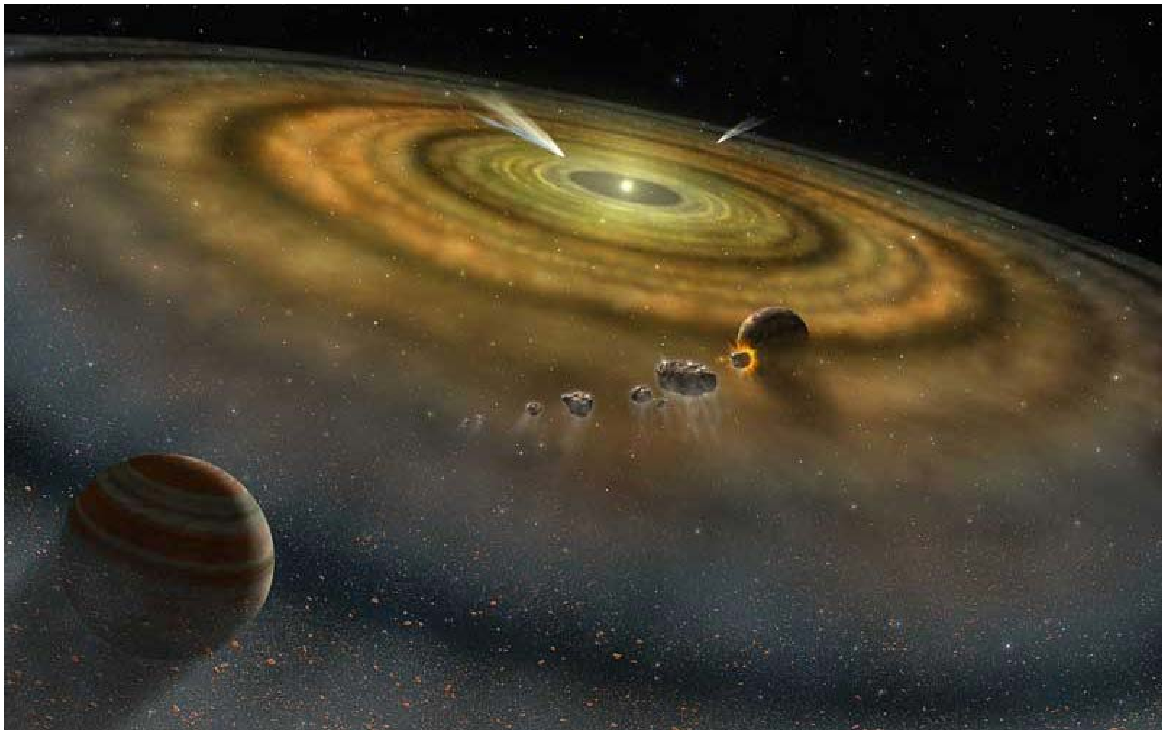
90 Pollack, Tauber and Burns, "Gas Drag in Primordial," 588.
91 Ibid.
92 Al Grossman, e-mail to the author, 3 November 2007.
93 Graboske et al. "Structure and Evolution," 1975.

were different. “Al Grossman’s model didn’t really do planet formation; it calculated the evolution of a planet, after it had already formed,” said Bodenheimer, an astronomy professor at the University of California at Santa Cruz.[94]

The original computer modeling was done in phases. The first phase was based on a planet-formation model of a gas giant with a very large radius. The model showed the planet contracting to a radius near the present value, slowly cooling its warm interior as it continued a very slow gravitational contraction. As was first shown by Hiroshi Mizuno, a space scientist at Kyoto University, Jupiter’s formation was different than most stars; it did not start with a uniform composition of pure gaseous hydrogen and then condense into a solid core, but instead it started with a solid core onto which the gas accreted. The models included an interior region of dense fluid, the most important ingredient. This interior region fed into the atmosphere and determined how radiation energy was liberated at the surface. “Jim’s contribution was again the atmospheric portion, including the opacities from various molecular sources,” said Bodenheimer.[95]

Opacities refer to the “opacity” values of various grains of dust thought to have been present in the early solar nebula surrounding the sun, and in the smaller primordial nebulae surrounding the outer planets. Scientists describe both nebulae as rotating, flattened clouds of gas and dust from which the sun and the other bodies in the solar system formed, about four and a half billion years ago. Pollack calculated these opacity values by determining the radiation absorption of different species of grains, such as ice and liquid water, magnetite, iron, silicate, obsidian and basalt. These opacities are important because they control the observable brightness and temperature of the planet.[96] These refined values [97] were included in Bodenheimer’s stellar evolution code. “We were trying to follow the entire evolution to see if we ended up with the present Jupiter,” said Bodenheimer.[98]

94 Peter Bodenheimer, e-mail to author, 14 November 2007.
95 Ibid.
96 Ibid.
97 Pollack and McKay, “Calculation of the Rosseland,” 471-492.
98 Peter Bodenheimer, e-mail to author, 14 November 2007.



With a consistent scenario of the early evolution of gas giants successfully modeled, Pollack next sought to study the path by which they achieved their massive initial state, the origin of these gas giants. After a decade, Jim and his research teams successfully constructed models of the "origin and evolution" of the outer planets and their moons and ring, and were the first, self-consistent, realistic, quantitative models of the epoch. Photo credit: NASA

In very early planetary development, these massive objects go through stages in which they initially grow slowly by aggregating small solid bodies and gas from the surrounding nebula. As they grow in mass, they start to simultaneously generate heat from the internal energy caused by the compressing and shrinking mass. They then undergo dramatic and rapid growth of the gas, when the envelope ionizes and loses the ability to retain heat. Finally, they follow a lengthy evolution on cosmic timescales, slowly radiating away their internal heat, as shown by the excess heat fluxes observable even today in three of the four gas giants, and further sweeping-up volatile-rich planetesimals into the dense, giant planet atmosphere.[99]

Jim and his teams constructed models of these developmental and evolutionary stages, and were the first, self-consistent, realistic, quantitative models of the epoch.[100] Today, these models provide foundations for contemporary studies in these areas. Scientists Jack Lissauer, Olenka Hubickyj and others, have continued their legacy in gas giant formation. This research so inspired scientists that they proposed a new program, called the "Origins" program, to NASA management; Jeff Cuzzi and Sherwood Chang of Ames were among the first to suggest it. At the time, HQ managers Joseph Boyce, Jeffrey Rosendahl and Joseph Nuth considered

99 Cuzzi, J.N., "James B. Pollack."
100 Ibid, 9.

it novel and invigorating, and committed themselves to its initiation and implementation. Many believe NASA's "Origins" program can be traced to Jim's big picture approach, and probably also to his early mentor and collaborator Carl Sagan.

Stardust Properties

Pollack's studies of the origin and early history of the Solar System and outer planets were centered on the primordial stuff of the universe, namely "stardust." According to some theories, after the Big Bang, thin clouds of mostly hydrogen and helium gases started to form in the cold, dark universe. The first stars contained only hydrogen and helium, but later created the heavier elements, such as carbon, nitrogen, oxygen, silicate, iron, etc. in their interiors by nuclear fusion. When they exploded, these heavy elements were ejected into space – stardust. Minute dust grains started to form from these heavy elements throughout the universe. These dust grains, then and today, are composed of mostly ices, but also consist of carbon, silicates, organics and iron. As these clouds of gas and dust became denser, they became more and more opaque. The tiny grains of dust block starlight causing the clouds' interiors to be very cold.

Samples of obsidian from Little Glass Mountain, Calif., were analyzed to determine the opacity value of stardust in interstellar clouds, called nebulae. Photo credit: US Forest Service

Pollack understood the importance of detail and how it influences a theorist's assumptions and future experiments. He thought it essential to estimate real opacity values for these dust grain species. The opacity determines temperature and energy balance of a molecular cloud, or a planet's atmosphere. Typically, opacity values are based on grain composition, size and physical properties. Refining these opacity values may have been Pollack's first actual contribution to "Stardust" research.[101]

To determine these values, Pollack and Sagan designed a practical experiment in 1972, using material they considered plausible as stardust. They wanted to build reliable models of planets' atmospheres. To obtain quality results, they needed quality opacity values. To better control this one variable, the opacity of stardust, they purchased two samples of obsidian (from Little Glass Mountain, Calif. and Lake County, Ore.) and one sample each of basaltic glass, basalt and andesite. Once in hand, they chemically analyzed these rock samples and studied their interactions with light. Because rock surfaces vary chemically and structurally, the optical properties were difficult to determine. These inconsistencies scatter light and make studies difficult to interpret. The purpose of these optical studies was to give "real" values to rock surfaces, atmospheric dust and interplanetary and interstellar dust grains.[102] "Jim and Carl wanted these numbers for two reasons. First, they thought the Martian wave of darkening was due to giant dust storms. They wanted to model these dust storms, which we now know occur. Second, they were interested in terrestrial volcanic clouds, which were

101 Ibid.
102 Pollack, et al. "Optical Properties," 372-389.

then thought to be rocks, but are now known to be sulfuric acid," said Brian Toon, Jim's second postdoctoral student at Ames and a former graduate student of Carl Sagan's.[103]

But Pollack and Sagan also wanted these optical values to measure "interstellar dust grains," called "stardust."[104] Today, these values (now known as the Rosseland mean opacity tables) are used routinely to limit computer time, when running very large and complicated models. "In these calculations, Jim accounted for variety and size of particles in the surrounding nebula of a planet," said Cuzzi. "Most nebula modelers were not familiar enough with these details to calculate these opacities. Jim was one of few people who knew how to use a Mie scattering code,[105] which was a big deal 30 years ago."[106]

Modeling projects took years to conclude, in which time Pollack showed a great deal of patience. If a calculation was not going well, or if there was some delay, he didn't get angry, but was encouraging. One of the ways he motivated people was to have group meetings, usually at Ames, where people reported the status of their various projects. "Generally, as long as Jim sensed that progress was being made, which was usually the case, he was in a good mood. He definitely was interesting to talk to about his work," said Bodenheimer.[107]

Even Today

The Rosseland mean opacity tables have become increasingly valuable to scientists, as they now are part of routine research methods. In 1994, the paper "Composition and radiative properties of grains in molecular clouds and accretion disks," by Pollack, et al was published posthumously in the *Astrophysical Journal*,[108] and may be one of Pollack's most heavily cited papers. Although values are difficult to estimate, the table is not stagnant; updates include more abundant and refractory organic materials that cover a broader range of size distribution. When new grain species are added to the models, they have an impact on the temperature range, where they are present, according to Ted Roush, a space scientist at Ames. Roush also was recruited by Pollack as a postdoctoral researcher from the University of Hawaii, Hilo.[109]

When asked if their models stood the test of time, Bodenheimer replied that the same modeling approach is currently used to study the extrasolar planets. "Jim engineered the combination of codes and was the driving force in generating results." The improved model brought together three different computer codes: the stellar evolution code by Bodenheimer, a calculation of core accretion by Yuval Greenzweig and Jack Lissauer, and a calculation of the interaction between planetesimals and the planet's gaseous envelope by Morris Podolak.

Jim made contributions across a wide range of topics in planetary science. His special talent was developing sophisticated computer models to explain spacecraft observations of planets in our Solar System. "To put it another way, he built models to interpret spacecraft observations, and, based on the results, designed future observations based on the new

103 Brian Toon, e-mail sent to author, 1 November 2007. Dr. Toon was a research scientist at Ames from 1975 to 1997.
104 Pollack, et al. "Optical Properties," 372.
105 Simplified, the "Mie solution" is a computational, analytical solution for concentric spheres, or layered spheres.
106 Jeff Cuzzi, e-mail to author, 14 November 2007.
107 Peter Bodenheimer, e-mail to author, 14 November 2007.
108 Pollack, et al. "Composition and Radiative," 615-639.
109 Ted Roush, e-mail to author, 15 January 2008.

questions that came up," said Bodenheimer. "Thus, he was an ideal theoretician in the sense that his work was always very closely connected with observations."[110]

Trailblazing

Once a spacecraft is launched, destined for the outer Solar System, scientists wait several years before seeing any results. More than six years passed before Pioneer 11 made it to Saturn. Launched in 1973, NASA's Pioneer 11 encountered Saturn's bow shock, the place where the solar wind is captured by the planet's magnetic field, in 1979. The most dangerous part of the six-and-a-half year, two-million-mile voyage was entering the area outside the visible ring system. This tiny, inconspicuous spacecraft risked potentially fatal collisions with unknown materials in the two-minute wide third ring. Crossing the path of "dangerous ring debris" at 48,000 mph takes only a second, but Ames scientists waited three and a half hours before learning its fate. When radio signals were received, spectators cheered the moment.[111]

The last predicted hazard for the spacecraft was crossing the ring plane again when it reemerged from behind the planet. Once again, Ames controllers had to wait two hours before they knew Pioneer 11 had survived another crossing and was still on course. As it left Saturn, it measured the rings from the dark side of the planet. When it flew by Titan, it took pictures, recorded its temperature and atmospheric methane, and attempted to detect "life chemicals." Titan's surface was not seen, but its brightness and polarization was successfully measured by Pioneer 11; it showed Titan's atmosphere thick with microscopic aerosol particles.[112]

According to project manager Charles Hall, Pioneer 11 was not designed in 1967 for a Saturn mission; the decision to retarget the spacecraft arose only after a successful Jupiter flyby in 1974. Forty years after its launch, Pioneer 11 was approximately eight billion miles from the sun and traveling in the direction of the constellation Scutum. It then took a full 12 hours for a radio signal (traveling at the speed of light) to reach the spacecraft. Its successful mission ended on 30 September 1995, when the last transmission from the spacecraft was received.

Performing as a true pioneer, the tiny spacecraft established a safe passage for the two Voyager spacecraft soon to follow.[113]

The Gas Giants - Voyager Mission (1977 - 1989)

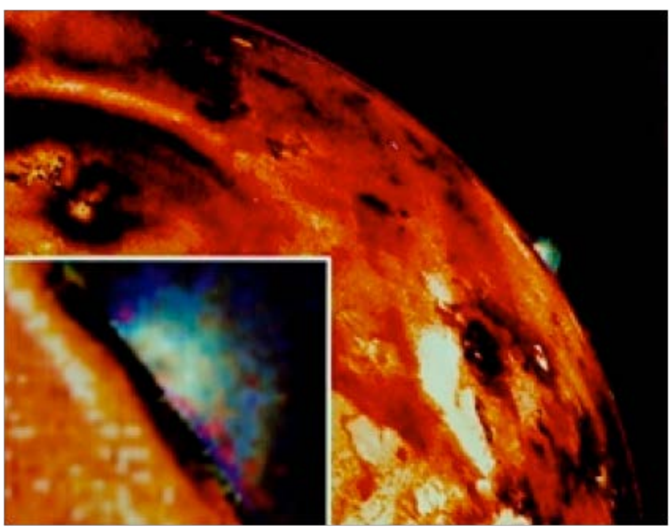
The Voyager mission was an exploratory expedition that was designed to study Jupiter and Saturn, their satellites and interplanetary medium. Five years before its scheduled launch, NASA selected a small group of scientists for the Voyager Imaging Science Team, led by Bradford A. Smith. According to Smith, the team lacked sufficient scientific breadth, so he added nearly a dozen team members. "NASA objected very strongly to my taking this action on my own, and they never accepted any of them as formal members of my Voyager team," said Smith. "They were, however, readily accepted by the scientific community. And, in fact, many of them, including Jim Pollack, Andy Ingersoll, Jeff Cuzzi, Hal Masursky

110 Peter Bodenheimer, e-mail to author, 14 November 2007.
111 Janson and Ritchie, *Astronautics and Aeronautics*, 1979-1984, 59.
112 Kathy Rages, e-mail to author, 31 October 2007.
113 Janson and Ritchie, *Astronautics and Aeronautics*, 1979-1984, 60.

and Carolyn Porco, performed better than some of the originally selected NASA scientists."[114]

Smith had known Jim Pollack for many years. He worked with Jim on the Mariner 9, when Smith was the deputy leader of the imaging science team. "Jim Pollack was a close colleague of Carl Sagan, who was one of the 'official' Voyager imaging science team members," recalled Smith. When Jim began helping Carl unofficially with Voyager science, Smith decided to add him to the team. It turned out to be a very good choice. The science team had many observational-type scientists, but not many had a strong theoretical background. Jim helped fill that void. Jim Pollack was an active and productive member of the Voyager imaging team from 1980 until the time came to shut off the cameras in 1989, following the Neptune encounter, according to Smith.[115]

Formally christened on 7 March 1976, NASA Administrator James C. Fletcher announced the names of the two planetary probes: Voyager 1 and Voyager 2. The two identical spacecraft would view Jupiter, Saturn, and their respective satellite systems, and possibly look at Uranus and Neptune.[116] According to the NASA Historical Data Book[117] and Wikipedia,[118] Voyager 1 arrived at Jupiter in January 1979. Its closest approach to Jupiter was at a distance of about 217,000 miles. The spacecraft returned 18,000 images over 98 days that were popular with the general public. Voyager 2 arrived at Jupiter in July 1979. It came within 350,000 miles of the planet's cloud tops and recorded 13,000 images of the planet and its satellites. The two Voyager space probes made numerous important discoveries about Jupiter, including its satellites, radiation belts, and never-before-seen planetary rings. High-resolution photos showed the eruption of nine volcanoes on the moon Io, and internal activity due to tidal heating on the moon Europa. Three new, small satellites were discovered: Adrastea, Metis and Thebe. Adrastea and Metis were found orbiting just outside the ring, while Thebe was found inside the ring between Amalthea and Io.



Pollack took an active interest in volcanic activity and its effect on climate change on Earth and other planetary objects. In 1979, Voyager 1 captured this image of Jupiter's moon Io, as it made its closest approach to the moon at a range of 304,000 miles. An enormous volcanic explosion is seen silhouetted against dark space over Io's bright limb. (JPL ref. No. P-21305 c) Photo credit: NASA

114 Bradford A. Smith, email to author, 22 June 2008.
115 Ibid.
116 Ritchie, *Astronautics and Aeronautics*, 1977, 49.
117 NASA Historical Data Book Volume III, http://history.nasa.gov/SP-4012/vol3/ch3.htm (accessed April 1, 2014).
118 Wikipedia, "Voyager 1 and 2." http://en.wikipedia.org/wiki/Voyager_1 and http://en.wikipedia.org/wiki/Voyager_2 (accessed 14 March 2014).

