History of Rocketry and Astronautics

Proceedings of the Fifty-Third History Symposium of the International Academy of Astronautics

Washington DC, USA, 2019

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AAS History Series, Volume 52

A Supplement to Advances in the Astronautical Sciences

IAA History Symposia, Volume 39

AAS Publications Office
P.O. Box 28130
San Diego, California 92198

Affiliated with the American Association for the Advancement of Science
Member of the International Astronautical Federation

First Printing 2022

ISSN 0730-3564

ISBN 978-0-87703-681-4 (Hard Cover Plus CD ROM)
ISBN 978-0-87703-682-1 (Digital Version)

Published for the American Astronautical Society
by Univelt, Incorporated, P.O. Box 28130, San Diego, California 92198
Web Site: http://www.univelt.com

Printed and Bound in the U.S.A.

Chapter 7

The Family Portrait of the Solar System: The Last Set of Images Taken by Voyager 1 and the Fascinating Story of How They Came to Be*

William J. Kosmann,† Candice J. Hansen,‡
and Carl Sagan (posthumous)

Abstract

On Valentine's Day, February 14, 1990, the Voyager 1 spacecraft executed a sixty-image mosaic of portions of the solar system, which came to be known as "The Family Portrait." The set of observations was the sixth request by the Voyager Imaging Science Team, and Mission Planning Office. The fascinating story of why it took eight years and six (ultimately seven) requests to gain approval has never been told.

The Family Portrait taken by Voyager 1 remains the first, and still the only time, a spacecraft has attempted to photograph our home solar system. Only three spacecraft have been capable of such an observation, Voyager 1, Voyager 2, and New Horizons. New Horizons just completed its second target body encounter in

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* Presented at the Fifty-Third Symposium of the International Academy of Astronautics, October 21–25, 2019, Washington, DC, United States. Paper IAC-19-E4.1.08.

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January 2019. The observation opportunities have been few and far between in human history.

The first Voyager 1 observation request consisted of a single set of three Narrow Angle camera images of the Earth, and whatever other planetary objects occurred in the frame at the time. The Voyager Project denied the request, for many reasons. The next four requests followed this same observation design, with minor variations, with all disapproved. The sixth request intended to image seven of the then nine planets (all but Mercury and Pluto). The Voyager Project approved this request. The observation imaged six planets, with Mars too dim to detect. A seventh request intended to replicate the Voyager 1 observations on Voyager 2, but the Voyager Project denied this request.

The Observation design consisted of slewing the cameras to Neptune, taking Narrow Angle images through three separate color filters plus one Wide Angle context image, taking a set of Wide Angle images from Neptune to Uranus, repeating the Narrow and Wide Angle images at Uranus, then stepping in turn to Saturn, Jupiter, Mars, Earth, and Venus. The observation concluded with a set of Wide Angle context images around the Sun, with the final two images taken of the Sun itself.

This chapter discusses in depth the history of the seven observation requests, the individuals involved in conceiving the various aspects of the ultimately successful observation set, the challenging spacecraft and project resource constraints, the resulting observation design and the phenomenal results. The image of Earth, a pale blue dot, shows us how small, tiny, and vulnerable "spaceship Earth" remains in the vast cosmos in which we live.

Keywords: Voyager, Family Portrait, Solar System

Acronyms/Abbreviations

dn—data number
DSN—Deep Space Network
E—Earth
ERT—Earth Received Time
FDS—Flight Data System
FY—Fiscal Year
GMT—Greenwich Mean Time
J—Jupiter
JPL—Jet Propulsion Laboratory
km—kilometers
IAC—International Astronautical Congress

IRAS—Infrared Astronomical Satellite
IRIS—Infrared Interferometer/Spectrometer
ISS—Imaging Science System
M—Mars
N—Neptune
NASA—National Aeronautics and Space Administration
OPG—Operations Planning Group
PPS—Photo Polarimeter System
S—Saturn
U—Uranus
UV—Ultraviolet
UVS—Ultraviolet Spectrometer
V—Venus

I. Introduction

Spaceship Earth … Earth as a planet … These phrases have almost become trite, yet they've never been more important than today. We as a species must face the depletion of the Earth's protective ozone layer, the loss of our rainforests, and global warming, to name of few of the major issues currently occurring. We as a species, capable of destroying our own habitat, must recognize both how fragile and how irreplaceable that habitat is.

The goal of the Voyager Imaging Team in asking the Voyager Project to take a picture of the Earth was to build that recognition of our vulnerability. We wanted to give the world a graphic illustration of just what a small, lonely place in the universe the Earth occupies. Our nearest planetary neighbors remain too hot or too cold for life; their atmospheres do not provide us with the oxygen we need, and they lie very far away. A picture of our tiny planet alone on a black backdrop could represent a very literal symbol of our vulnerability.

As time went by and the Voyager mission progressed, our ideas of what we wanted to do with the spacecraft expanded. We could take pictures of the entire inner solar system, showing the Earth and its neighbors. Perhaps a picture of the Earth with Halley's Comet, a once-in-seventy-six-year opportunity, could be taken. Project resources did not permit using valuable engineers' time to design something perceived as a frivolous exercise.

Ultimately, the historic nature of the Voyager 2 completion of the Grand Tour [2], travels that took it past Jupiter, Saturn, Uranus, and Neptune, led to the project decision to allow a Family Portrait of the solar system to mark Voyager's "last light." This mosaic not only accomplished the Imaging Team's Planet Earth goal, it recorded the travels of our tiny spacecraft. The Family Portrait represents a first look back at the Earth in its place in the solar system. It also represents Voyager's last look back at home, as it heads into interstellar space, never to return.

II. Evolution of the Observation

Lack of Voyager Project engineering resources always plagued this observation. (Figure 7–1. A presentation, describing the design of the observation, given to the Voyager Project, in May 1990, contained this cartoon.) Time always caught the observation between the cruel irony that from an efficiency point of view the best time to do it occurred right after a planetary encounter; but that also became precisely the time that the Voyager Project staffed down as a result of the long cruise immediately ahead to the next planet. When the designers proposed the observation at the end of a long planet-to-planet cruise, then it competed with the engineering resources allocated to the upcoming planetary encounter. The observation could not win. Lack of timely project resources being available prevented its approval and execution in 1981, 1985, 1986, 1988, and 1989 (Table 7–1).

"Am I to understand that my proposal is greeted with some skepticism?"

Figure 7–1: Typical Earth/Solar System Observation Request Reaction. Cartoon Courtesy of the *New Yorker* magazine. Used with permission.