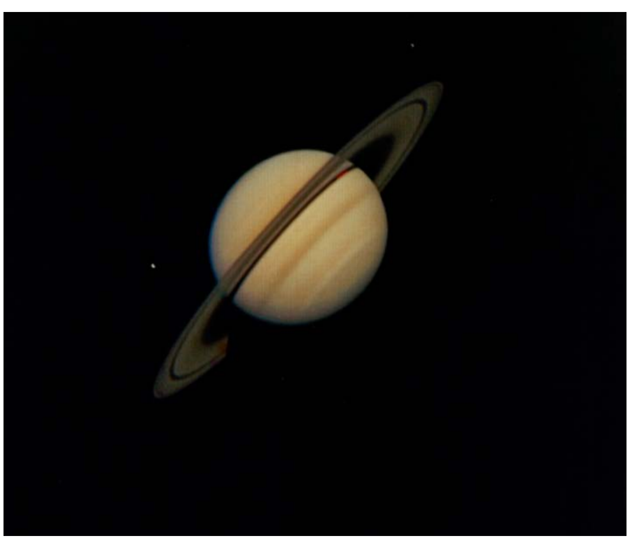
Meanwhile, Jim was taking an active interest in atmospheric aerosols produced by volcanic activity and their possible effect on climate change. The discovery of volcanic activity on Jupiter's moon Io was an unexpected bonus of Voyager. He used these data to publish a paper,[119] describing mechanisms that may have led to the elimination of volatiles (water, nitrogen, argon and neon) from Io's atmosphere and surface, and assessed the volcanoes' relative importance for both past and current conditions on Io. Pollack presented this paper on 13 May 1980 at the annual conference of the International Astronomical Union in Kailua-Kona, Hawaii. Little did he know that the following week, he would have occasion to study a major volcanic eruption closer to home. On 18 May 1980, a major volcanic eruption occurred at Mount St. Helen in Washington.

Voyager Visits Saturn

One month before Voyager 1 arrived at Jupiter on 4 December 1978, Pollack sent a memo[120] to S. A. Collins, the person responsible for conveying the Voyager imaging team's requests to the engineers who commanded the spacecraft. The memo provided "… detailed imaging sequences for Titan and Saturn that are directed towards aerosol objectives…" Collins not only received requests for the Voyager spacecraft, but also organized and prioritized them before handing them to the engineers.

According to Voyager's leader of the atmospheres working group Andrew Ingersoll,[121] the spacecraft resources were limited. The tiny vehicle flew by these planets at incredible speeds, which constrained the performance of its instruments. The camera, photopolarimeter, infrared spectrometer and ultraviolet spectrometer were all bolted to the same scan platform, where they all simultaneously were looking at the same targets, and sharing the same electrical power and radio link to Earth.

Pollack was well aware of this competition for spacecraft resources, so he made his case for camera observations as strongly as possible. He was concerned that the study of Titan (and Saturn) aerosols had been ignored during the planning stage of the Voyager mission, and he wanted to correct this omission. In



Five years before its scheduled launch in 1977, NASA selected a small group of scientists for the Voyager Imaging Science Team, led by Bradford A. Smith. According to Smith, he added nearly a dozen team members, including Jim Pollack, Andy Ingersoll, Jeff Cuzzi, Hal Masursky and Carolyn Porco. Voyager 1 and Voyager 2 spacecraft encountered Saturn on 12 November 1980 and 26 August 1981, respectively. Voyager 1 image (left) shows the Cassini division, between the A- and B-ring. Photo credit: NASA

119 Pollack and Witteborn, "Evolution of Io's Volatile," 250.
120 NASA Ames History Office, Acquisition # 003-2005, 1978.
121 Andrew Ingersoll, email to author, 11 June 2014.

the memo, he briefly discusses the scientific objectives of the sequences that (1) define atmospheric particle characteristics and (2) determine the aerosol to methane mixture ratio, variation of aerosol density and height of stratospheric aerosol layer. His data request came with specific instructions, including targeting requirements and timing, which could be slightly altered but it was important that phase angles be quite close to those he submitted in an attached table. He also compared his imaging experiment to other Voyager experiments, and made remarks about the design of the sequences. He ended the memo with "I hope this material is helpful to the imaging team. Please feel free to call me about questions you may have."[122]

Although Voyager would not encounter Saturn for more than a year and a half, the spacecraft team was already planning the observations. The long lead time was necessary to distribute the workload evenly over the year, given the limited number of people, who were highly motivated and highly trained. "The letter was probably overkill, because Pollack was too highly regarded to be ignored, and people respected his scientific opinions," said Ingersoll.

Once Jupiter was encountered, both spacecraft used the planet's gravity assist to travel to Saturn, arriving November 1980 and August 1981, respectively.[123] The resolution of the Voyager imaging system had already equaled ground-based telescopes three months earlier.[124] Voyager scientists expected surprises from Saturn, but few were prepared for the information Voyager's cameras and instruments sent back to Earth --- Saturn's atmosphere had numerous cloud features and a circulation pattern significantly different than that of Jupiter. Voyager spacecraft recorded surface detail for the first time on eight satellites, showing characteristics quite different than the Galilean satellites. Titan was shrouded in a thick, opaque haze, and the icy satellites varied in density, brightness and surface features. It discovered several new satellites and revealed new rings, hundreds, perhaps a thousand ringlets in Saturn's broad rings and divisions. As a result of Voyager 1's spectacular findings, the original tasks were changed for more emphasis on the rings. Information retrieved in just a few days around Saturn enabled the greatest leap forward since the 17th century in knowledge about the Saturn system.[125]

Although Pollack was interested in all aspects of the Voyager mission, he had a special interest in Saturn's moon, Titan. In the early 1970s, he and Conway Leovy had built a computer model of Titan to study its atmospheric dynamics and temperature variations.[126] They thought complex organic chemistry, or even life in its atmosphere may be a possibility. Titan is the only satellite in the Solar System known to have a substantial atmosphere of mostly nitrogen, also the major constituent of Earth's atmosphere. Astronomers thought that the chemistry in Titan's atmosphere may be similar to a young Earth's atmosphere.[127]

Voyager 1's close approach to Titan showed its surface diameter is about 5,150 kilometers (3,200 miles) - - slightly smaller than Ganymede, Jupiter's largest satellite. Both are larger than Mercury. Titan's surface cannot be seen in any Voyager photos; it is hidden by a dense,

122 NASA Ames History Office, Acquisition # 003-2005, 1978.
123 NASA Space Science Data Center, http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1977-084A (accessed 8 May 2014).
124 Collins et al.. "First Voyager View," 439.
125 Smith, et al.. "Encounter with Saturn," 163.
126 Leovy and Pollack, "A First Look," 195.
127 NASA JPL-CIT, "Voyager: The Interstellar Mission," http://voyager.jpl.nasa.gov/science/saturn_titan.html (accessed 14 March 2014).

photochemical haze that breaks into a main layer with several distinct, detached layers above it.

Titan Experiments

Pollack and Kathy Rages, an Ames National Research Council (NRC) Associate, believed that Titan's thick haze consisted of two layers with different proportions of aerosols and methane gas. But they didn't know the correct aerosol/methane mixture, or its density. To find these quantities, they modeled Titan's atmosphere. Albedo is the reflectivity of a planet, which is an important clue to its physical properties. To determine the correct methane/aerosol mixture, they matched Titan's reflected light (albedo) to models, across the many wavelengths of Titan's color spectrum and into the near infrared. Rages made various combinations of the methane/aerosol mixture, calculated its spectrum, and compared each combination to Titan's known albedo. Various combinations were also compared to Voyagers' images to find a match. Because of the many complicated calculations, Rages used the supercomputers at Ames.

In the late 1970s, supercomputers finally had the power to calculate the brightness of the thick atmosphere of Titan. Before this breakthrough, it was difficult to characterize the properties of an atmosphere. Rages said that building the Titan computer model was her NRC project, when she first came to Ames.[128] At the time, the CDC 7600 (Control Data Corporation) was one of the fastest computers in the world,[129] although its computing process required diligence and patience. The process began by feeding punch cards into a reader, after which the computation took a minimum of five minutes --- if there were no other users. The output results then were retrieved from a line printer, numbers were checked, and data were refined for the next feed into the computer. "The CDC at Ames may have been the only supercomputer in the world at the time that wasn't used exclusively for classified information," said Rages. "At Cornell University, I was using an IBM (International Business Machine) that took thirty minutes for a run, rather than the five minutes on the CDC 7600 computer."[130]

The amount of light a planet reflects, called albedo, is an important clue to its physical properties. Voyager 1 images (left) were used to determine the composition of Titan's hazy atmosphere. Photo credit: NASA

The process was so time-consuming that researchers awaiting their output returns, had access to various software programs on other computers. There was a flight simulator program on one of the first Silicon Graphics (SGI) workstations, and a 16K memory *Star Trek* computer game loaded on a nearby, smaller computer. In the late 1970s, computer

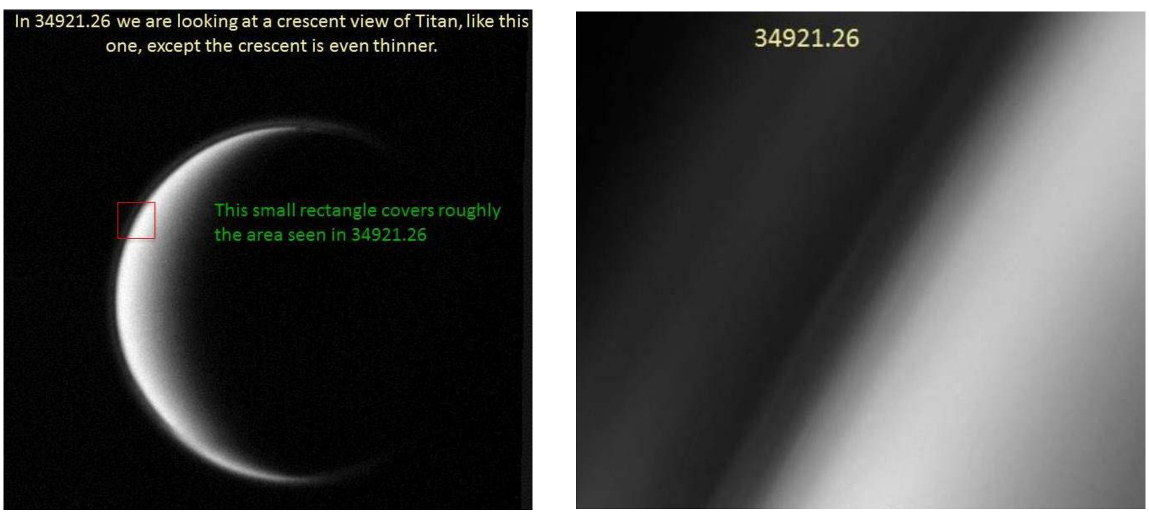
128 Kathy Rages, e-mail to author, 1 July 2008.
129 Wikipedia: History of Supercomputing http://en.wikipedia.org/wiki/History_of_supercomputing#The_Cray_era:_mid-1970s_and_1980s (accessed 17 March 2014).
130 Kathy Rages, e-mail to author, 1 July 2008.

games were just beginning to emerge as a form of entertainment. At Ames, the *Star Trek* game, based on the popular television series, was a rudimentary, text-based program.[131]

After reading the results, Pollack and Rages thought Titan's aerosols may have been "the most complicated non-terrestrial organic material in the Solar System."[132] They also thought the aerosol composition had a profound effect on Titan's temperature. They used Voyager 1 images to test their assumptions and found their suspicion about its affected temperature to be correct. Voyager's data also revealed that Titan's atmosphere contained gases, including acetylene and propane, which indicated a "methane cycle" was occurring. Pollack theorized that the ultraviolet radiation from the sun converts high-altitude methane into heavier hydrocarbons such as ethane and acetylene. As these heavy molecules drift downward, they fall into a warmer atmosphere and condense into solid particles, which break down into methane. The warm methane becomes buoyant, and bubbles upward, perpetuating the cycle. Once it reaches the cold stratosphere, the methane again condenses into cirrus clouds, and rains down the heavier hydrocarbons.[133]

Titan's methane, influenced by photochemistry, contributes to a perpetual cycle, where it is converted into an oily mixture of ethane, acetylene, ethylene, and (when combined with nitrogen) hydrogen cyanide. The last molecule is especially important because it is a building block of amino acids, which is required for all living things. Titan's cold temperature undoubtedly inhibits more complex organic chemistry.[134]

Voyager Observations



Pollack and NRC Associate Kathy Rages used Voyager data to build models of Saturn's moon Titan. Voyager 1 image FDS# 34921.26 (above) spectacularly reveals the complexity of Titan's multiple haze layers. Photo credit: NASA

As amazing as the data were, the Voyager mission still left many mysteries unsolved. Titan's stratosphere is still unknown today; just the "hydrocarbon gunk," which also has been found

131 http://en.wikipedia.org/wiki/Star_Trek_(text_game) (accessed 17 April 2014).
132 Rages and Pollack, "Titan Aerosols," 119.
133 Henbest. "Neptune - Voyager's," 1989.
134 NASA JPL-CIT, "Voyager: The Interstellar Mission," http://voyager.jpl.nasa.gov/science/saturn_titan.html (accessed 14 March 2014).

in the stratospheres of Uranus and Neptune, said Rages.[135] "And we've found 'hydrazine/hydrocarbon gunk' on Jupiter, and Saturn. …And who knows what's going on under the surface of Europa, Enceladus, and Triton. … So, no, Titan's atmosphere does not hold any records in the complicated-non-terrestrial-organic category," she explained.[136] However, one exception was image FDS# 34921.26 (above) taken by Voyager 1, which spectacularly reveals the complexity of Titan's multiple haze layers. The image shows Titan's main atmospheric haze layer totally obscuring the surface, a detached layer above the main layer, an additional layer at some points along the limb and a very diffuse haze well above the limb.

Voyager detected discrete absorbing layers. "The brightness of the main layer of haze was quite inconsistent with what Jim and I thought was the particle size, which was as small as one-tenth of a micrometer," said Rages.[137] To help them find Titan's correct albedo value, they used a realistic range of surface albedos from Saturn's inner satellites.[138] Their estimates showed the aerosol layer to be quite opaque and dense, at least as great as that on Mars at the height of a global dust storm.

Before Voyager 1 encountered Saturn, another group of researchers was simulating Titan's clouds and atmosphere. Pollack, Brian Toon and Richard Turco, a National Research Council postdoctoral fellow, were studying the aerosols in Earth's atmosphere and took the opportunity to study Titan as well. They also were interested in the relationship between Titan's albedo and aerosol production. They found that the more aerosols produced, the smaller their size in the clouds. The size of the particle affected the planet's albedo.[139]

Return on Investment

Some scientists think that Titan may be a young Earth. If so, then its inherent characteristics and evolutionary development may help explain similar questions about Earth. Past studies show that Titan's aerosols affect its albedo and hence the temperature of the planet. Can Titan's results be used to understand Earth's evolutionary history?

The Voyager 1 encounter with Saturn extended the U.S. program of planetary exploration to more than 900 million miles from the sun, adding more than a dozen new worlds as well as Saturn's extraordinary ring system to our catalog of Solar System discoveries. Voyager 2 images complemented those of Voyager 1 by revealing many characteristics of Saturn and its satellites and rings. When the Pioneer spacecraft encountered Saturn, the golden rings of Saturn seemed to be divided into seven segments. Voyager 2 observations showed those rings to be subdivided into thousands of ringlets caused by gravity waves extending concentrically out from the planet, creating tiny moons found "shepherding" ice and rocks in the rings. Average thickness of the rings now seemed to be a maximum of 500 feet, rather than a mile or more.[140] Based on these findings NASA and ESA planned and executed the highly successful Cassini-Huygens mission, which is outside the scope of this era and paper. (For more information, see: http://www.nasa.gov/mission_pages/cassini/main/)

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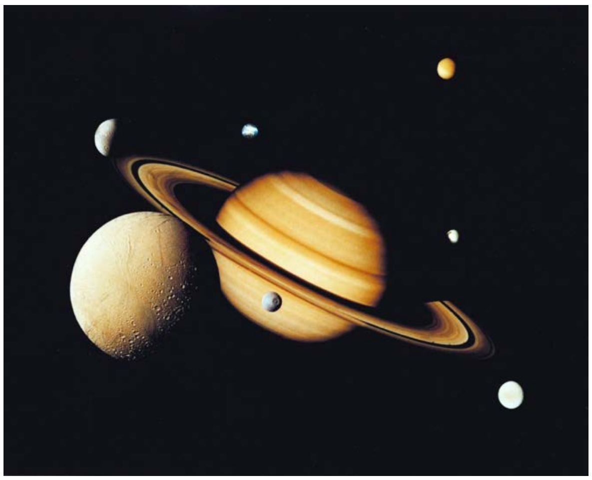
135 Kathy Rages, e-mail to author, 1 July 2008.
136 Ibid.
137 Kathy Rages, e-mail to author, 31 October 2008.
138 Rages and Pollack, "Titan Aerosol," 1980.
139 Toon, Turco and Pollack, "A Physical Model of Titan's Clouds," 261.
140 NASA ARC, "Voyager 2 Finds Saturnian," 2.

Interpreting Results

Ames scientists had a special interest in Saturn's weather because of their expertise in planetary atmospheres. When Voyager 2 encountered Saturn, Pollack and Jeff Cuzzi, both experimenters on Voyager's imaging science team, were at JPL awaiting new pictures of the planets and its rings.[141] Visible Saturnian weather systems seem to be driven by ammonia reactions. The planet's cloud tops appear to consist of ammonia ice, with lower "warmer" ammonia. Near the equator, winds scream around the planet at 1100 mph speeds that literally rip apart storms, and hence limit them in these latitudes.

Despite a crippled camera platform, Voyager 2 obtained thousands of high-resolution pictures achieving 99 percent of the Voyager's mission objectives.



Pollack had a special interest in Saturn's largest moon, Titan. Its atmosphere suggested the possibility of complex organic chemistry, or even life. Four years after its launch, Voyager 2 flew by Saturn on 26 August 1981, obtaining 16,000 images. Its largest moon Titan comprises more than 90 percent of the mass in orbit around Saturn, including the rings. Photo at left is a composite image of Saturn and its seven principal moons: Dione, Tethys, Mimas, Enceladus, Rhea, Titan and Iapetus. Photo credit: NASA JPL

The leader of the Voyager Imaging Science Team Bradford A. Smith said that Voyager data on the composition of Saturn's satellites and rings can be related to models of the early history of the Saturn system done by Pollack, Graboske and Grossman.[142] Voyager was science at its best – "the most successful mission that NASA has carried out," said Smith. It is an assessment many scientists endorse. Despite political attempts to halt the mission in 1981, Voyager 2 earned the right to head for Uranus. Once arrived in January 1986, Smith called Uranus "…the most disappointing object encountered..."[143] But then went on to Neptune in 1989, where huge atmospheric winds and a new ring system were discovered.

141 NASA ARC. "Voyager 2 Finds Saturnian," 1.
142 Smith, et al., "Encounter with Saturn," 191.
143 Wilford, "Voyagers Reap," 13.