Request	Date	Objects to Be Imaged	Spacecraft	Shielding Maneuver
1	1981, Summer	Jupiter, Saturn, Earth	Voyager 1	Yes
2	1985, Summer	Earth, Mars, Halley's Comet	Voyager 1	Yes
3	1986, Spring	Earth, Mars, Halley's Comet	Voyager 1	Yes
4	1988, Summer	Earth, Mars, Jupiter	Voyager 1	Yes
5	1989, Spring	V, E, M, J, S, U, N	Voyager 2	Yes
6*	1989, Spring	Sun, V, E, M, J, S, U, N	Voyager 1	No
7	1990, Spring	Sun, V, E, M, J, S, U, N	Voyager 2	No
* Successful				

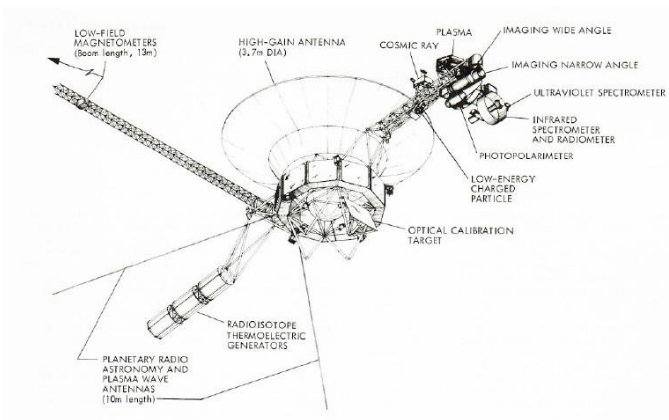
Table 7–1. Earth/solar system Imaging Request History.

II.1. 1981

Each Voyager spacecraft carries two cameras: a Narrow Angle and a Wide Angle [3,4]. Carl Sagan (Voyager Imaging Team member) conceived of the original idea to use the Voyager cameras to image Earth, in 1981 (Table 7–1, Request 1). Sagan's original concept included taking three separate images of just the Earth, through separate color filters, using the Narrow Angle (high resolution) camera, and reconstructing a single-color image on the ground. Shortly after, Sagan and Charles E. Kohlhase (Voyager Mission Planning Office Manager) independently added to the concept by proposing using the Wide Angle camera to shoot a black and white stellar background image, with the Earth at the center, at the same time as taking one of the Narrow Angle images. About the same time, Dr. Brad Smith (Voyager Imaging Team Lead) further evolved the concept by suggesting timing the images to include any other planets that might be near the Earth, from Voyager's point of view.

The Voyager Imaging Science Team designed the cameras to take images of relatively close dark outer planets, their moons, and rings. This new observation of imaging the Earth from beyond Saturn attempted to image a planet very remote, one that appears as a point source, and one very close to the Sun (within 5.7 degrees). Pointing the cameras too close to the Sun destroys them as well as the other three science scan platform instruments. To eliminate this problem, the designers proposed a shielding maneuver, whereby the Voyager spacecraft would turn so that its 3.7-meter diameter high gain antenna (Figure 7–2) shielded the science scan platform instruments, other than the Wide Angle camera, (Figure 7–3) from the Sun, thereby protecting them from damage [1].

Because of the way the four science instruments are mounted on the Voyager science scan platform (Figures 7–2 and 7–3), and because of the elevation and azimuth rotation pattern of the platform, only the Wide Angle camera could be used for imaging the inner solar system, when a high gain antenna shielding maneuver was used. The high gain antenna blocked the Narrow Angle camera view when the antenna shielded the Sun from the science scan platform instruments. Observation designers could not execute a high gain antenna shielding maneuver and use the Narrow Angle camera to obtain high resolution images of the Earth, or any other planet. This fact modified the original observation proposal to include only three Wide Angle images of the Earth (through different color filters), and whatever other inner solar system planets or objects happened to be near the Earth and in the Wide Angle camera field of view when taking the images. Color reconstruction of a single true color Earth image would take place at JPL (Jet Propulsion Laboratory). The observation included no black and white Wide Angle camera background star image. This summarized the original form of the Earth-imaging proposal, and the form the observation maintained until 1989.



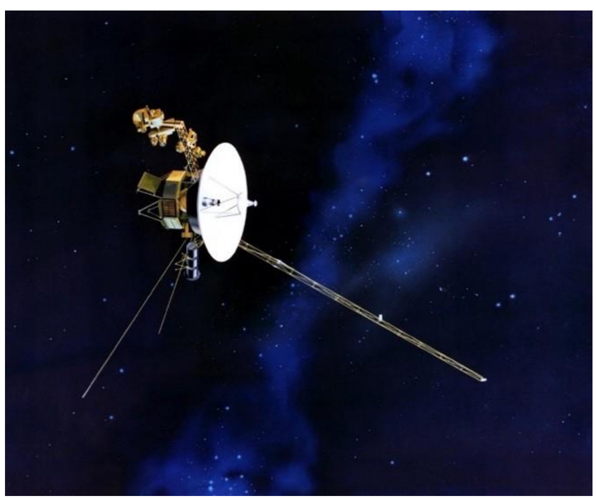


Figure 7–2a and 7–2b: The Voyager Spacecraft.

Figure 7–3: Voyager Science Scan Platform.

Candy Hansen (Voyager Imaging Team Experiment Representative at JPL) submitted the Earth-imaging request to the Voyager Project Office, in the summer of 1981 (Table 7–1, Request 1). Voyager 1 ended its planetary encounters with the Saturn encounter of November 1980. Thus, Hansen chose it as the imaging platform, to avoid any risk of damage to the Voyager 2 science scan platform instruments, which had planetary encounters at Uranus (1986) and Neptune (1989) upcoming. By properly timing the Earth-imaging observation in 1981, Earth, Jupiter, and Saturn could be captured in each single Wide Angle image. The Voyager Project denied the request, primarily because staff levels severely decreased for the five-year Voyager 2 Saturn-to-Uranus cruise (1981 to 1986). The high gain antenna shielding maneuver required a brand-new technique, which had never been tried before on either Voyager spacecraft. This meant extensive engineering resources were needed to plan, design, sequence, test, and execute the new technique properly. The engineering resources were simply not available for this observation in 1981.

Once the Voyager 1 Jupiter and Saturn planetary encounters completed in 1979 and 1980, respectively, why did protecting that spacecraft's science scan platform instruments, other than the Wide Angle camera (which would be used for the Earth imaging), even merit consideration in approving the Earth-imaging observation? It turns out that Voyager 1 played a very important role in the success of the upcoming Voyager 2 Uranus and Neptune planetary encounters.

The Voyager Project used the Voyager 1 science scan platform instruments as test beds for testing changes to be made in the operation of the Voyager 2 instruments. This became particularly important for the Infrared Interferometer/Spectrometer (IRIS). IRIS had temperature-dependent operational problems that had to be characterized, and for which optimal operation traded off several key instrument modes. In addition, the Voyager Project still used the Voyager 1 Narrow Angle camera to take images of Uranus and Neptune at high phase angles unobtainable from Earth. Planetary atmospheres scatter light in different amounts in different directions. Knowing the behavior of the Uranian and Neptunian atmospheres, even at the small sizes as seen from Voyager 1, became important in modeling optimal exposure times for the upcoming Voyager 2 planetary closest approaches. Once Voyager 2 completed the Neptune encounter, these considerations became no longer relevant.

II.2. 1985

By 1985 things changed. Carolyn Porco, a new member of the Voyager Imaging Team, joined the band of advocates (Sagan, Kohlhase, Smith, and Hansen). She proposed using the Voyager 1 Wide Angle camera to accomplish two separate observations that required the high gain antenna shielding maneuver (Table 7–1, Request 2). IRAS (Infrared Astronomical Satellite) had discovered dust bands in orbit about the Sun, near the Asteroid Belt, thought somehow to be associated with the belt. Imaging them from Voyager's perspective allowed determination of the optical depth of the dust bands and yielded information on particle scattering properties. In addition, Halley's Comet orbited near perihelion again, and multiple spacecraft traveled to observe the comet in- close-proximity for the first time. Porco proposed to study the forward and backward scattering properties of the Asteroid Belt dust bands, by taking a series of images of the bands. Smith proposed to image the tail of Halley's Comet in conjunction with simultaneous ground-based observations, providing the possibility of stereoscopic image reconstruction.

The originators of the first Earth-image observation request reasoned that by timing the Halley's Comet image such that the Earth was in the Wide Angle camera field of view, their goal could be satisfied at the same time. As an added bonus, Mars just happened to be in the same area (from Voyager 1's point of view), so that Mars, Earth, and Halley's Comet could be imaged at the same time. Hansen made a second observation request in the summer of 1985. The Voyager Project denied the now quadruple Asteroid Belt dust band-Halley's Comet- Earth-Mars request, again due to a lack of engineering resources available. The upcoming Voyager 2 encounter with Uranus required maximum effort devoted to designing observations of the planet, its rings, and its moons, with minimum effort devoted to Voyager 1 observations. However, the Voyager Project encouraged the observation requestors to resubmit the request after the January 1986 Uranus encounter, the first time any encouragement had occurred.

II.3. 1986

In 1986, early spring, Hansen resubmitted the Voyager 1 quadruple imaging request (Table 7–1, Request 3). The Earth, Mars, and Halley's Comet could still be captured in one Wide Angle image, as part of the Asteroid Belt dust band images. The Voyager Project, for the first time, agreed to commit the engineering resources to turn the high gain antenna shielding maneuver from an engineering proposal into an actual spacecraft capability. Success was in the air. Unfortunately, further Imaging Team analysis indicated that the Voyager Wide Angle camera could not detect Halley's Comet's tail. The Halley's Comet tail imaging opportunity had provided the urgency to the quadruple observation in 1986. Earth imaging had no chance of being approved on its own. The Asteroid Belt dust band observations could be done at any time. With the Halley's Comet tail opportunity gone, Hansen withdrew the quadruple observation request, and none of it occurred in 1986. The Asteroid Belt dust band observations alone later occurred in 1987.

II.4. 1988

Two years passed on the Voyager 2 Uranus-to-Neptune cruise. Imaging had been limited during cruise to high phase angle photometry on Saturn and Uranus, and low phase angle photometry on Neptune. But hope springs eternal. In summer 1988, Hansen made a fourth observation request (Table 7–1, Request 4), to image the Earth from Voyager 1. An opportunity to capture Earth, Mars, and Jupiter in one Wide Angle camera image existed later in the year. Again, the Voyager Project denied the observation request, again because the upcoming August 1989 Voyager 2 Neptune encounter consumed all the scarce project engineering resources. Voyager 1 observations received a minimum of engineering resources.

From 1981 through 1988, the Earth-imaging proposal consisted of a Wide Angle image, shot through three separate color filters, with the Earth and as many nearby planets/objects as possible captured in the single image, using the high gain antenna to shield the rest of the non- imaging science scan platform instruments and the Narrow Angle camera from the destructive intensity of the Sun. Four times the designers proposed this observation to the Voyager Project Office, and four times it had been denied.

II.5. 1989

In early 1989, the observation concept substantially evolved to a portrait of the solar system. In a hallway conversation outside the elevators on the third floor of building 264, William Kosmann (a member of the Voyager Mission Planning Office) proposed to Sagan to explicitly image not only the Earth, but all nine of the planets, in color. Kosmann reasoned that, if one is going to expend the resources to image the Earth from beyond the solar system, why not image the whole solar system? Imaging the entire solar system required relatively few additional resources if one intended to image the Earth. Sagan immediately agreed to the new proposal.

In October 1989, all of the planets (except Pluto) appeared to Voyager 2 in a straight line, an aesthetically pleasing geometry (Figure 7–4). As a further bonus, this opportunity occurred after the Voyager 2 Neptune encounter completed, except for some post-encounter instrument calibrations. The observation still required a high gain shielding maneuver. Thus, the observation could only take Wide Angle color images of all the planets detectable. In 1989, early spring, Hansen submitted the fifth request (Table 7–1, Request 5). The Voyager Project denied the request, because the design of the software computer load that controlled Voyager 2 in fall 1989 had advanced too far along in early spring 1989 to incorporate such a large new observation.

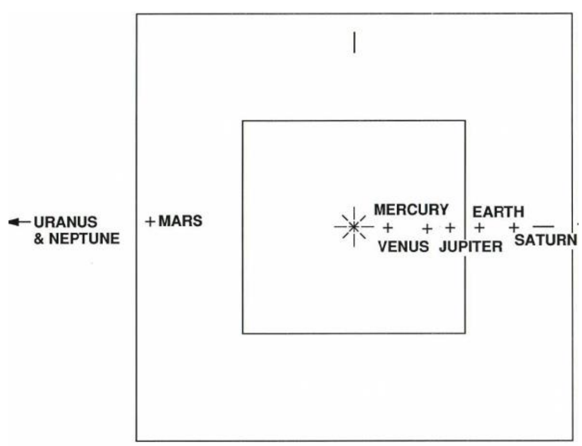


Figure 7–4: Solar System Planets as Viewed from Voyager 2 on October 15, 1989.

After the rejection of the fifth request, it became crystal clear to the observation proposers that only one more opportunity to request approval could occur, and that the observation had to be performed without the use of the high gain antenna shielding maneuver. Further, the sixth request had to be made and approved before the Voyager 2 Neptune Encounter started in June 1989, as it would be all hands-on deck for the last planetary encounter in the Grand Tour. Early in the Voyager Interstellar Mission (1990, late winter to spring) provided the last solar system-planet imaging opportunity, before the Voyager Project intended to turn off the imaging cameras, forever. Finally, the observation design had to occur during the spacecraft computer software load design in the fall of 1989, after the Neptune Encounter completed. Nothing quickens the pulse more than realizing this is the last opportunity.