As part of the Voyager Science Imaging Team, Pollack (middle, back row) was one of the first scientists to see in situ data of our Solar System's outer planets: Jupiter, Saturn, Uranus and Neptune. Voyager 2 arrived at Neptune in 1989, where huge atmospheric winds and a new ring system were discovered. Photo credit: David Morrison

Pollack was one of the first scientists to see close-up, remote sensing data of our Solar System's outer planets: Jupiter, Saturn, Uranus and Neptune. He was an author or co-author to more than 83 publications about these planets, their rings and satellites. His first Jupiter publication was a 1972 paper, published with Al Grossman, Harold Graboske and Ray Reynolds, which showed the evolutionary calculations used when developing Jupiter's model. As early as 1973, he and Conrad Leovy, a visitor to Ames at the time, built a computer model of Titan to estimate its atmospheric dynamics and temperature variations.[144] To quote the paper's title, it was a first look. On the subject of Saturn, he published 36 papers, of which 16 were on Titan. He published 16 papers on Jupiter and its satellites; his remaining publications were on Uranus, Neptune and their satellites, including Pluto.

"Pollack had models for lunar radar scattering, the rings of the outer planets, and the Pluto-Charon system. He also applied his expertise to the atmosphere and climate problems of our own Earth," said Cuzzi. "All this might seem easy, but in reality each object has its own community and literature, and even learning what the critical problems and appropriate datasets are for each different object is a significant hurdle."[145]

Pollack's work on the gas giants represented another major part of his NASA career. But these planets were no rival for his continued interest in Venus. It had marked the beginning of his planetary research career. Throughout the years, he always returned to the source of his original fascination. Pollack's special interest was the greenhouse effect of Venus. Cloaked in gaseous cloud layers, the clue to the planet's deadly demise for life may lie beneath. He always returned to this mysterious place.

Earth's Sister Planet – Pioneer Venus Mission (1978)

Mariner 2 and Mariner 5 were both early Venus missions. Mariner 2 launched in 1962 and was the first fly-by of another planet. It passed below the planet at its closest distance of 34,773 km (approx. 21,600 miles). Mariner 5 followed in 1967, flying within 4,000 kilometers (approx. 2,500 miles) of the planet. Nearly 50 million miles from Earth, these two

144 Leovy and Pollack, "A First Look," 195.
145 Jeff Cuzzi, e-mail to author, 1 August 2008.

tiny, 500-pound spacecraft relayed information about the planet's mass, surface temperature, solar wind and evidence that a magnetic field was missing.[146]

Venus was one of NASA's first spacecraft targets. Often called Earth's sister planet, Venus resembles Earth in mass, size, density and volume. Both planets were formed about the same time and born out of the same primordial nebula. Yet the two planets have evolved so differently. Prior to these missions, some scientists thought that Venus' atmosphere was a steam bath under perpetual clouds and that it consisted largely of carbon dioxide gas. Still others held that the surface was mild and the observed clouds were simply water clouds, like our own. By 1958, its temperature was believed to be near the melting point of lead, an impressive 600 K (620 degrees Fahrenheit). Some scientists doubted that a 600 K surface temperature was possible. When the Mariner 2 spacecraft flew by in 1962, it confirmed that Venus' surface temperature was indeed scorching hot.

Although it absorbs less sunlight than Earth, Venus has a surface temperature that is about 310 K (560 degrees Fahrenheit) higher than Earth's, and has an atmospheric pressure that is about 90 times larger than Earth's pressure. These two remarkable properties are both affected by its massive atmosphere, which generates enough infrared opacity (heat absorption of clouds) to effectively prevent the surface and lower atmosphere from cooling. The high surface temperature also leads to fewer reservoirs of volatiles, such as water or carbon dioxide, on the surface and subsurface.

Over the years, attempts at explaining Venus' high surface temperature included "aerosol" layers in the atmosphere, sun-exposed dust, dynamical heating, and greenhouse models. According to the aerosol model,[147] the planet's winds stir up such enormous quantities of dust that the surface is heated by friction and gusts of heat-retentive dust particles. However, Pollack and others[148] found few particles present at altitudes below 31 kilometers (about 100,000 feet), making this model an unlikely candidate for a satisfactory explanation. The sun-exposed-dust model was based on similar postulations made by the aerosol model, revealing an increased infrared opacity, but also suggested the heat released from the planet's interior as the major heating agent.[149] This model, like the aerosol model, was another unlikely candidate for the same reason.

Other scientists[150] suggested that differences between day and night temperatures may have created a weather pattern that forced the heat toward the surface. These scientists assumed that the sun's energy was absorbed near the cloud tops and the surface was capable of maintaining extremely hot temperatures. However, the density of the cloud layers fluctuate with altitude, and simulations showed that the sun's energy did not circulate to any great depths.

By 1980, the most popular explanation of the high surface temperature was the greenhouse effect. This theory suggests that the high surface temperature is due less to the clouds' opacity, which would allow more visible sunlight to reach the surface, than heat being

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146 National Space Science Data Center, Mariner 2: http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1962-041A and Mariner 5 http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1967-060A (accessed 15 April 2014).
147 Opik, "The Aeolosphere," 2807.
148 Pollack, Toon, and Boese, "Greenhouse Models," 8223.
149 Hansen, "The Atmosphere of Venus," Ph. D Thesis, 1967.
150 Goody and Robinson, "A Discussion of," 339-353.

prevented from escaping the planet.[151] This explanation was first advanced by a young Sagan,[152] who was the first to show that carbon dioxide in combination with water vapor supplied the needed infrared opacity to produce a "very efficient greenhouse effect."

Soon after the Mariner and the Soviet's Venera missions, Pollack and Sagan wrote a landmark series of four papers (1969) that determined the structure and composition of Venus' atmosphere by comparing changing temperatures and their greenhouse effect. In these papers, Pollack published equations to solve the problem of thermal energy transfer.[153] These equations[154] were the first set of calculations to produce the desired greenhouse effect. Pollack would use these same "radiative transfer"[155] equations throughout his career[156] to study the atmospheres of other planets.

Leovy, emeritus professor in atmospheric sciences and geophysics at the University of Washington, Seattle said, "Jim was clearly a rising young star in planetary sciences. When he worked on the optical and thermal properties of Venus, he demonstrated that Venus' excessively high surface temperature was due to a carbon dioxide-water vapor greenhouse effect. He and Carl Sagan may have proposed this together. Jim was Carl's graduate student, and they shared common interests in variable features and windblown dust."[157]

A Great Opportunity

One year later, Pollack moved to California where he started his NASA career. No longer needing a mentor, he single-authored his first NASA publication (1971), "A Non-Grey Calculation of the Runaway Greenhouse: Implications for Venus' Past and Present," in which he argued "Venus might once have had oceans like Earth's…It seemed that such a 'runaway greenhouse' could have turned the Earth too into a furnace, if the starting conditions had been only a little different." His findings showed Venus' surface temperature was most likely due to an incredibly effective greenhouse.

Earlier researchers had also speculated about "greenhouse instability," a phenomenon caused by too much moisture in the atmosphere. Water is a powerful heat absorber. As the oceans warm, water evaporates into the atmosphere, which causes greater heat retention and even warmer temperatures. But no one had built a quantitative model that explained why it wouldn't happen on Earth, or why it would have happened on Venus. "My model explained those events," said Andrew Ingersoll of Caltech in Pasadena, Calif., who coined the phrase "runaway greenhouse" in a 1969 paper titled "The Runaway Greenhouse: A History of Water on Venus." "Pollack improved on my early model by using the best information available at that time about the Venus atmosphere. Pollack made lasting contributions to many fields, and I admired him greatly."[158]

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151 Pollack, Toon, and Boese, "Greenhouse Models," 8223.
152 Sagan, "The Radiation Balance," 32-34.
153 Cuzzi, "James B. Pollack," 7- 16.
154 Pollack, "A Non-gray Carbon Dioxide," 314-341.
155 Radiative transfer is the exchange and circulation of energy in the atmosphere of a planet, including emission, absorption, and scattering of electromagnetic radiation.
156 Toon, Cuzzi and Sagan, "In Memoriam," 227-231.
157 Conway Leovy, e-mail sent to author, 31 October 2007.
158 Andrew Ingersoll, e-mail sent to author, 27 March 2007.

Although Venus has been studied for decades by scientists, it continues to be of special interest to them. Sagan said, “Venus is a hot, dry, sandy… and probably lifeless planet.”[159] He thought that Venus had started out with roughly the same amount of carbon dioxide as Earth. But on our planet, most of the carbon was tied up as minerals and buried sediments. On Venus, its surface was so hot and dry that carbon-bearing compounds such as carbonate rocks would decompose rather than stay rocks. Or, if Venus never had liquid water, the carbonates might never have formed in the first place. At one time, Venus’ climate may even have been hospitable to life, but as water and carbon gradually evaporated into the warming atmosphere, and the water decomposed, losing hydrogen to space, and the oxygen combined with surface rocks, the planet became hostile to life. Key studies of Venus’ past climate and atmospheric evolution have included the existence of hot oceans of water in its earliest history due to a lower solar luminosity,[160] and a hot ocean may have been conducive to massive water loss by a combination of solar ultraviolet photodissociation and escape of hydrogen to space in a hydrodynamical wind. [161] Venus was home to an extreme, harsh environment.

Lear Jet Observations of Venus

In pursuit of answers to the many questions about Venus, Pollack talked to Fred Witteborn, chief of the Astrophysics Branch at Ames in the spring of 1971. He wanted to investigate the clouds of Venus.[162] Pollack speculated that Venus’ clouds may be composed of the obvious, such as water, to the exotic, such as hydrochloric acid, mercury, carbon suboxide and ammonium chloride. Others had suggested that Venus’ clouds consisted of a concentrated sulfuric-acid solution. He wanted to test those speculations, but needed data at wavelengths that had to be collected at stratospheric heights, far above the clouds. Conveniently, Ames operated a fleet of research aircraft, one of which was the NASA Learjet Observatory (photo below). Spectroscopy separates an object’s reflected light into various colors, or wavelengths, which reveals details about the molecular structure of a planet’s atmospheric composition and temperature. To determine those findings, however, data had to be collected within a specific range. He needed spectra [163] in the one-to-four-micron wavelength range (or the near-infrared).

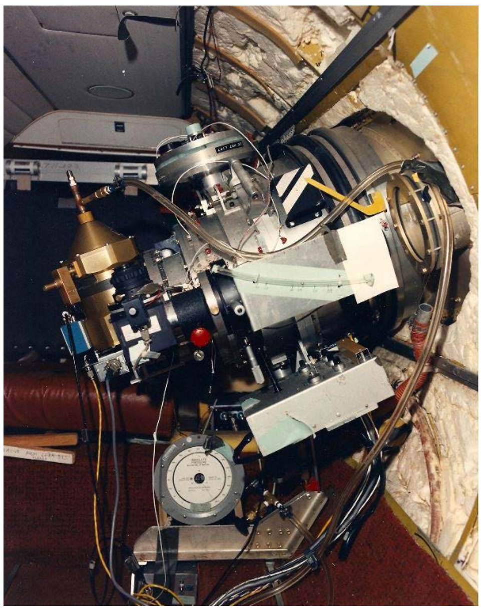
The NASA Learjet Observatory. Photo credit: Fred Witteborn

The flight experiment was not an easy task. Many competing factors had to coalesce for a successful experiment. Jim was one of many scientists who used airborne research, so selecting a date was partially limited by aircraft availability. In addition, Venus had to be far enough away from the sun, and the phase angle of Venus to the aircraft had to fit

159 Weart, “The Discovery of Global Warming,” http://www.aip.org/history/climate/Venus.htm (accessed 17 March 2014).
160 Pollack, “A Non-gray Carbon Dioxide,” 314-341.
161 Kasting, J.F. and J.B. Pollack. “Loss of Water from Venus,” 479-503.
162 Witteborn, e-mail sent to author, 14 March 2008.
163 Measurement requirement taken by the near-infrared reflection spectrum.

Pollack's model requirements. Also, a special photoconductor was needed for the telescope. Finally, the flight crew agreed to fly two research expeditions, one in the summer of 1972 and the other in the spring of 1973. Both flight times were synchronized to Venus' place in orbit, high in the sky.

On 16 July 1972, all systems were go. Venus is always observed near the sun because its orbit around the sun is interior to Earth's. It is a luminous, lemony-yellow color due to its thick layer of clouds. It also reaches its maximum brightness shortly before sunrise, or shortly after sunset. Given these factors, the NASA Learjet took off before dawn when sunlight was faint. For an unobstructed view of the planet, the tiny jet flew at cold, high altitudes between 45,000 and 47,000 feet. The crew consisted of a pilot, a co-pilot, and two observers. A Lear jet is a tiny aircraft; its cabin height, width and length measure 4 by 5 by 9 feet. Carrying four men, extra gear, instruments and a 12-inch telescope mounted in the cabin, made for a tight fit.



The telescope operator sat on a tiny stool peering out the finder telescope (photo below), and listening to frequency sounds that guided his pointing. "We were wearing headphones. The sound pitch went up when we were on the object and down when we were off the object. It sounded like …eee…ee...oooo…u, u, u…," said Witteborn.

The telescope operator sat on a tiny stool peering out the finder telescope. Photo credit: Fred Witteborn

In spite of the engine noise and crowded conditions, the two observers managed to simultaneously operate the telescope, spectrometer control and the data-acquisition system. As the dawn started to edge over the horizon, it signaled the last call for data collecting; it was nearly time to head home to Ames. When asked about Pollack's expression when the data were handed to him, Witteborn replied, "Jim always gave the same reply each time we collected data for him. He said, 'real good.' I always thought it meant that he was pleased with the situation."

After the data were analyzed, the crew was told the experiment was a success. "Jim did the most important part of this experiment. He provided the ideas for doing the observations and interpreted the data. He also did most of the writing," said Witteborn. "He found that aerosols comprising 75 percent concentrated sulfuric acid in water provided a convincing fit."[164]

As it turned out, the Learjet experiment was award-winning. The team of Ames scientists, headed by Jim Pollack, had discovered that the upper levels of Venus's brilliant clouds consisted of droplets of sulfuric acid more concentrated than the acid in an automobile

164 Pollack et al., "Aircraft Observations," 1974.

battery. The team had measured the infrared "color" of Venus from a Learjet aircraft and compared results with a computer simulation of the color properties of various substances.[165] Pollack received the H. Julian Allen award in 1975 for the paper he wrote describing major findings about the atmosphere of Venus. "Jim announced his preliminary results in March 1973. In his 1974 paper, [166] he notes that the airborne data provided the first good observational data throughout the whole band (1.2 to 4 microns) and that his theoretical model provided a match to the spectra," said Witteborn.[167]

Pollack shared honors with eight other Ames employees; the award, given for outstanding papers written by members of the Ames staff, was accompanied by a $1,000 honorarium.[168]

Mission Preparations and Launches

Ames scientists were not the only researchers studying Venus in the early 1970s. Goddard Space Flight Center, Greenbelt, Md., was managing a study, called the Planetary Venus Explorer Program. Although Ames was known as an aeronautics center, no one could deny its extraordinary successes with the Pioneer 10 and Pioneer 11 missions. According to Larry Colin, [169] the Pioneer Venus (PV) project scientist, Ames Center Director Hans Mark was instrumental in getting the program reassigned to Ames. Once at Ames, it was renamed the Pioneer Venus Program by NASA headquarters, and Charlie Hall, the former Pioneer project manager, was given the new program. In 1976, the Pioneer Venus Program was approved as a mission.

Once given the status of an official NASA mission, the PV project office soon started writing requests for proposals (RFPs). Scientists, both in- and outside of NASA, were asked to submit science proposals for research they wanted performed on the mission. Two types of researchers submitted proposals: one type built the spacecraft instruments (called experiments) and later helped analyze the data; the other type, called now interdisciplinary scientists (IDS), helped design the experiments of other scientists. The interdisciplinary scientists had their own special interests in data collecting and analyses. They made proposals to work on not just one experiment, but several or all of the experiments. "The Pioneer Venus project may have been one of the first missions that used the concept of interdisciplinary scientists," recalled Colin.[170]

After years of studying this planet from ground-based and flight observatories, Pollack and his colleagues finally would have *in situ* measurements to test their models' assumptions about the planet's atmosphere and greenhouse phenomenon. The PV mission would give scientists their first in-depth look at its cloud layers. To be selected as an interdisciplinary scientist, researchers had to propose a broad, comprehensive research effort. Pollack was known for his research about the greenhouse effect. The experiments proposed by other scientists were of particular interest to him as well, because he could use their data to further study this phenomenon. He wanted atmospheric data; data that described the winds, clouds

165 Science, *Astronautics and Aeronautics*, 1973, 332.
166 Pollack et al., "Aircraft Observations," 1974.
167 Witteborn, e-mail sent to author, 14 March 2008.
168 Ritchie, *Astronautics and Aeronautics*, 1976, 48.
169 Colin interview with author 15 January 2009.
170 Ibid.

and radiation effect on Venus. "This is why Jim was selected as the interdisciplinary scientist, he had a broad, broad perspective," said Colin.[171]

As part of the initial stage of the mission, scientists were selected and made members of the PV science steering group. They met periodically to define the science objectives, strategy and plans for the mission, coordinate the experiments, and later to analyze the flight experiment data. "I remember meetings with Jim because meetings with Jim were a joy. It was a riot," said Colin.[172]

According to Colin, when Jim came to meetings, he didn't just come in and sit down and listen, he always wanted to know upfront the meeting's agenda. He would stand up and say 'Why are we here today? And what are we going to discuss?' It forced people to come up with a clear agenda, which annoyed some people. But what seemed to annoy them most was Jim's behavior at the end of every meeting. He would stand up and say 'Let me summarize what we have done here today.' He would not only summarize the meeting, but specify who had what action item. He'd say, 'we agreed to do the following: *you* have this job to do before the next meeting, and *you* agreed to do this. Does everybody agree?' "He looked like he was running the meeting, but he was brilliant at it. It was my meeting and Jim co-opted it. It was Jim's style and I loved it. Sometimes after learning of the agenda, he'd say, 'there's nothing I can contribute.' And get up and walk out of the meeting," said Colin.[173]

During the course of the mission's development, Pollack was selected as an interdisciplinary scientist for the Pioneer Venus Probe Bus.[174] His commitment to the project was reflected by his strong working relationship with the experiment and test engineers in the PV Project Office at Ames. Bob Boese was one such colleague who shared Pollack's interest in the radiation on Venus and how it drives the weather pattern. Scientists suspected that Venus lost as much energy to space as it gained from the sun; overall, the planet's energy seemed to be in balance. But locally, the atmosphere gained excess energy during the day at the equator. Theory suggested that to redistribute the excess energy, the atmosphere's circulation needed to transport the excess energy from day to night and from equator to pole. Horizontal as well as vertical transports were needed to bring the atmosphere's heat distribution back into balance. "In a real sense the atmosphere is a heat engine driven by radiation."[175]

One of Pollack's greatest talents was getting good science from data. He was a master at it. But he needed to see specific data from each experiment. He and Boese wanted to see thermal infrared readings that they hoped would explain the radiation effects of the atmosphere's circulation. To study this phenomenon, Pollack and Boese designed experiments, which required new technology be developed. The instrument was called a "net flux radiometer" and was built by the Diamond Window engineers at the University of Wisconsin, Madison; its primary purpose was to map the radiation as it circulated throughout the atmosphere.

171 Ibid.
172 Ibid.
173 Colin interview with author 15 January 2009.
174 NASA National Space Science Data Center, "Interdisciplinary scientist," http://nssdc.gsfc.nasa.gov/nmc/experimentDisplay.do?id=1978-175 078A-12 (18 March 2014).
175 Sromovsky, Revercomb, and Suomi, "Pioneer Venus Small," 117.

At the time, very little was known about the clouds, or chemistry of Venus' atmosphere. Boris Ragent, another Ames scientist who worked with Pollack, designed an experiment that measured the location and vertical structure of the clouds using an instrument called a "nephelometer." Vance Oyama, also an experimental scientist at Ames, worked on an atmospheric experiment. He and Jim were interested in the data from the gas chromatography system. All instruments recorded measurements at four widely separated locations on the planet.

Prior to Pioneer Venus, the modeling of Venus' clouds, winds and temperature, was severely limited by the lack of three-dimensional observations. To get a 3-D effect, scientists needed vertical measurements of the atmosphere, which was a significant accomplishment by the PV probes. This elegant experimental technique [176] was invented and refined by Alvin Seiff, who was one of the more remarkable scientists in the agency. He was known as an astrophysicist during the latter part of his career, but was an innovative and creative engineer who developed hardware technology for NASA missions.

The PV mission was a two-spacecraft orbiter-probe combination that launched separately. The Pioneer Venus Orbiter (Pioneer 12) mapped the upper atmosphere of Venus. The Pioneer Venus Probe Bus (Pioneer 13) carried four probes, one large and three small, to Venus and released them into the atmosphere. Two small probes entered the nightside, and one large and one small probe entered the dayside; all four mapped the atmosphere vertically. While the spacecraft orbited the planet, the four probes would fall through the atmosphere, all systems would radio back to Earth the local and general state of the planet.[177]

After years of planning, the Pioneer Venus mission launched the orbiter in May and the multiprobe bus in August, 1978. Mission objectives included investigating the atmosphere, clouds, radiation field and energy exchange in the lower atmosphere, and local weather patterns. The PV Orbiter carried 17 experiments, including many specialized spectrometers, analyzers and field detectors. It studied the planet for more than a decade. The PV multiprobe bus carried one large probe equipped with seven

At left is an ultraviolet image of Venus' clouds, as seen by the Pioneer Venus Orbiter on 26 February 1979. Photo credit: NASA

176 The Planetary Atmosphere Experiments Test (PAET), originated and designed by Seiff, consisted of dropping a fully instrumented probe from a helicopter, plane and balloon into Earth's atmosphere at 6.6 km/ second. The success of PAET led to the application of the technique to future NASA missions, including the four Pioneer Venus probes, and the Galileo and the Cassini-Huygens probes. Seiff originally published the concepts used to reconstruct the atmospheres of Mars,Venus, Jupiter and Titan in a 1963 seminal report titled "Some Possibilities for Determining the Characteristics of the Atmospheres of Mars and Venus from Gas Dynamic Behavior of a Probe Vehicle."
177 NASA National Space Science Data Center, "Pioneer Venus Space Probe Bus," http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1978-078A (accessed 19 March 2014).

science experiments, and three identical small probes equipped with special sensors.[178] Two of the three small probes continued transmitting data after they hit the surface, at least for a few seconds.[179]

The success of the PV mission was largely due to the design and use of the probes in the mission. As each probe entered the atmosphere, its descent was mapped by a combination of Doppler and radio methods. "In this experiment, we did not measure wind velocities directly; but rather, monitored the velocity of the probes as they fell through the atmosphere," said Pollack.[180] These probes were creative solutions to measuring and assessing the vertical structure of the atmosphere of Venus.

The Truth Is In the Numbers

The Pioneer Venus mission was triumphant in the amount of new information it brought back from Venus. Once the data were in-hand, Pollack and other scientists started analyzing it and publishing reports. Jim was a cautious and meticulous scientist. Imagine his surprise when he thought he found a discrepancy in one of his earlier reports. He immediately co-authored a paper citing the error. He reminded scientists of the importance of accurate reporting. They relied on each other's honesty and integrity. In the paper, Pollack questioned the "apparent discrepant data" between two studies; one using *in situ* data from an assumed well-mixed lower atmosphere, and the other using extrapolated data from the upper atmosphere. "We are currently scrutinizing and testing in detail our analytical findings to evaluate disparities," he wrote. "The accuracy of compositional data is critical for testing validity of and for evolving working hypotheses about the origin, evolution, and dynamics of planetary atmospheres, the nature of clouds, and the origin and evolution of the planets in our Solar System"[181]

"After the data were available, there appeared to be discrepant results between the mass spectrometer and the gas chromatography system," recalled David Black, a former Ames theoretical astrophysicist and planetary scientist, and colleague of Pollack. "Jim and his collaborators conducted tests to determine whether the gas chromatograph might have suffered from some error sources. They concluded it did not, and that was important from the point of view of data interpretation."[182]

Mission experiments returned encouraging results. Data from the nephelometer successfully exhibited the vertical cloud structure of Venus. The main cloud bank, an upper haze region, had three separate layers. Below this region are occasionally dense strata consisting of concentrated sulfuric acid particles. The highest stratum of cloud layers is primarily where near-ultraviolet radiation is absorbed. Findings from the large probe infrared radiometer experiment were equally satisfying. Results showed that the clouds were an important source of infrared opacity, or heat absorption. It appeared that the cloud particles played an important role in producing Venus' burning temperatures; the greenhouse effect was more than gases. From the experiments, scientists also were able to deduce the amount of water

178 Wikipedia, "Pioneer Program," http://en.wikipedia.org/wiki/Pioneer_program (accessed 19 March 2014).
179 NASA NSSDC, "Pioneer Venus Probe Bus," http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1978-078A (accessed 19 March 2014).
180 Oyama et al., "Venus Lower Atmosphere," 802 -805.
181 Oyama et al., "Laboratory Corroboration," 52.
182 David Black, e-mail sent to author, 7 March 2008.

vapor below the clouds. They reported that "the amount of water vapor present below the clouds is comparable to the amount needed to close the major carbon dioxide windows in the infrared and achieve the greenhouse effect. Thus, the high surface temperature of Venus may be explained by the opacity of carbon dioxide and water vapor, but with a significant assist from the cloud particles."[183]

Measurements from the PV probes and orbiter allowed Pollack, Toon and Boese to significantly improve the definition of the gaseous composition, temperature structure and cloud properties of Venus' lower structure. They used these measurements in Pollack's greenhouse equations to assess the chief contributors to the greenhouse effect, which disclosed new sources of heat absorption (infrared opacity), including sulfur dioxide, carbon monoxide, hydrochloric acid, and carbon dioxide. From these equations, they were able to model the surface temperature and the structure of the lower atmosphere quite closely on a greenhouse model that contained a small amount of water vapor. Due to the Pioneer Venus and Venera 11 and 12 spacecraft missions, they reported that "…the greenhouse effect can account for essentially all of Venus' high surface temperature. The prime sources of infrared opacity are, in order of importance, carbon dioxide, water, cloud particles, and sulfur dioxide, with carbon monoxide and hydrochloric acid playing very minor roles…"[184]

Basic Science Rewarded

The Pioneer Venus mission produced reams of information just waiting for a theorist's touch. "When the noble gas studies from the Venus probe were available, Jim and I began to chat about how they might be useful as a way to understand the histories of Venus, Earth, and Mars -- at least in a relative sense," said Black. "After much discussion, a few concrete ideas emerged, and we published them in a paper. The data were tricky to interpret for many reasons. There were some inconsistencies in the results between instruments, but all in all, our ideas were provocative enough for us to at least expose them to professional scrutiny."[185]

In this paper, titled "Noble Gases in Planetary Atmospheres: Implications for the Origin and Evolution of Atmospheres" (1982), the authors proposed that the noble gases present in the terrestrial planetary atmospheres provided valuable clues concerning the planets' origin and evolution. Noble gases are elements so stable that they rarely react with other elements. They include helium, neon, argon, krypton, xenon and radon. Because noble gases are inert, they are not absorbed by the surface of rocks. And, except for the lightest noble gas, helium, they cannot readily escape into space. Therefore, they reasoned, the noble gases -- neon, argon, krypton and possibly xenon--- have been present in terrestrial planetary atmospheres over the entire history of the planets. By comparing the abundances of the noble gases, they thought it possible to assess the validity of alternative hypotheses for planetary formation.[186]

Venus' Past Relates to Earth

While the Pioneer Venus spacecraft was en route to its final destination, Pollack was involved in yet another flight experiment, this time using the NASA Kuiper Airborne

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183 Boese, Pollack and Silvaggio, "First Results," 797.
184 Pollack, Toon and Boese, "Greenhouse Models Of Venus'," 8223.
185 David Black, e-mail sent to author, 7 March 2008.
186 Pollack and Black, "Noble Gases."

Observatory at Ames. The Kuiper, a retrofitted Lockheed C-141 Starlifter, was the world's first major airborne astronomical research laboratory. It carried a 36-inch telescope capable of conducting infrared astronomy, and flew at altitudes of 41,000 to 45,000 feet, which was above the Earth's infrared-absorbing clouds. The Kuiper telescope had nine times more collecting area than the Lear jet telescope, and its excellent guidance system kept the higher spatial resolution telescope on target. The airborne observatory provided seven and a half hour missions. A typical flight crew consisted of two pilots, a flight engineer, and mission staff and science team.

Once again Pollack requested a flight experiment to study the clouds of Venus. Once on board, it was a shirtsleeve environment with a crew of 40 people. It took five people just to run the telescope, and the requesting astrophysicists could have three to five researchers on board as well.

The flight experiment was successful in that researchers were able to collect "strong confirmatory evidence" that showed the clouds consisted of an 85 percent sulfuric acid water solution. Kuiper observations were compared to theoretical observations to get a good determination of sulfuric acid concentration, and to estimate the depth of cloud coverage.[187] Their findings were used to calculate the greenhouse effect of sulfates, which was identified with carbon dioxide as responsible for the basic state of Venus.

Jupiter and Saturn Revisited – Galileo (1989), Cassini (1997) Missions

In 1976, NASA's successes were impressive. President Carter's first budget proposal in 1976 recommended an additional $15 million for NASA to study potential missions to Mars after Viking. Support from the President[188] meant the time was right to request a new mission to the planets, now long overdue. The logical next step was a follow-up to the ambitious Pioneer and Voyager flybys. Scientific interest in Jupiter was high among scientists because they believed it held many clues to the origin and evolution of the Solar System. With 14 moons, this gas giant was theorized to be comprised of the primordial building blocks of the universe. NASA requested an impressive Jupiter orbiter mission.

The mission was initially called the Jupiter Orbiter Probe, but in 1978 it was christened Galileo. Designed after the highly successful Pioneer Venus mission, it consisted of a powerful orbiter and an atmospheric entry probe. Its primary mission was a two-year study of the Jovian system. The spacecraft would use gravity assist maneuvers from Venus and Earth to arrive at Jupiter. Once in orbit around Jupiter, it would travel in elongated ellipses, each orbit lasting about two months. The differing distances from Jupiter afforded by these orbits allowed Galileo to sample different parts of the planet's extensive magnetosphere and various close-up flybys of Jupiter's largest moons.[189]

According to Larry Colin, the project scientist for Pioneer Venus and then Galileo,[190] there is a greenhouse effect on Jupiter. Greenhouse theories are based on atmospheric studies, which include clouds, chemistry and winds. Although a terrestrial planet, Venus can be studied to understand Jupiter, a giant gas planet. The same physics apply when studying the infrared

187 Pollack et al., "Properties of the Clouds," 28.
188 Ritchie, *Astronautics and Aeronautics*, 1977, 48.
189 http://en.wikipedia.org/wiki/Galileo_(spacecraft) (accessed 15 April 2014).
190 Larry Colin was the Galileo project scientist until he retired in 1988, when Richard Young assumed the position.

absorption of both Venus and Jupiter. "It's about the level and composition of the clouds, where things in the atmosphere are absorbed, and the amount of water present. The physics of the atmospheres are the same on both planets. The results are not the same, but the equations, the circulation equations, are the same for both planets," said Colin.[191]

In 1978, NASA announced its selection of 114 scientists to participate in the Jupiter-orbiter-probe mission, originally scheduled for launch in 1981 or 1982. Thirteen scientists were selected for interdisciplinary positions; they would coordinate the research with the instruments to ensure best results from the mission. The other scientists were assigned to the 17 experiments onboard.[192]

Jim was selected as the interdisciplinary scientist for the thermal and dynamical properties of the Jovian atmosphere experiment, and principal investigator for the Galileo bus.[193] His role was to coordinate, integrate and combine data from the probe experiments. Scientific objectives were to determine the temperature structure and dynamics of the Jovian atmosphere and study the energy sources in the atmosphere.[194] Of all the experiments aboard the Galileo Orbiter Probe, Pollack had a special interest in the Ames Doppler wind experiment.

Out of the Blue

All interdisciplinary scientists were expected to attend the Galileo steering committee at NASA headquarters in Washington D.C. For Pollack, going to headquarters was anything but a desirable occasion. In the past, he had difficulty convincing NASA administrators of the merits of some research efforts, or new projects. No one appreciated detail quite like he did. He spent his life analyzing detail, meticulously refining data, from analyzing dust samples to building sophisticated, large models of different planets and celestial bodies in our Solar System. An important value to him was accuracy in reporting, he reminded scientists to be careful when reporting findings, for they relied on each others' objectivity, integrity and honesty. It was all extremely important for future studies.

"Jim hated going to D.C.," said Ray Reynolds, one of Pollack's supervisors at Ames. "He didn't like to argue, and he had trouble making his point sometimes. He would always end each argument the same way. He would pound his fist on the table and conclude: '*Because it just makes good science!*'"[195]

When back at Ames, he moved into a more comfortable role, and started to lead the development of the Doppler wind experiment. This experiment would answer one of the many questions that had been debated ever since the winds of Jupiter were first observed as cloud features in its atmosphere: just how deep are the winds on Jupiter?

Winds of Change

Jupiter's winds are important to the understanding of the planet's atmosphere and climate. Its winds above the clouds cast suspicion on the planets' energy source. If the winds were

191 Colin interview with author on 15 January 2009.
192 Ritchie, Astronautics and Aeronautics, 1977, 159.
193 NASA NSSDC, http:// http://nssdc.gsfc.nasa.gov/nmc/experimentSearch.do (accessed 20 March 2014).
194 NASA NSSDC, http://nssdc.gsfc.nasa.gov/nmc/experimentSearch.do (accessed 20 March 2014).
195 Reynolds interview with author on 12 November 2007.

driven by the sun's energy, the winds would be below the cloud tops, not above. However, if a more exotic energy source was driving the winds, such as latent heat released from water clouds, there would be a change in the winds' profile.[196] By tracing turbulent winds at different altitudes, clues to the energy source that drives the circulation of Jupiter's atmosphere could be discovered during its observation.

The Galileo mission consisted of two spacecraft: an orbiter and an atmospheric probe. The orbiter was the sixth spacecraft to explore the Jovian magnetosphere, but the first to orbit the giant planet. Its scientific objectives were to investigate its atmosphere and moons. The spacecraft launched on 18 October 1989 from Kennedy Space Center, Cape Canaveral, Fla., inside the cargo bay of Space Shuttle Atlantis. Once in Earth's orbit, it was fired into interplanetary flight by a two-stage, solid-fuel motor. It was a six-year flight that encountered Jupiter on 7 December 1995.

The Galileo Probe was critical to the Doppler wind experiment. It descended several hundred miles through the atmosphere by parachute carrying several instruments. One of the more remarkable facts about Jupiter is its size; it is so large it can contain all the planets in the Solar System. For such a large planet, it is surprising that Jupiter rotates rapidly. When the Galileo Probe encountered Jupiter's winds, it picked up speed and momentum from the planet's rotation. A sudden shift in motion caused a sudden change in the frequency of its radio signal, known as the Doppler effect.

Although descending at a rapid pace, the Probe successfully transmitted radio signals to the orbiting spacecraft, which relayed them to Earth. By measuring the frequency of the probe's signal, the probe's motion was traced and the wind speed recorded throughout its descent. If the probe was pushed toward the orbiter, the Doppler effect increased the frequency. If the probe was pulled away from the orbiter, the Doppler effect decreased the frequency. Although wind speeds are of scientific interest, the experiment did not actually measure the winds. Instead it traced the Probe's motion as it was swept up by wind speeds of 100 mph or more. As the Probe descended deeper and deeper, the atmosphere became thicker, the parachute opened and the Probe slowed its spiraling fall, allowing sensitive instruments to record the vertical structure of the atmosphere.

"When I met Jim Pollack at Ames, he was the principal investigator on the Doppler wind experiment," said David Atkinson, an associate professor at the University of Idaho, Moscow. "He eventually gave me the overall responsibility, although he maintained a deep interest in the progress of the experiment. The current acceptance of the Galileo Doppler wind experiment as an important, viable probe science investigation is mostly due to Jim Pollack."[197]

"The probe detected extremely strong winds and very intense turbulence during its descent through Jupiter's thick atmosphere. This provides evidence that the energy source driving much of Jupiter's distinctive circulation phenomena is probably heat escaping from the deep interior of the planet," said Richard Young, project scientist for the Galileo Probe at Ames. "The probe also discovered an intense new radiation belt approximately 31,000 miles above

196 NASA Quest, "OFJ Field Journal from Dave Atkinson - 11/22/95," http://quest.nasa.gov/galileo/bios/fjournals/atkinson-ofj10.html (accessed 20).
197 Ibid.

Jupiter's cloud tops, and a veritable absence of lightning," he added.[198]

Based on Pollack's probe expertise and support, his protégé Jeffrey Cuzzi, when still a fresh postdoctoral researcher, designed an instrument package for a Titan entry probe that was eventually developed and built by the European Space Agency (ESA). The Titan probe became part of the NASA-ESA Cassini-Huygens mission that sent a robotic spacecraft to the Saturn system. The spacecraft included a Saturn orbiter, called Cassini, and an entry probe named Huygens. The Huygens probe was designed to enter and land on Saturn's moon Titan.