Hansen resumed investigation of the necessity of the high gain antenna shielding maneuver in preparation for the sixth request. The Voyager engineering resources needed to develop, test, validate, and execute such a maneuver had always been a major stumbling block in getting the observation approved. An observation request that did not need a high gain antenna shielding maneuver stood a much higher probability of gaining approval.

After the Voyager 2 Neptune encounter, neither Voyager spacecraft would have any more planetary encounters. Therefore, damage to the science scan platform instruments (Figure 7–3), except for the Ultraviolet Spectrometer (UVS) no longer concerned the Voyager Project. (The project intended to use the UVS for UV stellar observations during the Voyager Interstellar Mission.) The Voyager Project intended to turn permanently off all the science scan platform instruments, except for the UVS, near the beginning of the Voyager Interstellar Mission, slated to start early in 1990. The UVS instrument team determined that the proposed solar system observation would not harm their instrument. Except for scattered light considerations, this removed the requirement for a high gain antenna shielding maneuver, allowing use, for the first time, of the Narrow Angle camera (Figures 7–2 and 7–3) to image the planets in high resolution.

The sixth (and ultimately successful) observation request (Table 7–1, Request 6) included a further major evolution (all for the first time): elimination of the high gain antenna shielding maneuver, use of the Narrow Angle (high resolution) camera to image the planets in color, inclusion of black and white Wide Angle camera stellar background images around the Sun and between the planets, and imaging the Sun itself directly (Table 7–2). The designers chose Voyager 1 as the observation platform and February 1990 as the time of the observation. (See Observation Implementation for the details).

For the first time, the Voyager Project Scientist, Ed Stone, supported the observation. This was crucial to it being approved. It had been telling that, for all five previous observation requests, the Voyager Project Scientist had not been present in the decision meetings to support the observation. The Voyager Project

Office knew that its Project Scientist did not supported these previous requests, and this made it easier to deny those requests. Now, Stone's support for a solar system observation made it harder for the Project Office to deny the sixth request.

To Produce a Mosaic of the Solar System
Containing the Earth
Containing as many other planets as possible
Imaging the planets in color using the Narrow Angle camera Including an image of the Sun
Including Wide Angle stellar background images
Minimizing spacecraft and other instrument risk

Table 7–2: Family Portrait of the Solar System Observation Objectives.

In addition, Sagan had been busy lobbying NASA Headquarters for resources to accomplish the now solar system observation. Sagan obtained informal NASA endorsement of the imaging the solar system observation. The informal NASA endorsement carried weight to also help overcome the reluctance of Voyager Project management to execute the observation. The event to mark the culmination of the Grand Tour would be a final postcard home, as seen from the Voyager spacecraft that performed the observation, as it proceeded to leave the solar system forever, and orbit about the center of the galaxy.

The Voyager Science Team had used an observation naming convention since the beginning of the Grand Tour. The first letter of each observation referred to the instrument making the observation. All imaging observations used the letter V (for visible). An eight-letter limit existed, related to spacecraft software coding limitations. It somehow just seemed fitting that the observation of the solar system should be called VPLANETS. So, all project documentation and the software load coding used that name for what ultimately came to be called The Family Portrait of the solar system.

Kohlhase proposed imaging the Sun directly, using only the last Wide Angle camera stellar background image of the observation. (This limits camera damage, if any, to only the end of the observation, and at the end of the camera's life on the Voyager mission.)

Ken Klaasen (Galileo Imaging Science Coordinator) investigated the scattered light performance of the Voyager Narrow Angle cameras as a function of solar off-axis angle (Figure 7–5). The camera signal to noise went below unity (meaning objects were then undetectable) if the Sun appeared within about 1 degree of the optical axis of the camera. By starting with Neptune, then stepping into each succeeding planet and staying more than 1 degree from the Sun for all Narrow Angle camera observations, the observations would probably succeed without the use of the high gain antenna shielding maneuver. This substantially reduced the cost (in spacecraft and ground engineering resources) of the VPLANETS observation. Hansen submitted the sixth request (Table 7–1, Request 6) in May 1989. The Voyager Project Office provisionally approved the request.

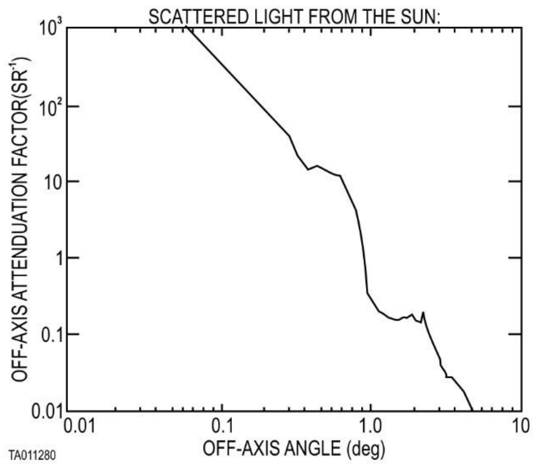


Figure 7–5: Voyager Narrow Angle Camera Scattered Light Performance.

One final hurdle remained. The Voyager Project Office had estimated the amount needed for the observation design, coding, testing, execution, ground receipt, and image processing. The Planetary Society hosted a dinner, at Caltech, on the Athenaeum lawn in August, during the Neptune Encounter. After dinner, Len Fisk (NASA Science Mission Directorate Associate Administrator), Norm Haynes (Voyager Project Manager), Sagan, and Stone held a brief meeting in the Athenaeum library. At that time, the Voyager budget for FY1990 faced a significant drop and it needed \$2.2M to take the Family Portrait. Sagan explained the significance of such an observation and Fisk agreed to commit \$2.2M [5]. This resulted in the sixth observation request being formally approved by the Voyager Project Office.

Hansen designed the VPLANETS observation described in the Observation Implementation section of this chapter. Porco supplied the apparent visual magnitude calculations for each planet that allowed calculation of the proper exposure time for each of the Narrow Angle camera high resolution images. Steven Matousek (Voyager Navigation Team member) provided the spacecraft trajectory and planetary ephemerides that allowed calculation of the proper science scan platform pointing angles as a function of time from Voyager 1 to each of the planets.

As a historical footnote, Hansen made one final observation request, to essentially repeat the Voyager 1 Family Portrait of the solar system observation, using Voyager 2 (Table 7–1, Request 7). She made the request to provide redundancy in case part or all of the Voyager 1 observation failed to properly execute, in case some or all of the observation data failed to reach Earth, to provide the opportunity to construct stereoscopic images of the solar system from beyond it, and to provide the opportunity to include a crescent Neptune and Triton image in the Family Portrait. The Voyager Project denied this last observation request, due to lack of engineering resources, because of the severe permanent staff drawdown for the Voyager Interstellar Mission.