The Cassini investigation was familiar to Pollack. He was confirmed in 1992 by NASA Headquarters Associate Administrator for Space Science and Applications L.A. Fisk, as an interdisciplinary scientist for the Origin and Evolution of the Saturn System experiment[199] and a member of the Cassini Project Science Group.[200] After nearly two decades of development, the spacecraft launched on 15 October 1997, and entered into orbit around Saturn on 1 July 2004. Its interplanetary voyage used gravity-assist maneuvers from Earth, Venus and Jupiter. Cassini was the fourth space probe to visit Saturn, and the first to enter orbit. It studied the planet and its many natural satellites, also observing Jupiter, the heliosphere, and testing the theory of relativity.

The Huygens probe reached Titan on 14 January 2005, when it entered Titan's atmosphere and descended to the surface. During that time, it successfully transmitted data to the orbiter, which then relayed it to Earth. This was the first landing ever accomplished in the outer Solar System.

As of this writing, Cassini continues its highly successful mission planned to end in 2017. In 2014, NASA was measuring the evidence for a large underground ocean of liquid water on Enceladus, a Saturn moon that had been found by Cassini. According to scientists, evidence of an underground ocean suggests that Enceladus is one of the most likely places in the Solar System to "host microbial life."[201]

It was unfortunate that Pollack never saw the rewards of such impressive and successful missions as the Galileo and Cassini-Huygens.

Discovering Our Home Planet – Mission to Planet Earth

By the early 1970s, an unpopular war in Vietnam and a slowing economy were the public's greatest concerns; both were burdening the government budget. As a result, the more costly space programs were eschewed in favor of more modest and, from the public's point of view, "practical" programs. Of all the programs submitted to President Nixon in 1969 by the Space Task Group, only the Space Shuttle was approved for 1972. NASA's annual budget, which had reached more than $5 billion in the mid-1960s was reduced to $3.7 billion in 1970.[202]

In compliance with this executive order, NASA Administrator James C. Fletcher announced (1972) that after a decade in which the moon was the primary focus of the U.S. space program, NASA now "…would emphasize earth-orbital programs geared to intensive study

198 NASA, "Galileo Probe Suggests," 22, January, 1996.
199 National Space Science Data Center, http://nssdc.gsfc.nasa.gov/nmc/experimentSearch.do?spacecraft=Cassini (accessed 17 April 2014).
200 NASA Ames History Office, PP05.03, Acq. 009-2005.
201 http://en.wikipedia.org/wiki/Cassini%E2%80%93Huygens (accessed 15 April 2014).
202 Gawdiak and Fedor, NASA Historical Data, 3.

of our homeland in the cosmos, the planet Earth …"[203] As a consequence, the government would fund the more practical environmental programs.

One of the first environmental programs NASA participated in was the Climatic-Impact Assessment Program (CIAP). Funded by the Department of Transportation, it would assess the effects of proposed high flying aircraft on the environment.[204] George W. Cherry, deputy associate administrator for programs in the NASA Office of Aeronautics and Space Technology, said the CIAP will "…assess the potential impact on the atmosphere of large fleets of supersonic transports (SST) operating in the eighties and the biological consequences of their potential modification of the stratosphere. We are cooperating with DOT by contributing to the technology needs of CIAP, with particular emphasis on the levels to which pollution can be limited..."[205]

At the time, supersonic transports and space shuttles had been granted permission for future flight entry into our open skies. But no one knew the effects of such engine emissions on Earth's atmosphere. In support of this program initiative, Pollack and other planetary scientists at Ames assumed the role of climate scientists to study Earth's atmosphere.

With funding from CIAP and the National Science Foundation, Pollack and Brian Toon[206] conducted studies that showed these stratospheric flights should have no significant change on Earth's climate, providing they operated at projected traffic levels for the next several decades. Their one caveat was that the SST's effects should be reevaluated when in operation.[207]

Above image shows a view of Earth from 36,000 nautical miles away, as photographed from the Apollo 10 spacecraft during its trans-lunar journey toward the moon. Photo credit: NASA 1969

During this time, they also evaluated the effect of the space shuttle's solid rocket boosters on the ozone layer. In *High Speed Dreams*,[208] a history of supersonic transport, Erik M. Conway argues that NASA's entry into political controversy came with this decision to conduct stratospheric ozone research. These studies revealed a relationship between chemistry and climate. This concept had started to emerge when the Mariner Venus and Mariner Mars missions revealed that relatively small initial evolutionary differences among the three "terrestrial" planets (Venus, Earth and Mars) had led to profound differences among these planets. By the 1960s, NASA scientists were

203 Science. *Astronautics and Aeronautics*, 1972, iii.
204 Science. *Astronautics and Aeronautics*, 1972, 305.
205 Science, *Astronautics and Aeronautics*, 1973, 74.
206 Toon was a research scientist at Ames from 1975-1997. Today, he is the founding chair of the Dept. of Atmospheric and Oceanic Sciences at the University of Colorado, Boulder.
207 Pollack et al., "Estimates of the Climatic," 247.
208 Conway, *High Speed Dreams*, 303.

aware that severe climatic changes can affect the habitability of a planet.

Pollack was one of many astrophysicists who now were beginning to see planet Earth differently. By the early1970s, environmental issues were starting to receive mainstream attention from activists, such as Rachel Carson, an American marine biologist and conservationist whose bestseller *Silent Spring* and other writings are credited with advancing the global environmental movement. The oil spill in the Santa Barbara Channel, hazardous smog in many urban areas, and photographs of a beautiful Earth from space all suggested the fragility and interdependency of our ecological systems, the "Environmental Movement" had become a social issue.[209] The Apollo project images of Earth revealed an integrated, life-supporting system, which captured the public's imagination. On 22 April 1970, the United States celebrated its first Earth Day, in which more than 2,000 colleges and universities and approximately 10,000 elementary and secondary schools participated.[210]

As part of this perspective, atmospheric aerosols became of interest not only for their related illnesses, such as respiratory disease, but also for their possible effect on the climate. As an example, carbon dust particles were polluting air over cities, and also known to absorb sunlight. Consequently, data were gathered on radiative properties of graphite, soot and coal particles of different sizes.[211]

To understand the Earth system, Pollack studied similar planetary systems. James E. Hansen, then (1972) a NASA astrophysicist at the NASA Goddard Institute for Space Studies (GISS), New York, also held a strong interest in comparative planetology, contrasting effects of Mars, Earth, Venus and the different magnitudes of their greenhouse effect. Hansen had met Pollack and Carl Sagan at planetary meetings in the early 1960s and remained a close friend throughout their careers. When Pollack and Hansen first met, they were both studying Venus. "We both had a strong interest in Venus, especially the clouds of Venus," said Hansen in an email to the author.[212] Hansen provided Jim with a powerful radiative transfer tool, called doubling code, for his growing toolkit, but ultimately left planetary science to study global climate change on Earth. (The doubling code was a fast way of calculating exactly the scattering properties of thick layers of particles of arbitrary size.)[213]

Scientists continue to study Venus; a planet similar to Earth that developed so differently. Its climate may have been hospitable to life at one time, but eventually became hostile to life. Earlier researchers speculated about a "greenhouse effect," but no one could explain why it wouldn't happen on Earth, or why it would have happened on Venus. The planet remains an unsolved mystery.

Throughout their careers, atmospheric science was a mutual, ongoing research topic for both scientists. These studies led to investigations of volcanoes, another source of aerosols in atmospheric phenomena. They simulated their climate effect and tested their use in climate research. When Hansen published a 1978 paper, "Mount Agung Eruption Provides Test of a Global Climatic Perturbation," in the journal *Science*, the NASA Administrator read it. According to Hansen, the Administrator told NASA's Chief Scientist that the agency should have a program to be ready for the next large eruption, per the paper's suggestion.

209 Badash, *A Nuclear Winter's Tale*, 26.
210 http://en.wikipedia.org/wiki/1970s#Environmentalism (accessed 22 April 2014).
211 Badash, *A Nuclear Winter's Tale*, 26.
212 James E. Hansen, email to author, 9 June 2009.
213 Jeff Cuzzi, interview with author 29 July 2014.

"Jim [Pollack] turned out to be the beneficiary, as Ames started a program of aircraft observations."[214]

Later that year, Ames established a climate office, the Ames Climate Office, which designed, planned and led the execution of numerous airborne research expeditions.

Past Records of Climate Change

In one of Pollack's more heavily cited studies, titled "Volcanic Explosions and Climatic Change: A Theoretical Assessment," he and Brian Toon started reviewing possible relationships between past records of volcanic activity and climate changes. As a reference point, they set the temperature scale at 1885. From the end of the nineteenth century until 1940, their theory of volcanic dust revealed temperatures increased as volcanic activity decreased. During the early part of this period, when volcanoes were more active, temperatures grew colder, but later, during volcanically quiescent times, there was no such drop in temperature. Their data suggested that volcanic activity made a significant contribution to cooler surface temperatures from the end of the nineteenth century to 1940, and less of a contribution from 1940 to the present. While volcanic explosions have a cooling effect on Earth, the magnitude is controlled by the effect of the sulfuric acid particles.[215]

Going back still further in time, they found that between 1430 and 1900, Earth was enveloped in the "Little Ice Age." Mountain glaciers and sea ice were more widespread than now, and records show that the Northern Hemisphere temperatures were approximately 0.5 K (.3 degree Fahrenheit) colder than the period between 1935 and 1945. Volcanic explosions were common. Volcanic activity between 1880 and 1905 was typical of the Little Ice Age in terms of number and magnitude of eruptions. According to Pollack, Sagan and Toon, highly active volcanoes during the Little Ice Age caused at least some variation in the cold temperatures during this period.[216]

Aerosols found in ice cores from that period provide a useful measure of the historical aerosol content of the stratosphere. Records of ice cores from Greenland and Antarctica were also analyzed for aerosol content and temperatures from approximately 75,000 BP to 12,000 BP (Before Present). They then used their findings to assess the importance of volcanic eruptions in generating and sustaining the last major ice age, called "Wisconsin."

Further support for their proposition came from examining volcanic dust and ash bands in Antarctic ice cores. They thought that small particles in the dust bands could be from far-away, and they observed that the coldest temperatures were related to large amounts of settled dust. Studies using volcanic ash layers in deep-sea cores suggested that global volcanic activity during the Quaternary, the time of the ice ages, was much greater than during the previous twenty million years. They concluded that volcanic aerosols greatly influenced past climate changes, but do not explain entirely all recorded changes.[217]

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214 Ibid.
215 Pollack et al., "Volcanic Explosions," 1082.
216 Ibid, 1071.
217 Pollack, et al., "Stratospheric Aerosols," 554.

The phenomenon known as the "year without a summer" was attributed to the Tambora, Indonesia eruption of 1815, the most violent volcanic explosion on record. It killed twelve thousand people in the Dutch East Indies as it spewed hot stones and volcanic ash into the air. One year after its explosion and halfway around the globe, New England had record low temperatures that summer. The snow and frost killed crops, which drove up the prices of wheat and corn and put farmers out of business. Similar weather conditions spread throughout Great Britain, France and Germany. In Europe, the Napoleonic Wars were over and recovery was just beginning. The bad weather led to crop failure, famines and riots.

The major climatic shifts of the past 500 years occurred in parallel with variations in the level of volcanic activity, however, there is no evidence that volcanic explosions preceded and initiated the ice ages, according to Pollack.[218] Pollack and Toon reported that most meteorologists and climatologists believe that dust particles and sulfur gases ejected into the stratosphere by volcanic explosions cause bad weather. However, not all volcanic explosions cause all the unusual weather on Earth, nor do they account for all the climatic changes.[219]

Pollutants in Stratosphere Linger Longer

Once Pollack and his colleagues understood the type and duration of volcanic aerosols, they then started studying the effect these aerosols have on the changing climate of Earth. To test the sensitivity of climate to varying quantities of stratospheric aerosols, they measured the heat transferred by these aerosols. Climate was characterized as a globally-averaged surface temperature, which was a balance between the energy absorbed and the energy bounced back into space. Since high-altitude aerosols scatter and absorb the sun's rays, and interact with and produce thermal radiation, changes in their quantity can cause a temporary global heat imbalance. In theory, volcanic aerosols can prevent Earth's surface from warming by reflecting sunlight back into space, causing a cooling effect. Conversely, the suspended particles can also absorb and retain Earth's warmth, causing a reverse effect.

Pollack and his colleagues developed sophisticated simulations to determine the amount of sunlight Earth was emitting into space. They found that the more silicate and sulfuric acid aerosols present, the more reflective and brighter Earth, which can affect climate. These computer models were used later to analyze the climate effect of windblown Saharan dust.[220] The Saharan dust and its associated warm and dry air, known as the Saharan Air Layer, is today an ongoing NASA investigation, called Hurricane and Severe Storms Sentinel mission.[221]

Eyewitness Account

By this time, there was a growing demand for flight expeditions, which effectively augmented the fleet of research aircraft at Ames. One such addition was due to the final planning phase of the Earth Resources Technology Satellite (ERST) program. ERST-1, or what became known as LandSat-1, was NASA's first unmanned satellite specifically dedicated to multispectral remote sensing. NASA researchers became concerned that they

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218 Ibid, 551.
219 Toon and Pollack, "Volcanoes and the Climate," 26.
220 Sagan and Turco, *Path Where*, 457.
221 http://www.nasa.gov/content/nasas-2013-hs3-hurricane-mission-to-delve-into-saharan-dust/ (accessed 22 April 2014).

would have trouble analyzing satellite data due to atmospheric distortions. However, if high-altitude photography and remote sensing from above the densest part of Earth's atmosphere could be obtained by aircraft, researchers could match these data to the satellite data for verification. To execute this strategy, NASA asked the U.S. Air Force for its two soon-to-be surplus, high-flying U-2 reconnaissance aircraft. After some negotiations, Ames was given the responsibility of managing and operating these special planes. The success of these Ames airborne science missions led to other scientists proposing their own flight research expeditions.

Between 1978 and 1984, Jim Pollack was the chief scientist of the Ames Climate Office. He also was the chief scientist for a program called Aerosol Climate Effects (ACE), a study of Earth's atmosphere. He wrote that "the volcanic eruption of Mount Agung in Bali in 1963 was the last major eruption, so it was not possible to determine if climatic changes are caused by volcanic explosions."[222] As chance would have it, Pollack and other Ames researchers were given unique circumstances to study two of the most catastrophic eruptions in modern time. In 1980, the Mount St. Helens volcano erupted in Washington, and in 1982, three powerful El Chichon volcano eruptions occurred in northwestern Chiapas, Mexico.

The Mount St. Helens eruption killed sixty-five people, causing massive mudflows west in Yakima, Washington, and falling ash east in Spokane, Washington. To examine the size distribution and quantity of ejecta, Ames scientists soon became part of a larger expedition. They flew NASA's U-2 at stratospheric heights to collect samples. The aircraft, carrying seven experiments, flew five ACE missions in May and June. The data obtained from these experiments, in conjunction with NASA's Stratospheric Aerosol Measurement (SAM) II and Stratospheric Aerosol and Gas Experiment (SAGE) satellite experiments, assessed the climate effects of the stratospheric aerosols, some 1000 times greater than those in the ambient air, by measuring the absorption and scattering of the volcanic aerosols.[223] Findings showed that the amount of sulfuric acid in the stratosphere was several hundred times greater than before the eruption.[224] The ACE data were the most complete set of observations ever recorded of volcanic aerosols in the stratosphere, according to the Ames newsletter *Astrogram*.[225]

El Chichon Flight Expedition

The 1982 eruption of El Chichon was the largest volcanic disaster in modern Mexican history. El Chichón is located between the Trans Mexican Volcanic Belt and the Guatemalan Belt. Prior to the 1982 eruption, there had been no volcanic activity since ca.1360. The presumed dormant volcano produced three powerful eruptions on March 29, April 3, and April 4, destroying nine villages and killing 2000 people. The region, about 16,000 square miles, was covered by more than a foot of ash, devastating coffee, cocoa, banana crops, and cattle ranches. The eruption's total damage was estimated at $132 million (in 1982 US dollars).[226] Three weeks after the eruption, the volcanic plume had encircled both

222 Toon and Pollack, "Volcanoes and the Climate," 9.
223 Pollack, "Measurements of the Volcanic," 815-838.
224 NASA ARC, "St. Helens Volcano," 1.
225 NASA ARC, "St. Helens Volcano," 1.

hemispheres.[227]

Pollack soon sent an Ames research team to monitor the pervasive and massive plume. He instructed them to collect aerosol particle samples and study the radiative properties of the plume using spectra between 4.5 and 13.5 micrometer wavelengths. A wavelength below 4.5 detects thermal radiation while minimizing interference from sunlight. A value above 4.5 microns still detects thermal radiation but excludes carbon dioxide. If the data are collected at wavelengths longer than the recommended range, between 13.5 and 20 microns, carbon dioxide makes the atmosphere opaque and overshadows any aerosol effect, according to the crew's manager Fred Witteborn.

To do the job, the crew chose NASA's Convair 990, a modified, four engine, jet transport that could fly relatively long distances and carry a heavy payload. This aircraft, named Galileo, was a medium-altitude research airplane, capable of flying multiple, lengthy missions. Although ideal for this mission, the aircraft still had to be customized, a special window needed to be built for the telescope. Window glass is opaque to infrared (thermal) radiation, so the glass had to be replaced with another material. Because salt crystals can be transparent to infrared radiation, a salt solution was chosen for the window pane. It was fairly transparent, and fell within the required infrared wavelength band. Another problem to be solved was the sun's intense heat at high altitudes, which required an entirely new spectrometer for the experiment.[228]

Once in flight, the aircraft flew below the plume, where the crew measured the opacity of the cloud and tracked its location. The customized spectrometer sampled the clouds' varying optical thickness on two occasions. "We were measuring the heat absorption of the cloud of volcanic aerosols," said Witteborn. "The data provided the thermal effects on Earth that might have resulted from the volcanic clouds."[229]

According to their study, the dominant aerosol observed was sulfuric acid. The volcanic cloud reflected the sun's energy, which cooled much of the lower atmosphere and northern hemisphere. Another result was a warmer, lower stratosphere in northern latitudes in the winter of 1982. This thin layer of particles absorbed the warm, upwelling radiation from the surface and troposphere, and reemitted it at much colder temperatures. The net impact of volcanic particles on temperatures in the troposphere and at the surface is far from obvious, according to Pollack.[230]

Over the years, Pollack continued to design planetary science experiments using NASA aircraft at Moffett Federal Airfield. These data samples were applied to some of the most unique and sophisticated computer simulations in the world.

Ames was always a special place: Even today, it is one of few government laboratories that has a supercomputer facility. Ames Center Director Hans Mark initiated this world-class facility when he signed an agreement with the Advanced Research Projects Agency (ARPA), part of DOD, to house and manage the Illiac IV computer complex, which was the

226 http://en.wikipedia.org/wiki/El_Chich%C3%B3n (accessed 22 April 2014).
227 Bernard and Rose, "The Injection of Sulphuric."
228 Fred Witteborn, e-mail sent to author, 22 March 2008.
229 Pollack and Ackerman, "Possible Effects," 1057.
230 Ibid 1058.

largest and most sophisticated in the world. Its acquisition was a triumph for the center, and although some time was needed to make it operational, by early 1973 it was in use.[231] During this time, silicon chip innovators and manufacturers were starting to crop up in the farmland near Ames, transforming the landscape into a fast-paced, commercial technology region, called Silicon Valley. One tiny computer chip was changing the culture and business of the San Francisco South Bay in California. With a computer facility, Ames was changing with the times. Over the years, supercomputers had become faster, smarter and more powerful, increasingly capable of managing and executing massive sets of complex data. Without this supercomputing power, the sophisticated atmospheric modeling done at Ames would not have been possible. Ames researchers proceeded to test the limits of this new technology.

The Start of Nuclear Winter

Pollack's long hours of meticulous work gave him an impeccable reputation as a scientist. In some cases, his scientific judgment was so trusted that it was even sought before papers were published. So it was no surprise when he received a pre-print of an article postulating that great masses of dust lofted by an asteroid or cometary impact caused the extinction of the dinosaurs 65 million years ago. The paper[232] was written by Luis and Walter Alvarez at the University of California, Berkeley. Scientists now knew that different kinds of aerosols produce different effects. Even their size, shape and composition make a difference in their effect. Volcanic explosions produce ash and sulfuric acid that can linger in the stratosphere for years. Ground explosions produce different aerosols and not necessarily gases. Large particles may not make it into the stratosphere and could fall out quickly.

Pollack wanted to test the paper's assumptions. He called Brian Toon and Thomas Ackerman, a climate and radiation expert, into his office to discuss the hypothesis and start the process to simulate the atmospheric extinction problem properly. Toon worked the particle evolution problem, and pulled Rich Turco into the discussions. Ackerman worked the climate problem, and developed a simple model to test it. "Jim drove that problem intellectually in our group, and deserves the credit for putting us on that road," said Thomas Ackerman, director of the Joint Institute for the Study of the Atmosphere and Ocean at the University of Washington, Seattle.[233]

They soon developed a state-of-the-art model to study the impact effects. From these modeling results, Toon wrote a key paper[234] that won the prestigious H. J. Allen award at Ames. In October 1981, Toon presented their preliminary findings at the annual meeting of the Geological Society of America held in Snowbird, Utah, where attendees discussed the general problem of an asteroid, or comet, hitting Earth and the physical and biological consequences. Toon's results supported Alvarezes' paper, and showed that severe climate cooling and loss of light needed for photosynthesis would occur for a year, or longer after a large impact. Members from the National Research Council (NRC) were present and heard Toon's presentation. They decided the issue of dust raised by nuclear explosions needed

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231 Muenger, E. A., *Searching the Horizon*, chap. 7.
232 Alvatez, L. W. "Extraterrestrial Cause."
233 Thomas Ackerman, e-mail sent to author, 26 June 2008.
234 Toon, O.B., et al."Evolution of an impact," 187-200.

further investigation, which resulted in the National Academy of Sciences (NAS) being asked to study the issue.[235]

At this time, Turco had been working as a consultant for the Department of Defense at R&D Associates (RDA) in Marina del Rey, Calif., for more than a decade. RDA had developed analytical models on nuclear explosions in the past. As an employee, he was given access privileges to unclassified information on the quantity and size of dust particles raised by atomic explosions. He later used his expertise and the data set to construct the original nuclear winter model. They even found an earlier NRC study (1975), titled "Long-term Worldwide Effects of Multiple Nuclear-Weapon Detonations," which used a similar scenario and the same nuclear dust data base, but its focus was mainly on ozone depletion.

In 1982, Paul J. Crutzen and John W. Birks[236] published a paper, titled "The Atmosphere after a Nuclear War: Twilight at Noon," in the journal *Ambio*, which talked about the importance of smoke from burning cities. When Toon and Ackerman modeled a nuclear conflict that included the effects of smoke, they were surprised to find a massive cooling of the global climate, to temperatures lower than the last ice age. Turco and Toon presented their results at an April meeting of the NAS panel investigating the possible climate changes from a nuclear conflict.[237]

By 1983, Pollack, Toon, Ackerman, Chris McKay and Turco published the paper, "Environmental Effects of an Impact-Generated Dust Cloud: Implications of the Cretaceous-Tertiary Extinctions," in *Science* magazine. The article discusses the climate effects of such a large impact, and was largely based on the earlier (1982) paper by Toon, et al. They argued that such a thick cloud of dust may prevent photosynthesis for many months, and for perhaps six months it might be too dark for animals to see. In addition, the surface might cool to ice age temperatures for as long as six months to a year. [238] They found that the thick dust may remain long enough, to strongly cool the continents, but not the oceans.[239]

After Sagan finished his *Cosmos* television series and his responsibilities on the Voyager 1 and 2 spacecraft, he came to Ames to join their research. Soon afterwards, the scientists Turco, Toon, Ackerman, Pollack and Sagan, formed an unofficial research team. The group was given the acronym TTAPS, based on their surnames. The name, Sagan and Turco wrote, seemed eerily foreboding of the "Taps" played as a bugle call to put out the lights or played at military funerals.[240]

At this time, Sagan was told about the Crutzen and Birks publication, which identified smoke from fires caused by nuclear detonations as an issue. However, Crutzen and Birks thought the smoke would come from burning forests, while the TTAPS group argued urban fires were more important. Crutzen and Birks assumed the smoke would stay in the lower atmosphere, where it would only last for days or weeks, and mainly be toxic. The TTAPS group thought the smoke would go into the stratosphere, where it could last for months or years, and impact the global climate.

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235 Sagan and Turco, *Path Where*, 458.
236 Crutzen, "The Atmosphere After," 114-125.
237 Sagan and Turco, *A Path Where*, 459.
238 Pollack, "Environmental Effects," 287-289.
239 Pollack, "Kuiper Prize Lecture," 173 – 198.
240 Sagan and Turco, *A Path Where*, 20.

The results were to be presented in December at the American Geophysical Union (AGU) meeting in San Francisco, Calif. However, Ames management forced the talk to be withdrawn, arguing that it was an important topic and needed to be reviewed before presentation. Sagan, therefore, organized a workshop in Boston to review the results. From the workshop, two papers in the journal *Science* appeared in December 1983: the TTAPS paper "Nuclear Winter: Global Consequences of Multiple Nuclear Explosions," and the Ehrlich, P.R. et al. "Long-term Biological Consequences of Nuclear War."

According to Pollack,[241] many scientists thought about tackling this problem, but the technology wasn't ready until the early 1980s. He and Sagan had discussed calculating this problem in the early 1970s during the early phases of the Mariner 9 mission, while waiting for the Mars global dust storm to clear.[242] Pollack said that there were two events that made the early 1980s the right time for this type of investigation. First, the Crutzen and Birks 1982 study[243] showed that smoke from fires caused by nuclear detonations was an issue. Second, the National Academy of Sciences was reconsidering the problem of the long-term effects of nuclear exchanges.[244]

In the provocative 1983 paper "Nuclear Winter: Global Consequences of Multiple Nuclear Explosions," TTAPS argue that the dust and smoke in the atmosphere after a nuclear explosion would have a major effect on the stability and climate of the Earth. They wrote that particles produced in a nuclear exchange would probably cause major temperature changes, including cooling the northern hemisphere continents. The nuclear explosions would ignite pervasive and massive fires, not just forest fires but city fires with burning plastics and chemically treated materials like furniture and carpets. Burning synthetics would generate enough sooty smoke to darken daylight and perturb the weather. The atmosphere would warm immensely due to the heat and sunlight absorbed by the pitch-black soot. But Earth's surface would cool because sunlight would be blocked by an impenetrable barrier of large-carbon-chains of soot. "Had we considered only the dust excavated by near-surface detonations," said Pollack, "we would have obtained a much weaker thermal perturbation."[245] Dust doesn't absorb much sunlight by itself. The soot and smoke made a difference in their numbers. These findings led NASA's TTAPS group to go public despite risky consequences to their careers.

During this time, Turco, Toon and Ackerman had about ten years experience successfully modeling the atmospheres of planets millions of miles away. They also were mentored by the best planetary scientists in the world. Pollack and Sagan joined them and their quest to quantify the effects of a nuclear war and publish the results. At the time, there were still enough weapons in the world to devastate every city on Earth twenty-five times over.[246]

They used three models for their nuclear exchange simulation: a nuclear war scenario model, an aerosol particle model, and a "radiative transfer" (heat transfer) model. The nuclear war scenario model specified the altitudes of dust, smoke, radioactivity, and nitrous oxide, given the size, number, and type of detonations, their geographic locations, and the atomic impact

241 Pollack, "Kuiper Prize Lecture," 173 – 198.
242 Sagan and Turco, *A Path Where*, 455-456.
243 Crutzen and Birks, "Atmosphere After a Nuclear War."
244 Turco et al., "Nuclear Winter," 1283.
245 Pollack, "Kuiper Prize Lecture," 188.
246 Sagan and Turco, *Path Where*, xvii.

of each blast. The aerosol particle model predicted the rapid and uniform dispersal of smoke and dust clouds. The radiative-convective model calculated light and temperature changes over time. Because air temperatures depend on the surface's heat absorption, separate simulations were performed for land and ocean.

They acknowledged that the models could provide rough estimates only. Who could predict how fast explosion clouds and fires would spread, and their extent? They thought "thousands" of dust and smoke clouds would spread throughout the northern hemisphere at altitudes greater than 98,000 feet after a large nuclear exchange. Weather patterns would almost certainly be altered. Although their simulation results may vary due to uncertainties in scenarios and conditions, they reported that "the most probable effects are serious."[247] They thought that the clouds would be impenetrable to sunlight, and temperatures would drop below freezing. Smoke and dust clouds would absorb the sun's energy causing temperatures to change and accelerate the movement of particles and radioactivity from the northern to southern hemispheres. The human race might be seriously threatened by long-term exposure to cold, darkness and radioactivity.[248]

For their nuclear winter research, the TTAPS group received the Leo Szilard Award (1985) by the American Physical Society "in recognition for outstanding accomplishments by physicists in promoting the use of physics for the benefit of society in such areas as the environment, arms control, and science policy."

According to Pollack, the nuclear winter problem was his first "practical" work on a pr oblem with such enormous impact to society. There were major political reactions to their nuclear winter study. "I and some of my colleagues were unaware of such an impact at the beginning," he said. At Ames, they had some pretty tricky discussions with upper management, "who to their credit did not suppress the *Science* article" and their discomfort with the word "war" in the title led to the catchy phrase "nuclear winter." Despite the unexpected response, Pollack and his colleagues were proud that their initial paper stood the test of time. Many more sophisticated calculations have been performed to determine the effects of nuclear-generated particles and their aerosol properties, said Pollack.[249]

While nuclear winter was extremely controversial at the time, the work was supported by a 1985 NAS study [250], and later by SCOPE (an organization of National Academies around the world) in 1985[251] and 1986[252].

Searching For Common Ground Among The Terrestrials

Pollack wrote numerous papers with colleagues about the past and present climates of the terrestrial planets. One of his most heavily cited works was a 1978 paper titled "Climatic Change on the Terrestrial Planets," in which he masterfully analyzed and compared the mechanisms causing "climatic" changes on the terrestrial planets. It also was his chosen lecture topic when awarded the prestigious Gerard P. Kuiper Prize in 1989.

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247 Turco et al., "Nuclear Winter," 1283.
248 Ibid., 1292.
249 Pollack, "Kuiper Prize Lecture," 188.
250 National Research Council, *The Effects on the Atmosphere.*
251 Harwell, *Environmental Consequenc*e, 1985.
252 Pittock, *Environmental Consequence*, 1986.

According to Pollack, until the 1950s, people generally assumed that planetary atmospheres were naturally stable, changing only slightly over millions of years. But on Earth, climate changes ranged from the heated temperatures of the pre-Cambrian age, through the alternating glacial and interglacial epochs of the last few million years, to the small but significant variations of the recent past. On Mars, evidence for climate change is found in its morphological features. Channel-like features suggest an earlier epoch of a warmer and wetter climate, and the layered polar regions imply more recent periodic climate changes. No evidence existed for Venus, but its present climate state may provide important clues about mechanisms for affecting climate. Pollack suggested that to better understand climate change, knowledge of past climates on one planet may be used to postulate climate change mechanisms for another planet. He discussed ways in which a given mechanism might operate similarly on several planets and questioned when it may lead to very different consequences due to the intrinsic differences among the terrestrial planets. He emphasized the importance of understanding similarities and differences in what influences climate on Venus, the Earth and Mars.[253]

Past and Present Conditions

To gain perspective on the past and present climates of the terrestrial planets, Pollack compared their early and present conditions. In theory, all four terrestrial planets formed in the same vicinity of the primodial solar nebula, and are made almost entirely of cosmically abundant, "refractory" elements, which condense from a gas at high temperatures. They include magnesium, silicon and iron. The atmospheres of the terrestrial planets evolved from small amounts of more volatile material that may have been indigenous to the inner solar system, or exported from the outer parts of the solar system via asteroids or comets. Yet each developed differently. Mercury is essentially an airless body; Venus has a massive atmosphere with a surface pressure 90 times greater than Earth's, a scorching surface temperature of 735 K (863° F), and a layer of dense clouds made of sulfuric acid; Earth is the one place in the solar system where liquid water exists and is stable on the surface, a feature that supports life; and Mars is a cold, dusty place with a low surface pressure, and has mostly carbon dioxide in its atmosphere. Given their initial and present states, Pollack asked, "What components of their atmospheres and surfaces determined their present climates?"[254]

Pollack summarized past climate changes of Earth and Mars, and acknowledged the limited information available about Venus. He said that various techniques have reconstructed Earth's past climatic changes over billions of years. Although it has been only within the last 100 years that direct quantitative measurements of climate variables, such as temperature, have been made, meaningful global averages can still be derived. To go back further into the past, it is necessary to use proxy records, he said. For example, by measuring the oxygen in ice cores it is possible to reconstruct the air temperature changes above the ice core. Different proxies are used for different time scales. Tree rings can measure the last 1,000 years; fossil pollen for the last 10,000 years; ice cores for the last 100,000 years; sea cores for the last 100 million years; and sedimentary rocks for the last billion years. Over the last million years, the Quaternary, extensive ice sheets covered large portions of northern Europe, Asia and North America. These large ice sheets were the net effect of accumulated snow in

253 Pollack, "Climatic Change," 480 – 481.
254 Pollack, "Kuiper Prize Lecture," 174.

the winter months and evaporation, or ablation, in the summer months; colder temperatures could cause growth of an ice sheet.[255]

Since the last glacial period, ending 12,000 years ago, there has been a slight increase in temperature of one degree Celsius. "Such a temperature change is not trivial," Pollack explained. "It can affect the growing season at high altitudes, and can cause abnormal rainfalls." The last ice age, the Wisconsin, reached its peak about 20,000 years ago, the transition from glacial to interglacial conditions began 150,000 years ago, and the present interglacial period, the Holocene, started several thousand years later. "Today's interglacial period has lasted as long as the total duration of past interglacials," said Pollack.[256]

His knowledge of Mars was mostly based on the data collected by the Mariner and Viking missions. The Mariner 9 observations of channel-like features appeared to be carved by running water in its past. These channels suggest that the climate was once warm enough for liquid water to exist on the surface. It is possible that some channels on Mars were formed, in part, by a thicker liquid. "Given the conditions on Mars, the only plausible, cosmically abundant substance that meets this requirement is liquid water," he said.[257] However, it was too early to assume that Mars had a warmer and wetter past. If liquid water was released on the surface today, it would ice over. The resulting ice layer might effectively insulate the interior and prevent liquid water from quickly freezing. "Thus, one could argue that the fluvial features are due to a purely geological change – the release of liquid water from the interior of Mars – and not the result of changed atmospheric conditions."[258]

The gullies are a different matter. He said that their most important property is their ubiquity. While not found everywhere on Mars, they are found in many places. They are present internally and externally on the walls of impact craters, suggesting they formed after impact. Their surrounding terrain reveals little evidence for widespread volcanism. The absence of gullies on the youngest volcanoes, such as the Tharsis volcano, suggests that the conditions necessary for gully formation have been absent on Mars for awhile.

More evidence for climate change on Mars is found in the underlying sediment layers at both polar regions, which are among the youngest geological features on the planet, Pollack wrote. There have been several alternating periods of deposition and erosion in the polar regions, which have a layered appearance. The layers look like a stack of dinner plates, with smaller plates on top of the larger plates. Each layer was estimated to be 30 meters (98 feet) thick. It is believed these deposits consist of fine grained dust particles wind blown from the equator, and water ice frozen out of the polar atmosphere. If nothing more than depositions occurred, then there would be domes covering the polar region, he continued. Although the layered areas appear to be caused by alternating periods of accumulation and erosion, they may possibly be due to a change in the material deposited or the transport mechanism. Lastly, analysis of the Viking landers' returned data on the composition of Mars' atmosphere implies that "from 10 to 100 times as much carbon dioxide has been outgassed over the history of Mars as is currently present in its atmosphere," Pollack noted.[259]

255 Pollack, "Climatic Change," 487.
256 Ibid.
257 Ibid., 489.
258 Ibid.
259 Pollack, "Climatic Change," 494.

Terms and Approach Defined

Jim started his comparative analysis of the terrestrial planets by defining his terms and approach. The term "climate" was the "average time it takes for a planet to smooth out the significant short term fluctuations that characterize the more instantaneous state of the atmosphere, or its weather." He decided there were five categories that determine a terrestrial planet's climate: (1) the absorption of the sun's radiation near the top of the atmosphere, which is determined by both the sun's output and the orbital and axial characteristics of the planet; (2) the gases and aerosols of the atmosphere; (3) the reflectivity of its surface; (4) volatile deposits, which readily vaporize; and (5) the planet's interior, which includes volcanic activity, outgassing history, and astronomical perturbations caused by the gravitational influences of the other planets. Each category can act as a primary driver for climate change, but several of them may change in response to an initial climate variation. Pollack believed these interactions, or feedback loops, could alter the magnitude of the resulting climatic change. To provide a frame of reference, he summarized a theory of climatic change for each of the terrestrial planets. He said that because recorded history shows that climatic changes have occurred over millions of years, it is suspected that there isn't any one cause of climatic change. By comparing the climate conditions on Earth, Mars and Venus, he hoped to gain some insight into their past.