III. Observation Implementation

III.1. Project Constraints

In provisionally approving the Voyager 1 VPLANETS set of observations at an Operations Planning Group (OPG) meeting in the spring of 1989, the Project Office laid down a series of constraints on the design and execution of the observations (Table 7–3).

Voyager Project Office Constraints
No interference with the Neptune Encounter
No interference with the existing software load development schedule
One observation attempt
From one Voyager spacecraft
No high gain antenna shielding maneuver One data return attempt
Approval from each at-risk investigation (ISS, PPS, IRIS, UVS)

Table 7–3: Voyager Project Constraints on the VPLANETS Observation Design.

The Voyager Project Office laying down a constraint, at any time over the entire Voyager Grand Tour, meant that designers did not violate that constraint. A designer could request a waiver to a constraint, if it looked like a constraint was likely to be violated. Sometimes the Project Office approved waivers, sometimes not. The Voyager Project Office made it abundantly clear to the VPLANETS observation design team that, for this particular observation, no constraint waivers would be approved. The observation remained on a very short leash.

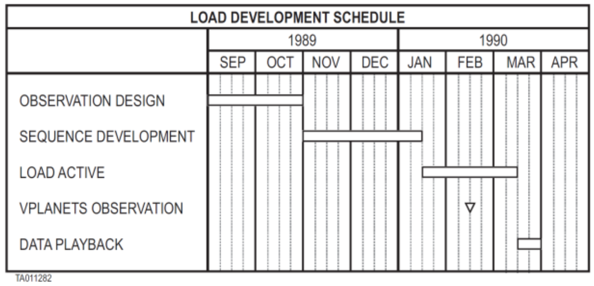


Figure 7–6: Voyager 1 Computer Software Load Development Schedule for the VPLANETS Observation.

The second constraint in Table 7–3 meant that the VPLANETS observation had to be developed within the development schedule of the first computer software load to control the Voyager 1 spacecraft at the start of the Voyager Interstellar Mission. Figure 7–6 shows the load development schedule. The VPLANETS observation had to be designed in September and October 1989.

III.2. Voyager Spacecraft Constraints and Resources, Geometrical and Timing Constraints

In principle either Voyager spacecraft could have been used for the VPLANETS observation. The desire to maximize the number of planets available drove the timing of the solar system Family Portrait. This also helped select Voyager 1 over Voyager 2 to execute the observation (Table 7–4). How close to the Sun each planet was at a given time as seen from the spacecraft essentially determined planet availability. Once a planet appeared within 1 degree of the Sun, it became unavailable. Scattered sunlight in the Narrow Angle camera optics overwhelmed the planet's signal, and it was not detectable (Figure 7–5). By this time in the Voyager mission, Mercury always orbited within 1 degree of the Sun as seen from both Voyager 1 and 2. Therefore, neither spacecraft could image Mercury at any time. Jupiter appeared within 1 degree of the Sun as seen from Voyager 2 from January to June 1990. Most importantly, Earth appeared >1 degree from the Sun as seen from Voyager 1 from about January 15 to March 30, and from July 1 to September 30 (Figure 7–7). As the Voyager Project could make available engineering resources to accomplish the observation in 1990, late winter or spring, and the best planetary phase angles occurred in February, the designers selected February.

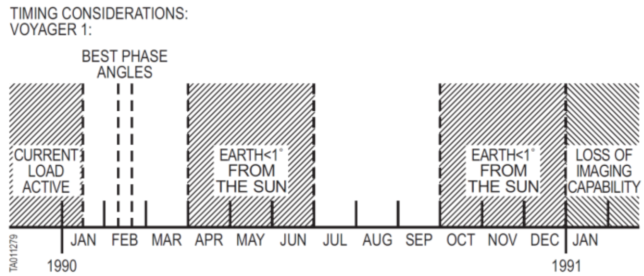


Figure 7–7: Voyager 1 VPLANETS Observation Timing Considerations.

Spacecraft Consideration	**Voyager 1**	**Voyager 2**
Potential instrument damage	IRIS	PPS, IR
Planets available	V, E, M, J, S, U, N	V, E, M, S, U, N
Planets resolved	J, S	S, N

Table 7–4: Voyager Spacecraft Considerations on Spacecraft Selection for VPLANETS.

Each Voyager spacecraft had a finite amount of resources available for observation design and execution. Table 7–5 shows the main resources available, and the amount of each used for the design and execution of the VPLANETS observation.

Voyager Spacecraft Resources Used
49 out of 50 Flight Data System (FDS) words
408 out of 2538 Command and Control System words
60 images, out of 96 possible, recorded on the Digital Tape Recorder
1 roll turn to eliminate spacecraft obscuration, prior to Jupiter imaging
315 degrees of science scan platform azimuth slewing
217 degrees of science scan platform elevation slewing
Narrow Angle camera
Wide Angle camera

Table 7–5: Voyager 1 VPLANETS Spacecraft Resources Used.

Pluto, then classified as a planet, but subsequently reclassified, remained too far away, tiny, and dark to be detected by either Voyager Narrow Angle camera. The observation design imaged each planet through three different color filters on the Narrow Angle camera: violet, blue, and green. This gave the highest resolution possible, with the ability to reconstruct the color of each body. (The cameras always send digital data to the Earth as a string of ones and zeroes that represent the brightness levels detected by the camera as shades of gray. By taking three images, one through each of three different filters separated sufficiently in wavelength, and doing special image processing, the target body's true color can be recreated.)

Kohlhase suggested using the Wide Angle camera to capture the stellar background behind the planets. A full Wide Angle image mosaic of the entire sky backdrop behind the solar system required 10 x 30 Wide Angle images, for a total of 300, a prohibitive number for the Voyager spacecraft to record, due to limited digital tape recorder space available. (The entire Digital Tape Recorder could hold just ninety-six images.) The designers decided to just image the star background at each planet, with Wide Angle images, taken through the clear filter, connecting the planets, and to take a series of Wide Angle images framing the Sun. Hansen targeted the Wide Angle stellar background images of Venus, Earth, and Mars such that, although the Narrow Angle camera images lay more than 1 degree from the Sun, the corresponding Wide Angle images, with their larger field of view, actually contained the Sun. (Figure 7–4 shows the Narrow and Wide Angle camera fields of view.) Further, given the risk already being taken by pointing the Wide Angle camera directly at the Sun for the Earth, Venus, and Mars images, opening the camera shutter to take an image with the Sun centered in that image became a small incremental risk to the camera hardware. The designers added two images of the Sun through the Wide Angle camera's most opaque filter with the shortest possible exposure time to the sequence, as the final two images. The final observation design consisted of three Narrow Angle images at each of the seven accessible planets, plus thirty-seven Wide Angle images for the star background and two Wide Angle images of the Sun, for a total of sixty images. Figure 7–8 shows the image targeting.