A Short History of Earth

According to Pollack, when Earth first formed, approximately four-and-a-half-billion years ago, the sun was 30 to 40 percent less bright. At this time, the terrestrial planets were finishing, or had finished, accreting, continued Pollack. Less sunshine would affect Earth's climate. Past studies have shown that if Earth had the same atmosphere as it has today, Earth's average global surface temperature would have been below the freezing point of sea water during its first 2.5 to 3.5 billion years. However, the earliest known microfossils of early life forms are dated back to approximately 3.2 billion years ago. "It is hard to see how the origin of life and the subsequent survival of life forms could have occurred on an ice-covered surface," said Pollack. "Second, there are rocks of comparable antiquity, whose morphology requires the presence of liquid water. Finally, isotopic analyses of pre-Cambrian charts suggest that the climate was warmer several billion years ago." He said that this conflict may be resolved by considering other factors.[260]

The discrepancy between the geological record showing the long-term stability of Earth's climate and the expected consequences of less sunshine was identified as "the faint young sun paradox" by Carl Sagan and George Mullen, and published in a paper (1972)[261] that is now considered classic. "There is more to the 'faint young sun story,' though," said Jim Kasting, distinguished professor of geosciences and meteorology at Pennsylvania State University. "Jim, of course, was well aware of the problem, being Carl's former student." And to get more minds involved in solving the problem, Pollack invited Kasting to Ames as a postdoctoral researcher, and encouraged him to learn radiative transfer (atmospheric heat transfer) and one-dimensional climate modeling.

260 Ibid., 507.
261 Sagan and Mullen, "Earth and Mars," 333 - 345.

They collaborated on a Mars climate project, and published a paper titled "The Case for a Warm, Wet Climate on Early Mars" (1987) in the journal *Icarus,*[262] which shows early Mars climate calculations that were based on the model Kasting constructed while working with Pollack. Kasting has used that same climate model, and its various updated versions, to revisit "the faint young sun" problem many times during the last 25 years. "Jim was my mentor, he taught me about carbon dioxide collision-induced absorption. This is an important part of 'the faint young sun' problem that is sometimes neglected by other climate modelers. Pollack knew about this phenomenon from his previous work with Sagan on the greenhouse effect of Venus. So, that part of the climate model came straight from him."[263]

To resolve the paradox between Earth's predicted early frozen state and its observed early origin of life, Pollack started to look at the history of Earth's atmospheric conditions. When the abundance of rare gases in Earth's atmosphere is compared with what is in meteorites and the solar wind, strong evidence suggests Earth never had a primitive atmosphere, continued Pollack. Its secondary outgassed atmosphere was another factor to consider. Studies showed that it may have had some nitrogen existing as ammonia, and almost all the carbon was tied up as carbon dioxide. Ammonia plays an important role in the greenhouse effect. "The simultaneous presence of both ammonia and carbon dioxide tends to maximize the greenhouse effect," said Pollack. According to his calculations, "…the greenhouse effect generated in…atmospheres with very modest amounts of ammonia will counteract less sunshine and lead to temperatures during the first several billion years of Earth's history that are compatible with Earth's geological and biological record." In addition, over the last ten million years or more, the continents and oceans have shifted locations. When a continent moves, its temperature and rainfall patterns change significantly, which cause its surrounding oceans to either recede or expand. Some scientists believe that the Pleistocene series of ice ages may have been set off by Antarctica drifting toward the South Pole and the northern continents toward more polar regions. As the continents drifted toward the polar regions, seasonal snow "deposits will be built up…and will cause a change in the overall albedo of the Earth," said Pollack.[264]

Earth's Shifting Continents

To illustrate the effects of Earth's shifting continents, Pollack discussed the belief of some scientists that approximately 200 million years ago, all the continents combined to form a supercontinent, Pangaea ("all lands"), which was centered near the equator. Today, continents had shifted. Antarctica is centered near the South Pole; the northern continents have migrated toward the North Pole and have nearly isolated the Arctic Ocean from the Pacific and Atlantic Oceans; North and South America have been united by Central America; and there is a broad gap between the tip of South America and Antarctica**.**[265]

Such geographic changes can be related to the effects of climate changes over the last 200 million years. As Antarctica and the northern parts of Europe, Asia and North America began to move toward the poles, these continents experienced an increasingly colder climate. The permanent ice sheets on Antarctica and Greenland and more seasonal snowfall

262 Pollack and Kasting, "The Case for a Warm," 203 - 224.
263 Jim Kasting, e-mail to author, 22 February 2008.
264 Pollack, "Climatic Change," 508.
265 Wilson. "Shaping of the Continent," 24 -48.

in the northern regions had the added effect of increasing the Earth's albedo. This effect can therefore account for part of the temperature decline experienced over the last tens of millions of years and may be a necessary condition, although perhaps not a sufficient condition, for the occurrence of prior ice ages, wrote Pollack.[266]

Sun's Radiation on the Planets

The 'astronomical theory' was another contributing factor for Earth's past climatic changes. Scientists thought that as a result of solar and planetary perturbations, the eccentricity of Earth's orbit and the obliquity (angle between its pole direction and orbit plane) and orientation of its axis of rotation have oscillated over the last 10,000 to 100,000 years. Earth's exposure to the sun, called insolation, is only slightly affected by eccentricity, "but the instantaneous summer solstice insolation in the polar regions has a strong dependence on the combined effects of the eccentricity and axial direction."[267] An asymmetry exists in how land is distributed between the polar regions; more land exists in the northern subpolar region than in the southern subpolar region. Since land is more thermally isolated than the oceans, large sheets of ice can build up in the subpolar areas, if more snow accumulated in the winter than melted or evaporated in the summer. Very thick deposits can build up into a mobile glacier, spread over the adjacent land, and travel a great distance before melting or falling apart. When timescales of obliquity and eccentricity and precession (allowing for epochs when Earth is slightly more tilted toward the sun and travelling in a more elliptical than circular orbit), are compared to timescales and epochs of climate change, there is a very close correlation. Thus, "…orbital perturbations are in part responsible for the fluctuations between glacial and interglacial epochs over the past one million years," said Pollack.[268]

Debris in the Air

Another category Pollack cited as influencing climate change on Earth is the aerosols and gases in its atmosphere. Volcanic explosions can generate and eject such aerosols into the stratosphere. Citing one of his earlier studies, Pollack reported that volcanic aerosols cause Earth to cool because these particles are small and are poor absorbers of light. Pollack said, "…multiple volcanic explosions, closely spaced in time, are required for volcanic aerosols to influence climate over an extended period of time."[269]

In theory, although the sun's brilliance may have changed over the last billion years, "there is no firm theoretical or direct observational evidence that its output varies on a shorter scale." Nevertheless, if the sun's output has increased over the lifetime of Earth, these shorter periods of change could also be important. According to some scientists, a change in the sun's output would cause a change in Earth's surface temperature. Over the centuries, solar activity has been measured by the increased number of sunspots; more frequent auroral displays; the shape of the sun's corona; and fewer carbon-14 isotopes produced.

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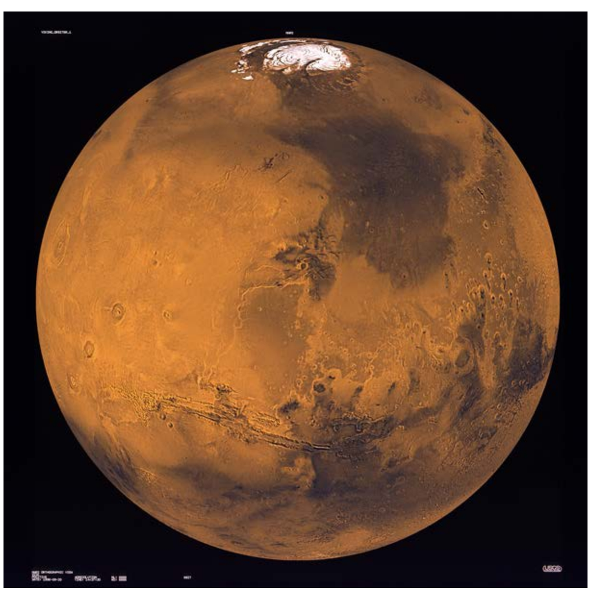
266 Pollack, "Climatic Change," 509.
267 Ibid., 511.
268 Ibid.
269 Pollack, "Climatic Change," 518.

Finally, an anthropogenic factor also was included as having an effect on Earth's climate change. Pollack, Toon and Sagan[270] report that in 1979 technology has reached a point where it may be inadvertently causing significant climatic changes. The primary concern was that man may be changing the atmosphere by introducing trace gases and aerosols, although other activities may be affecting the climate as well. At the time, they were concerned that Earth's ozone layer was being negatively impacted by chlorofluorocarbons (CFCs), nitrous oxides and hydrogen chloride. These molecules destroyed ozone and allowed more ultraviolet light to reach Earth's surface. Trace gases also may lead to global warming due to an enhanced greenhouse effect. In 1979, atmospheric carbon dioxide was ten percent higher than in the last century.

Other concerns were power generation and land use. He thought the world's energy production rate may eventually cause a significant increase in the surface temperature. "Increased power consumption could cause a significant global warming of about 2 Kelvin," he said.[271] Citing then recent studies on the drought in the Sahel area of Africa, he correlated overgrazing with an increase in surface albedo and, consequently, a drop in surface temperature. Such a drop in temperature decreases rainfall, which further denudes Earth of its vegetative coverage.

The History of Mars

Similar to Earth at times, Mars has had its own history of climate changes. Pollack thought that Mars was like Earth in that it experienced less sunlight in the days of the "faint young sun." That is, stellar evolution models show that after a star is born, it slowly but steadily becomes brighter throughout time. Thus our sun must have been about 30 percent fainter when Earth and Mars were "young." This would cause colder climates, *not* an epoch of warmer, wetter weather. Other variables needed be considered to explain Mars' climate history. Pollack proposed two concurrent changes to the present Mars atmosphere that may have contributed to a warmer, wetter climate in Mars' past.



At left is a Viking 1 composite image (AC96-0346-31) of Mars. The Viking 1 Mission was flown in June 1976. Photo credit: USGS and University of Arizona.

On Mars, early in its history, it was suspected that there was a short period of intense outgassing, related possibly to its core formation, or late heating from its accretional phase. In addition, Pollack theorized that almost all carbon gases outgassed over the history of Mars had been adsorbed by regolith, a reversible reservoir, and as carbonates within an irreversible carbonate

270 Pollack, Toon and Sagan, "Anthropogenic Albedo."
271 Pollack, "Climatic Change," 518.

rock reservoir. Over time, the more carbon dioxide tied up in both reservoirs, the less was available in the atmosphere. Therefore, in the past, the atmospheric pressure, which is heavily influenced by carbon gases, may have been greater because less carbon dioxide was tied up in these reservoirs. He said that higher atmospheric pressure also could have occurred periodically due to fine grains of dust heating the atmosphere at the equator or greater sun exposure at the poles.[272]

Disturbances in the Cosmos

Another comparison Pollack made between Mars and Earth was their similar solar and planetary perturbations. These similarities caused quasi-periodic variations in their orbital eccentricity, sometimes stretching their orbits beyond circular into an elliptical shape; axial tilt, exposing the poles to more solar radiation and orientation. These variations lead to latitudinal and seasonal changes, on long-term climate change timescales. Pollack said that the amplitudes of the obliquity (tilt) and eccentricity oscillations (changes in the orbits) are much larger for Mars than those for the Earth. After reviewing other scientists' work, he determined that during periods of high eccentricity, the equatorial latitudes more easily achieved the greenhouse effect needed to prevent liquid water from freezing, which makes it easier to account for fluvial features at equatorial and midlatitude locations.

During times of high inclination, the polar areas also may become warmer. Earlier in his paper, he had suggested that increased atmospheric pressures may have occurred in the past due to smaller volatile reservoirs. He also suggested that higher pressures may be caused by more solar exposure at polar latitudes. Increased sun exposure raises temperatures in these regions and, therefore, depletes polar reservoirs of their volatile inventories, he said. "Of particular interest are carbon dioxide (or methane) reservoirs, since the total atmospheric pressure is dominated by carbon containing gases," Pollack said.[273]

Pollack suspected that changes in the planet's tilt played a major role in the formation of the laminated layers in the polar region, since high pressures allow more dust to be lofted into the atmosphere, and varying summer polar temperatures will affect the water vapor content. Global dust storms occur most often when Mars is nearest the sun during its orbit (perihelion), which is when the northern and southern polar areas will receive most of its dust deposits.

The History of Venus

Venus was a different story. During its evolution, its circumstances caused it to evolve very differently than Mars or Earth. Although Pollack stated that there was no direct evidence for climatic changes on Venus, he thought it meaningful to examine the possible effects of factors that have been important for the Earth and Mars.[274] Because of their different distances from the sun, Venus' atmosphere receives twice as much sunlight as Earth's atmosphere, which is similar to the amount of sunlight Earth receives compared to Mars. Venus also has dramatically different climate conditions than either Earth or Mars: the surface pressure is about 100 times greater for Venus than Earth and about 10,000 times larger than Mars. Each planet also has had a drastically different greenhouse effect.

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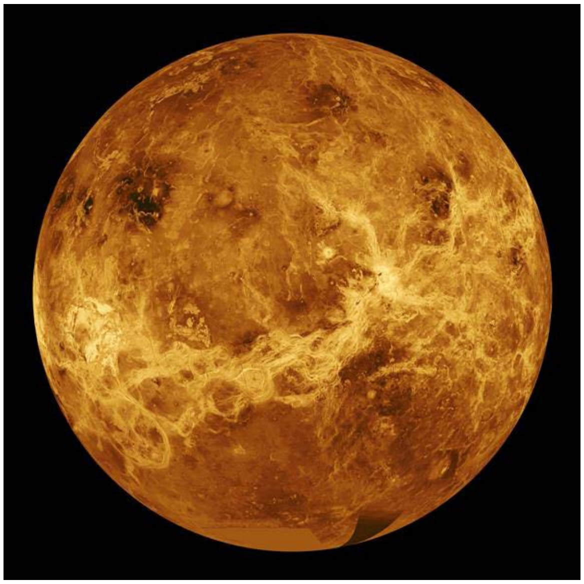
272 Ibid., 520.
273 Ibid., 530.
274 Ibid., 547.



Pollack: "It will be of extreme interest to examine high resolution radar maps of the surface of Venus." Launched in 1989 and ending in 1994, the Magellan spacecraft obtained coverage of 98 percent of the surface of Venus. *At left is a* computer simulated global *image of Venus terrain using Magellan data. Photo credit: NASA JPL*

Pollack thought that, in part, their differences may be attributed to the amount of sunlight they receive. But scientists found that water vapor and the greenhouse effect are sensitive to the surface temperature. Modest increases in sun exposure can lead to large increases in water vapor, which in turn leads to large increases in surface temperatures. Over time, a situation occurs where all water evaporates and the oceans cease to exist. When sun exposure becomes so intense that this situation happens, a "runaway greenhouse"[275] is said to occur, said Pollack.[276] "However, once a runaway has occurred, the magnitude of the greenhouse effect depends on the ratio of the surface pressure to…the mass of the atmosphere."

Pollack cited a study by Sagan (1960)[277] that showed a positive feedback between carbon dioxide and surface temperature. For Venus, doubling the amount of sunlight compared to Earth caused most of its water and carbon dioxide to evaporate. Thus, the gross differences between Venus and the outer terrestrial planets can be attributed to minor differences in their exposure to the sun, Pollack noted.[278]

Pollack speculated that Venus may have been formed from material that had much less water than the constituent material for Earth or Mars. If true, then there may have been less hydrogen in its early outgassed atmosphere, causing carbon and nitrogen gases to remain in their oxidized states. To study this hypothesis, Pollack assumed that Venus outgassed a little water that allowed carbonate rocks to form and serve as sinks for atmospheric carbon dioxide. From this discussion, he suggested an exciting and speculative possibility for a future spacecraft mission to Venus. He said, "If Venus had a moderate surface temperature in its early history, and if at least some water was present, then fluvial features may have been formed at that time and might still be recognizable at present. It will be of extreme interest to examine high resolution radar maps of the surface of Venus."[279]

Imagining an even more extreme possibility, Pollack suggested taking the study of Venus' atmosphere one step further. What if Venus formed without any water or sulfur? He said that the amounts of water vapor and sulfur gases that currently exist in Venus' atmosphere

275 Ingersoll, "The Runaway Greenhouse," 1191-1198.
276 Pollack, "Climatic Change," 543.
277 Sagan, "Radiation Balance," 1960.
278 Pollack, "Climatic Change," 544.
279 Ibid.

are minute compared with its total mass. They may have been added to Venus' atmosphere by outgassing from the planet's interior or by collisions with volatile rich comets and asteroids. He tested this hypothesis and found that if Venus outgassed carbon dioxide and no water or sulfur gases, then its surface temperature would have been moderate until a sufficient amount of such gases were introduced to the atmosphere by collisions of stray bodies. "Subsequent to these collisions and after sunlight had increased sufficiently, the surface temperature would have risen," said Pollack.[280]

According to Colin, scientists study different atmospheres to get one set of equations that describes planetary atmospheres. After the Venus and Jupiter missions, Pollack and James E. Hansen focused their attention on Earth science. "Jim Hansen is the master who wrote the coding that he and Pollack used to look at Earth's atmosphere.[281] These equations are what led to NASA's outstanding planetary climate modeling program at Ames.[282] It all came full circle."

In His Own Way

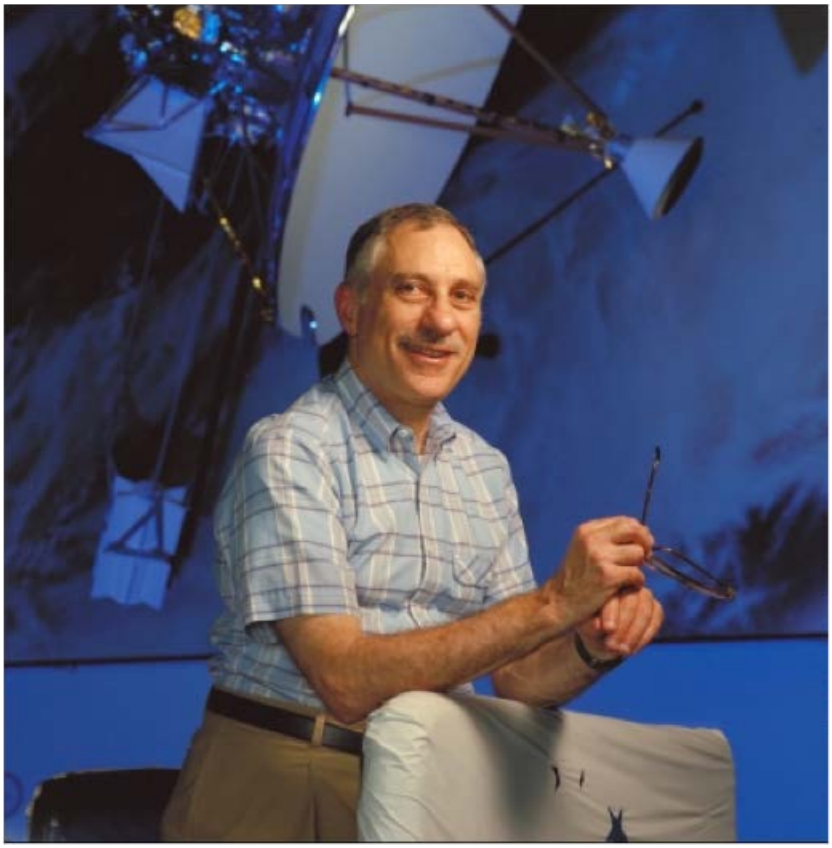
Pollack died on 13 June 1994 of Chordoma, a rare form of cancer. To this day, people still remember Pollack's unique talent. "Part of Pollack's genius was that he saw the big picture, and how it fit together to solve a problem, and how that problem related to even bigger questions," said Richard Young, a former NASA space scientist, Galileo project scientist, colleague and supervisor of Pollack. "Thus, he could bring together the appropriate mix of expertise to make progress. Part of being an outstanding researcher is knowing what you don't know. Jim was able to identify the expertise required on a problem. If he didn't have it, or couldn't get it in a timely fashion, he forged collaborations with the appropriate researchers. But it was almost always Jim who saw the end goal, why it was important, and how to achieve it. And hence he led the effort."[283]

Jim's encyclopedic knowledge covered almost every outstanding problem in the solar system. In the 1970s, most scientists had only a dim grasp of the origin and evolution of the planets. They were not thinking about modeling these processes in a systematic way to make testable predictions, but were still at a phase of observing these objects, recalled scientists. It was a natural evolution for him, they said, to extend his perspective from the origin of the gas giants and their atmospheres, to the origins of the atmospheres of all the planets and their moons. For many scientists, Pollack was one of the true pioneers who fostered this way of thinking about the Solar System.

Jim also cared deeply about the young people he mentored. Two weeks before he died, Jim asked Mark Marley, then a post doctoral researcher at Ames, to visit him at his home. Jim was clearly not well. He was in a hospital bed, but his mind was alert. He wanted to go over Marley's research plan with him to make sure he knew where the work should go and what difficulties might lie ahead. "I still have my notes from that meeting. I've always felt that his generosity in meeting with me under such difficult conditions was emblematic of both his dedication to his science and to the young people that he mentored," said Marley.

280 Ibid," 547.
281 Colin interview with author, 15 January 2009.
282 Dick and Launius, *Societal Impact of Spaceflight*, 279-80.
283 Rich Young, e-mail to author on 5 February 2008.

In 1989, Carl Sagan wrote a letter of recommendation on behalf of Jim Pollack for the Kuiper Prize, a lifetime achievement award given to outstanding scientists “for excellence and enduring contributions to planetary science.” This prize is given by the Division of Planetary Sciences of the American Astronomical Society. “I think it is clear that, in terms of combined depth and breadth, Jim is the leading planetary scientist on this planet. From elegant analytic solutions to the most elaborate numerical codes going, from contemporary planetary atmospheres and surfaces to the origin of the solar system, from theoretical to laboratory to airborne to spacecraft observations, from the study of other planets to issues of climatic change and ozone depletion on this planet, Jim has made fundamental and enduring contributions across the board.” Jim Pollack received the Kuiper Prize in 1989 at 51 years old.



The Right and Left Sides of the Brain

After Pollack's death, Sagan was still sought after for speaking engagements. At one point, he was invited to deliver the Gifford Lectures on Natural Theology at the University of Glasgow; lectures that he later compiled into a book titled *The Varieties of Scientific Experience: a Personal View of the Search for God.* In one lecture, Sagan said, "[Sagan] …never understood why anyone would want to separate science, which is just another way to search for truth, from what we hold sacred…The methodology of science, with its error-correcting mechanism for keeping us honest … seemed to him the height of spiritual discipline. If you are searching for sacred knowledge and not just a palliative for your fears, then we will train ourselves to be good skeptics…." "Science," he continued, "…opens the way to levels of consciousness that are otherwise inaccessible to us; that, contrary to our cultural bias, the only gratification that science denies us is deception…"

Throughout the years, Sagan sustained an ongoing relationship with his friend and colleague; he and Pollack often shared different perspectives of the same argument. In those arguments, one man was glib, the other a man of few words. Pollack's answer to the pursuit of truth may very well have been:

"*...Because it just makes good science!...*"

Addendum

Pollack's insight and inspiration helped guide the research of a generation of young workers. He was technical director or advisor for various teams of mathematicians, programmers and junior scientists; research supervisor for students in graduate programs at Harvard, Cornell, San Jose State, University of California at Santa Cruz, and the Universities of Hawaii and Washington. As a world-class scientist, he attracted more National Research Council Postdoctoral Fellows than any other individual in Space Sciences, and possibly at Ames.[284] He seemed to think that young people were our most important resource. "They are our future," he said. "I believe that planetary science is just reaching a mature state at which some of the fundamental issues can now be addressed…: It is essential that we find ways to involve our young people in the spacecraft missions…, of creating positions for them at the universities and research centers, and of providing adequate funding for them."[285] Ames recognized Pollack's mentoring skills by awarding him the Center's "Mentor" award in 1986.

Many people came to Ames to work with Jim because he was an outstanding leader in the field of planetary science. They knew that working with Pollack would advance their careers because they would be working on interesting and important problems. Pollack had the ability to identify key problems and knew how to address them. He worked on frontier problems in planetary science and was always a part of the latest research and data. Many of the post-doctoral researchers helped by Pollack were deeply appreciative of his guidance and the time he spent with them.

Pollack had his idiosyncrasies and sometimes had trouble communicating with other people. But people still lined up to work with him. Working with Pollack led to new insights into solving problems, or identifying new problems that would advance the field. It was scientifically rewarding. When working with Pollack, science was produced. For Pollack, it was always about the science.

*"Jim Pollack was my postdoctoral advisor in the early 1990s. I was working with him on understanding the surface and atmospheric composition of Mars, and this was an important time in the transition from telescope-based to spacecraft-base*d exploration of the Red Planet," said Jim Bell, an astronomer and planetary *scientist* at Arizona State University, Tucson. *"*Jim was a brilliant, patient mentor who had a seemingly intuitive grasp of physics, chemistry, geophysics, meteorology, and a number of other specializations in planetary science. A true polymath, he was a fixture in the front row of any major planetary science conference, and was usually the first person with his hand in the air, asking thoughtful and probing questions at the end of a colleague's talk. With young people in the field, he was especially kind and complementary, while at the same time striving to help us all develop more rigor in our work."[286]

"Jim's passion in life was science," said Jeffrey Cuzzi, a NASA space scientist and expert on planetary rings. "He loved it and was very good at it. He had a very gentle, deliberate, and measured style of expression that could give the impression he was slow. He saw to the heart of a problem very quickly, and had excellent scientific intuition. If I couldn't explain an idea to Jim, I knew I didn't understand it myself, and it was probably wrong. Working

284 NASA Ames History Office, Acq. 009-2005.
285 Pollack, "Kuiper Prize Lecture."
286 Email from Jim Bell 7 July 2014.

with Jim taught me to think in a big-picture way. I hadn't learned this from any of my previous mentors." Cuzzi left science after a postdoctoral fellowship at the University of Massachusetts, Amherst, but was encouraged by Pollack to come to NASA Ames and study Saturn's rings with him.[287]

"I met Jim Pollack in 1993. I was then a young engineer hired by the French space agency CNES to help prepare a balloon on Mars project for a Mars '98 Russian mission! I was sent to NASA Ames Research Center for 16 months to apply Jim Pollack's atmospheric models to the project," said Francois Forget, a space scientist at the Laboratoire de Météorologie Dynamique, Institute Pierre Simon Laplace in Paris, France. "While there, I found some time to do scientific research. Jim Pollack invited me to analyze thermal infrared observations of Mars polar regions obtained by Viking and Mariner 9. It was very exciting! Our goal was to detect and map the exotic carbon dioxide ice clouds that form in the polar nights. This project convinced me to become a scientist, and when I returned to France I started a Ph.D. (with a grant that was supported by Jim who wrote a recommendation letter). Unfortunately Jim died shortly after, in 1994."[288]

"Jim Pollack was a very important mentor to me. He is known, rightfully, as a great scientist with a wide range of interests, but he was equally great as a teacher," said David Grinspoon, an astrobiologist and senior scientist at Planetary Science Institute, Tucson, Ariz. "He was very patient and generous with his time and attention. I feel incredibly fortunate to have had him as my post-doctoral advisor. He taught me so much about radiative transfer in planetary atmospheres, about data reduction, about building appropriate models to tackle a specific problem, and more generally, how to approach scientific questions. Jim was also a kind and warm person who was great to be around. I miss him all the time and frequently, decades later, find myself thinking 'How would Jim approach this?'"[289]

"Jim showed enthusiasm, patience, and positive encouragement in his meetings," said Olenka Hubickyj, a science specialist at the University of California at Santa Cruz. For the last fifteen years, she has been operating planetary formation codes. "Problems were discussed, and solutions mapped out. I was always amazed that Jim was able to understand the computing and coding part of my work, especially since he didn't work with this particular code."[290] Hubickyj left the Goddard Institute for Space Science as a postdoctoral researcher from City University at New York to come to NASA Ames to do planetary coding for Pollack and the other scientists.

"Jim heard about my thesis work on the rise of oxygen, and invited me to Ames to work with him," said Jim Kasting, Distinguished Professor of Geosciences and Meteorology at Pennsylvania State University and former post-doctoral researcher from the University of Michigan, Ann Arbor. "He was wonderful to work with because he had such broad interests and was capable of juggling many balls at the same time. He was the nucleus of the planetary science group at NASA Ames and a pillar of the international planetary science community."[291]

287 Email from Jeff Cuzzi 31 March 2008.
288 Email from Francois Forget 8 July 2014.
289 Email from David Grinspoon, 3 July 2014.
290 Interview with Olenka Hubrickyj on 5 February 2008.
291 Email from Jim Kasting, 5 February 2008.

"I first met Jim Pollack at a planetary science meeting," said Mark Marley, a space scientist at Ames. "He encouraged me to apply for a NASA post doctoral research position at Ames, which I started in 1990. At Ames, Jim was a generous and helpful mentor." In a series of weekly lectures, Pollack taught key topics in radiative transfer and planetary atmospheres. Today, Marley still uses the computer code that he built with Jim to study the atmospheres of extrasolar giant planets and brown dwarfs. A key feature of the model (allowing for multiple convection zones inter-layered with radiative zones) turned out to be crucial for successfully modeling extrasolar giant planets, which is entirely attributable to Jim who knew this would be important for the hot, young Saturn case.

"There is no question in my mind that I would not have the privilege of working in Jim's former branch at Ames, if it were not for what I learned from him almost 25 years ago. When I mentor young people today, I try to follow Jim's generosity and approach. Three of my former postdocs now have faculty positions, including one at MIT and one at UC Santa Cruz. These young scientists don't know it, but I think they owe a debt to Jim as well," said Marley.[292]

"I first met Jim as a graduate student. I started working with him at Ames in the summer of 1980," said Chris McKay, a space scientist at Ames and NASA authority on Mars. "What impressed me most about Jim was that he treated all science colleagues the same, whether they were graduate students or division directors. He considered the content of what you said and presented, not the status of the person presenting it. For me, this was such a refreshing change from the culture in university departments that I decided to come to Ames and work. I have tried myself to imitate Jim's approach."

"I think I met Jim either at a conference, or when he gave a talk at Caltech, where I was going to grad school," said Julie Moses, a senior research scientist at Space Science Institute, Seabrook, Texas. "He was highly visible and approachable at conferences, and I think that is where his absence is felt the most, even today. Because of his breadth of knowledge, he was always standing up to ask questions after just about every talk. He was not short of ideas or opinions, and his questions and discussions during the conferences really clarified different subjects for me -- and made the conferences more entertaining. It actually benefitted students and non-experts in the audience, so I always appreciated that he would do it without seeming to be mean. He also kept trying to get me to work on different projects outside my comfort zone, which I resisted at first, but I eventually branched out and tried different things, which ended up being fun and ultimately useful."[293]

"Jim was an immensely important mentor in my career," said Jim Murphy, an associate professor in the Department of Astronomy at New Mexico State University, Las Cruces. "He was my NASA Graduate Student Researcher Program (GSRP) advisor at Ames from Jan. 1988 to April 1990. He subsequently served as my National Academy of Sciences Postdoc Advisor at Ames from 1991 to 1993. Jim always, always amazed me with the tremendously broad range of topics he studied, how well he kept them all distinct and separate and progressing, and how rapidly he could in conversation change from one topic to another and be right on point. It was, and remains intimidating to me, in a motivating way, that he was so good in so many areas. He was always aware of what I and others were doing. He asked

292 Email from Mark Marley, 8 July 2014.
293 Email from Julie Moses, 11 July 2014.

penetrating questions which enabled me to determine if I understood what I was describing/ talking about, and above all he did all of the above with a smile and a willingness to support others, such as he did me. I continued working at Ames up to and beyond his death in 1994."[294]

"Jim invited me to Ames chiefly as an experimentalist and observer. He encouraged, and allowed me the freedom, to expand my expertise into theoretical efforts," said Ted Roush, a space scientist at Ames, who was a former NASA Research Council postdoctoral associate from the University of Hawaii, Hilo. "Meetings with Jim were very exciting because he would undoubtedly, quickly identify the most important issue that arose during our meeting and provide some valuable input, in spite of my best preparation."[295]

"I first met Jim when I was working at SRI International in the 1970s," said Phil Russell, a space scientist at Ames and colleague of Pollack's. "Jim was working with Brian Toon on global aerosol modeling and potential climate effects of aerosols and greenhouse gases. In 1975, I led a study at San Francisco's Mount Sutro TV Tower that measured how aerosol particles change the balance between incoming and outgoing solar energy. A key instrument in the study was a tracking sunphotometer developed by SRI. One day at SRI, I got a call from Jim saying I should propose developing an airborne sunphotometer to fly on the Ames CV-990 to NASA. As the chief of the Atmospheric Experiments Branch, I proposed the airborne sunphotometer to the Director's Discretionary Funds, and received funding for its development. Today, Ames is still the world leader in airborne sunphotometry."

"Jim was involved in many planetary missions, and he was one of the leaders in radiative transfer in his day," said Brian Toon, founder and chair of the department of atmospheric and oceanic sciences at the University of Colorado, Boulder, and long time Ames scientist. "He pushed forward the development of new techniques, but he was best known for his many applications. For instance, he pioneered the two stream equations that dominated terrestrial climate models for many years (even now). He helped understand the rings of Saturn, dust storms on Mars, the clouds of Venus, the Venus carbon dioxide greenhouse effect, and many other issues, all using radiative transfer."[296] Toon also started his career working for Pollack at Ames as a post-doctoral researcher from Cornell University.

"I gave a seminar at NASA Ames about my work on Venus. Jim was interested in the same subject, and invited me to Ames," said Rich Young, a space scientist at Ames who was a former NASA Research Council postdoctoral associate from the University of Colorado, Boulder. "While Jim and I were working on Venus, he was also working on a number of other important problems, such as modeling Jupiter. I always regarded Jim as the most knowledgeable authority on so many planetary science issues. He really was unique among all the researchers I have ever known."[297]

294 Email from Jim Murphy, 20 July 2014.
295 Email from Ted Roush, 15 January 2008.
296 Brian Toon, e-mail sent to author, 14 November 2007.
297 Email from Richard Young 1 February 2008.

Awards and Fellowships[298]

NASA Honor Awards

1976 H. Julian Allen Award. This prize is awarded for the best paper at NASA Ames Research Center by a staff member. Pollack won the award for the paper “Aircraft Observations of Venus’ Near-Infrared Reflection Spectrum: Implications for Cloud Composition.”

1978-1981 Member of the Space Science Advisory Committee to NASA

1979 NASA Exceptional Scientific Achievement Medal for work on the Pioneer Venus spacecraft mission

1983 Certificate of appreciation for important scientific and managerial contributions to NASA sponsored studies of the climatic effects of massive El Chichon volcanic cloud

1983 H. Julian Allen Award. Co-winner for the paper “Evolution of an Impact-Generated Dust Cloud and its Effects on the Atmosphere”

1983 Selected Ames Associate Fellow for sustained innovative and creative contributions to research at Ames

1986 Honored by Ames as a mentor for helping the career development of young scientists

1987 Selected as an Ames Research Center Fellow, the highest honor bestowed by Ames for research on planets and Earth’s climate

External Awards

1975 Division of Planetary Science/ American Astronomical Society (AAS) lectureship series. Representing DPS, Pollack was invited by AAS to talk about the development of Jupiter and Saturn as analogues to stellar evolution.

1977 Arthur S. Fleming Award in recognition of his outstanding federal service

1978 Space Science Award of the American Institute of Aeronautics and Astronautics for work on planetary atmospheres and surfaces and climates

1979-1980 Member of the National Research Council panel on Pre-Pleistocene climates

1979-1981 Member of the editorial board of Icarus

1982 Elected Fellow of the American Astronautical Society

1982 Elected Fellow of the American Association for the Advancement of Science

298 NASA Ames History Office. James B. Papers. Acquisition 009-2005.

1982 Elected Fellow of the American Geophysical Union

1983-1985 Associate editor of Geophysical Research Letters

1985 Co-recipient of the Leo Szilard Award of the American Physical Society for research in the public interest (nuclear winter studies)

1987-1990 Associate editor of Journal of Geophysical Sciences

1989 Gerard P. Kuiper Prize of the Division of Planetary Sciences of the American Astronomical Society for "excellence and enduring contributions to planetary science" Pollack was the second in the agency and first at Ames to have received this award.

1990 Sherwin Fairchild Distinguished Scholar at the California Institute of Technology

1997 Pollack Crater named for James B. Pollack

Spacecraft Experience

Member of the imaging teams for the Mariner 9 orbiter of Mars, the Viking Lander on Mars, and Voyager for Saturn, Uranus and Neptune encounters

Interdisciplinary scientist for the Pioneer Venus, Galileo probe and orbiter, Mars Observer and Cassini missions

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