III.3. Phase Angle and Scattered Light Considerations

A known challenge included accounting for scattered light in the optics of both the Narrow Angle and Wide Angle cameras. Normally during the Voyager mission, observation design oriented the science scan platform, relative to the body of the spacecraft, such that it was looking away from the spacecraft structure and away from the Sun, toward an approaching planet. When observation design made it desirable to look back at a target, to take images at high phase angles, scattered sunlight and spacecraft obscuration had to be factored into the observation design. As Voyager 1 would have to "look back" for all of the Family Portrait images, observation design had to accommodate both of these constraints.

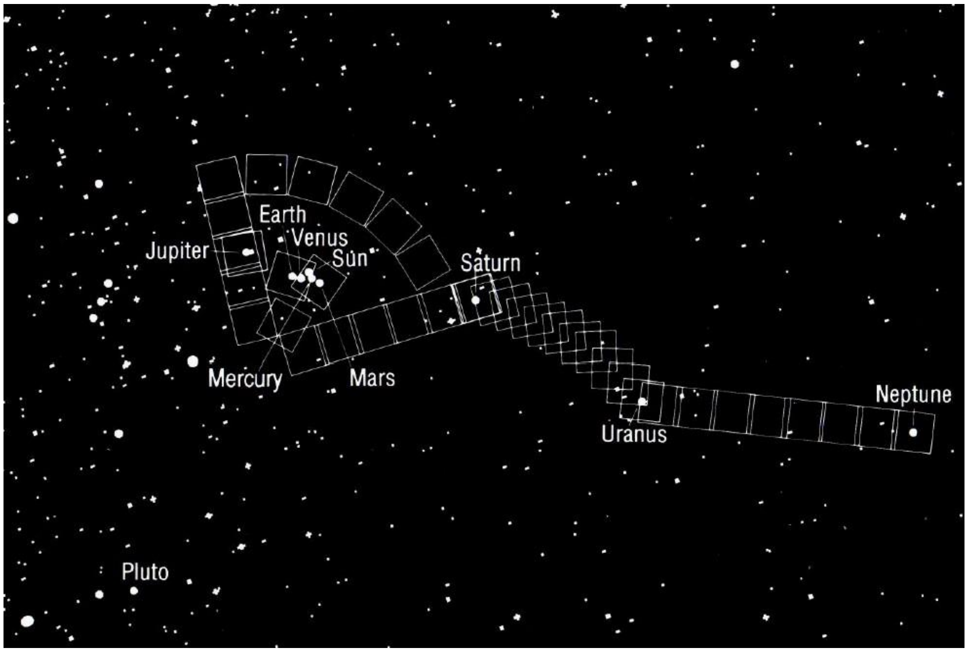


Figure 7–8: VPLANETS Observation Design. Simulation Image Courtesy of JPL and NASA.

At the normal Voyager 1 attitude, Jupiter, Earth, and Venus fell into a region of space that could be plagued by sunlight scattered from the body of the spacecraft. The observation designers inserted a roll from the Voyager 1 normal lockstar, Rigel Kentaurus, to another acceptable lockstar, Peacock, into the sequence to minimize this source of scattered light into the camera optics for the inner solar system images.

A more serious problem concerned predicting the effect of direct sunlight scattered into the Narrow Angle and Wide Angle camera optics. Voyager Flight Rules prohibited ever pointing the science scan platform closer than 15 degrees to the Sun. Data taken from images taken at 15 degrees from the Sun showed an elevated signal due to scattered sunlight. What would the situation be in images taken at a 1-degree separation angle from the Sun? Some Narrow Angle camera analysis existed. Klaasen used Voyager images taken with Jupiter just outside the field of view of the Narrow Angle camera to model scattered light in the optics coming from a bright source off axis. Klaasen scaled the model for the distance, brightness, and size of the solar disk. The results had a factor of two uncertainty (Figure 7–5), but Narrow Angle camera images with short exposures were judged to have a good probability of success.

No data existed for the Wide Angle camera. The designers selected a relatively short exposure time for the Wide Angle star background images, chosen to get a 2 dn (data number) signal on a seventh magnitude star. (The brightness level detectable by the cameras is encoded from 0 to 255 data numbers, or "dn," where 0 corresponds to black, 255 corresponds to white, and in between are shades of gray.) In addition, the series of images framing the Sun were held 5 degrees away from the Sun. For the pictures of the Sun itself, the designers knew that even a 5-millisecond exposure through the Wide Angle methane filter (effective wavelength = 6190 angstroms, width = 100 angstroms) saturated on the disk of the Sun. The designers hoped that the entire frame would not saturate from scattered sunlight. Good Wide Angle camera images near and of the Sun were by no means guaranteed.

Determination of the exposure times for the Narrow Angle planet images utilized both theoretical and empirical modelling, constrained by spacecraft FDS memory available (Table 7–5). A 15.36 second exposure was the longest duration available. Exposures longer than 15.36 seconds required more FDS words, and there weren't any more available.

Table 7–6 summarizes the filter/exposure combinations for each target. The three Neptune images used the maximum 15.36 second exposure time, because the planet appeared very dark due to its great distance from the Sun. In images acquired of Neptune in 1988 by Voyager 1 at these exposures, the planet had been just barely detectable. The number of available FDS words also limited Uranus images to 15.36 second exposures in all three filters. But being closer to the Sun made Uranus brighter than Neptune. From Voyager 1 images taken in 1988, Uranus was known to be readily detectable with these exposures.

Planet	Narrow Angle Filter(s)	Exposure (sec)
Neptune	Violet, Blue, Green	15.36, 15.36, 15.36
Uranus	Violet, Blue, Green	15.36, 15.36, 15.36
Saturn	Violet, Blue, Green	7.68, 5.76, 7.68
Jupiter	Violet, Blue, Green	0.36, 0.24, 0.36
Mars	Violet, Blue, Green	5.76, 3.84, 7.68
Earth	Violet, Blue, Green	0.72, 0.48, 0.48
Venus	Violet, Blue, Green	0.36, 0.24, 0.36

Table 7–6: Planet Filter/Exposure Combinations.

In 1988 Voyager 1 acquired Saturn images at high phase angles for phase function analysis. Porco used this data set to calculate optimum exposure times.

At > 1 pixel in diameter, the Voyager 1 Narrow Angle camera, in early 1990, still resolved Jupiter's disk. (A pixel is a picture element. Each camera image contains 800 by 800 pixels.) Porco calculated exposure times from the Voyager 1 Jupiter encounter at the appropriate phase angles, then reduced the times to minimize scattered light due to Jupiter's proximity to the Sun, as seen from Voyager 1.

Earth, Venus, and Mars all appeared substantially less than a pixel in diameter, and very close to the Sun, as seen from Voyager 1. The high phase angle made Mars even more difficult to detect. Porco calculated apparent visual magnitudes for each planet, incorporating the phase angle and phase function of each planet in her calculations (Table 7–7). The presence or absence of clouds made estimating the brightness of the Earth particularly challenging. Porco used the known Narrow Angle camera response for star images to determine optimal exposure times (Table 7–6). Earth and Venus exposure times were then reduced as much as possible to minimize the additional signal from scattered sunlight in the camera optics. The faintness of Mars also presented a particularly difficult problem. The design pushed the Mars exposure times to allow as much scattered light as possible without saturating the images, in order to bring the planet's signal up to a minimum detectable level. Table 7–6 summarizes the color filter exposure combinations for each planet's imaging.

Planet	**Range**	**Phase**	**Diameter**	**Apparent Visual**
Neptune	4.61	83	0.5	8.9
Uranus	4.51	107	0.5	8.3
Saturn	5.26	113	1.1	4.7
Jupiter	6.57	43	3.5	2.8
Mars	5.84	145	0.03	9.7
Earth	6.06	73	0.12	5.2
Venus	6.03	83	0.11	4.3

Table 7–7: Planet Range, Phase Angle, Diameter, and Apparent Visual Magnitude.

A very limited Voyager spacecraft resource also influenced the color filter/exposure selection. The FDS memory available for specification of camera shutter mode, filter, and exposure time consisted of a fifty-word table (Table 7–5). This translated to roughly fifty shutter mode, filter, and exposure time combinations available in the VPLANETS observation design. This limitation dictated that all the Wide Angle star images be the same exposure time, regardless of the brightness of the stars in the field of view.

In summary, the VPLANETS observation imaged seven of the (now) eight known planets, and the Sun, all using an observational system not designed to make this type of observation.

IV. Observation Execution

On February 13, 1990, Voyager 1 powered its cameras on. After three hours for warmup, the science scan platform slewed to point at Neptune and the VPLANETS observation started executing. The spacecraft onboard tape recorder saved all the images taken, for later playback to Earth. After imaging Neptune, Uranus, Saturn, and Mars, the Wide Angle images between each planet, and the Wide Angle images framing the Sun, the spacecraft executed the roll from Rigel Kentaurus to Peacock. The observation resumed with images of Jupiter, Earth, and Venus. The images of Earth were shuttered at 04:48 GMT, February 14, 1990, detecting light that had left the Earth five hours and thirty-six minutes earlier.

At 05:22 GMT, February 14, Voyager 1 powered the cameras off forever.

Drama continued to follow the observation. Two major NASA planetary missions (Galileo and Magellan), in progress in spring 1990, required most of the time of the antennas of the Deep Space Network (DSN). At the enormous distance of Voyager 1 from the Earth, receipt of all sixty VPLANETS images required four, ~four-hour DSN passes, initially scheduled for March 16, 20, 23, and 27 (Table 7–8). In addition, each VPLANETS DSN pass arrayed two DSN antennas, a 34-meter diameter antenna (DSS 65) and the 70-meter diameter antenna (DSS 63). On January 4, 1990, Kosmann wrote a memo from the Voyager Project to the Galileo Project, requesting that Galileo plan its DSN pass requests around the Playback 1 through four DSN passes listed in Table 7–8, to allow Earth to receive the Voyager VPLANETS images. This request was honored by the Galileo Project.

The first playback worked, as did the third and fourth, but bad weather at the DSN receiving antennas in Spain plagued the second. Violating one of its own constraints (Table 7–3, Line 6), the Voyager Project scheduled a retry of Playback 2 for April 17. An equipment failure at the DSN complex outside of Madrid caused this second replay to be unsuccessful. Violating the same constraint, a second time, the Voyager Project scheduled a third attempt for May 1. The third time worked perfectly. All sixty images from the Family Portrait finally resided safely on Earth! Figure 7–9 shows Stone, Hansen, and Torrance Johnson

(Galileo Imaging Science Team Lead) on the day the last of the VPLANETS images hit Earth, in the old Voyager Imaging Library, with all sixty images pinned to the wall in the background.

Date	DSN Antenna Scheduled	Activity	Time GMT ERT
1989, February 14	63	VPLANETS Imaging	1:15—12:45
1989, March 16	63/65	Playback 1	2:58—7:04
1989, March 20	63/65	Playback 2	2:40—6:40
1989, March 23	63/65	Playback 3	2:28—6:05
1989, March 27	63/65	Playback 4	2:12—6:12
1989, April 17	63/65	Playback 2 Retry 1	
1989, May 1	63/65	Playback 2 Retry 2	

Table 7–8: DSN Passes Scheduled for VPLANETS Observation Image Data Playback and Receipt.

Figure 7–9: Ed Stone, Candy Hansen, and Torrance Johnson, with the VPLANETS Images in the Background.

V. Results

As any amateur photographer knows, when pointing a camera close to the Sun, artifacts that are the result of light scattered in the camera optics become visible. These artifacts occurred in the Voyager 1 images taken close to the Sun.

Rays of light streak through the images adding drama to an already dramatic construction (Figures 7–10, 7–11, 7–12, and 7–13).

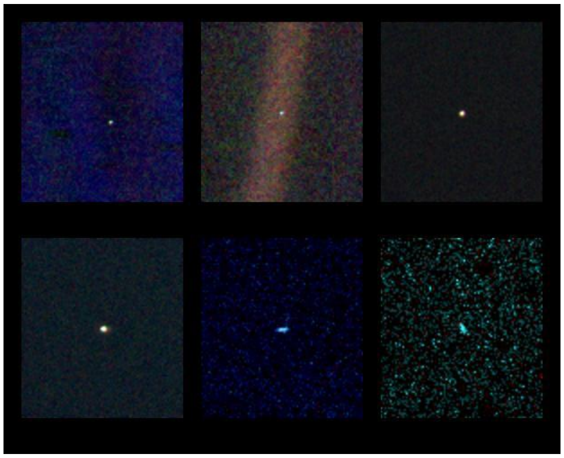


Figure 7–10: Narrow Angle High Resolution Images of Venus, Earth, Jupiter, Saturn, Uranus, and Neptune. Images Courtesy of JPL and NASA.

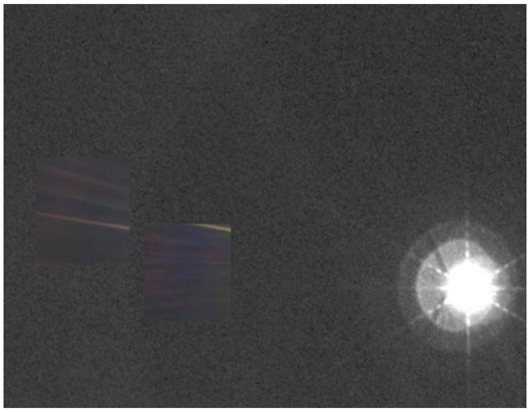


Figure 7–11 (left): Earth as a Pale Blue Dot. Image Courtesy of JPL and NASA.
Figure 7–12 (right): The Sun, with Venus and Earth. Images Courtesy of JPL and NASA.

The Narrow Angle camera detected Venus (Figure 7–10) at 10 dn above background. The mottled nature of the background probably results from sunlight reflecting off the ring of eight calibration lamps mounted around the barrel of the Narrow Angle camera [3,4]. The Earth (Figures 7–10 and 7–11) coincidentally landed in a ray of sunlight scattered in the optics. It was also easily detectable at

~10 dn above background. Scattered light in the optics prevented Mars from being identified with confidence.

The Narrow Angle camera resolved Jupiter (Figure 7–10) and Saturn (Figure 7–10). Both show up easily in the images. Spacecraft motion during the 15-second exposures elongate Uranus (Figure 7–10). Neptune (Figure 7–10) ended up barely detectable at ~1 dn above background. Spacecraft motion also elongated Neptune.

The Wide Angle camera images show a glorious, rayed structure from the light scattered in the camera optics (Figure 7–10). The stars expected to be detected indeed show up in their respective images.

The images of our Sun remain perhaps the most dramatic (Figures 7–12 and 7–13). Just as every schoolchild draws the Sun with rays, so too the spider holding the single Wide Angle camera calibration lamp cast a diffraction pattern around the Sun. The Sun shone so bright that the image saturated and it bloomed to a size larger than reality. Multiple reflections off various optical elements cause the rings surrounding the Sun.

The very size of our solar system caused processing of these images to be as challenging as acquiring them. How could they be portrayed at a scale suitable for publishing while maintaining the real relative sizes and distances of the bodies relative to each other? We opted to process and release multiple versions at multiple scales, shown here in Figures 7–10, 7–11, 7–12, and 7–13.

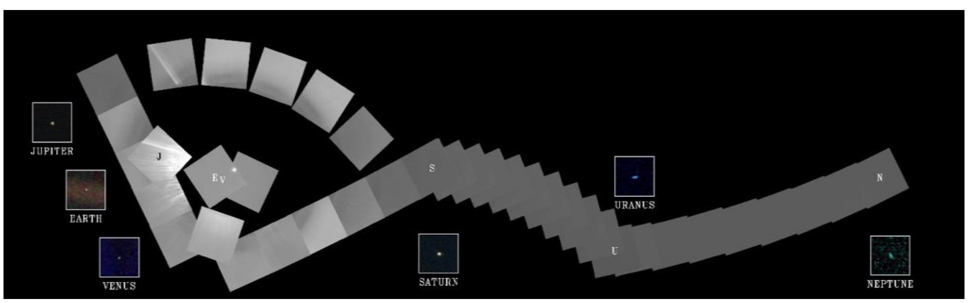


Figure 7–13: Family Portrait of the Solar System Mosaic. Mosaic Courtesy of JPL and NASA.

JPL mounted the entire mosaic (Figure 7–13) on a wall in the Von Karman auditorium, covering over 20 feet. The picture of the Earth had to be replaced often, because people would walk up and touch it—we are here.

Finally, among the first images produced by that the Earth and the Moon had been imaged together (Figure 7–14). Voyager 1 took these images on September 18, 1977, thirteen days after launch, at a distance of 11.66 million km (7.25 million miles) from Earth. Visible in the Earth image are eastern Asia, the western Pacific Ocean, and part of the Artic. The images were taken through the blue, green, and orange filters, and the JPL Image Processing Lab created the true color composite image. As the Moon does not reflect nearly as much light as the Earth does, the image creators artificially brightened it by a factor of five relative to the Earth, so that both bodies are clearly visible.

Figure 7–14: Voyager 1 Images of the Earth and Moon. Image Courtesy of JPL and NASA.

Among the initial images produced by Voyager 1 at the beginning of the Grand Tour include the first time that the Earth and the Moon had been imaged together (Figure 7–14). The Family Portrait of the solar system (Figure 7–13) represent the final images produced by the Voyager Grand Tour—fitting bookends for the greatest mission of scientific exploration in human history.

V. Conclusions

The Voyager Family Portrait of the solar system observation was fundamentally taken to make a statement: that this species had risen far enough out of the primordial ooze that it could send an emissary out beyond its home solar system, capable of looking back, and taking a last farewell picture of home. Further, for each species in the universe, there can only be one first time that such an "image" is taken. This observation was that first time for the human species.

In addition, the true color image of the Earth was taken to show that Spaceship Earth is but a tiny fragile spec in the vast cosmic ocean. As Sagan so eloquently said in his book *Pale Blue Dot: A Vision of the Human Future in Space*, Chapter 1, “You Are Here,”

> The Voyagers were guaranteed to work only until the Saturn encounter. I thought it might be a good idea, just after Saturn, to have them take one last glance homeward. From Saturn, I knew, the Earth would appear too small for Voyager to make out any detail. Our planet would be just a point of light, a lonely pixel, hardly distinguishable from the many other points of light *Voyager* could see, nearby planets and far-off suns. But precisely because of the obscurity of our world thus revealed, such a picture might be worth having.
>
> … There is no sign of humans in this picture [the famous Earth Rise image from Apollo 17], not our reworking of the Earth’s surface, not our machines, not ourselves: We are too small and our statecraft is too feeble to be seen by a spacecraft between the Earth and the Moon. From this vantage point, our obsession with nationalism is nowhere in evidence. The Apollo pictures of the whole Earth conveyed to multitudes something well known to astronomers: On the scale of worlds—to say nothing of stars or galaxies—humans are inconsequential, a thin film of life on an obscure and solitary lump of rock and metal.
>
> It seemed to me that another picture of the Earth, this one taken from one hundred thousand times further away, might help in the continuing process of revealing to ourselves our true circumstance and condition. It had been well understood by the scientists and philosophers of classical antiquity that the Earth was a mere point in a vast encompassing Cosmos, but no one had ever *seen it* as such. Here was our first chance (and perhaps also our last for decades to come).
>
> Look again at that dot [Figure 7–11]. That’s here. That’s home. That’s us. On it everyone you love, everyone you know, everyone you’ve ever heard of, every human being who ever was, lived out their lives. The aggregate of our joy and suffering, thousands of confident religions, ideologies, and economic doctrines, every hunter and forager, every hero and coward, every creator and destroyer of civilization, every king and peasant, every young couple in love, every mother and father, hopeful child, inventor and explorer, every teacher of mortals, every corrupt politician, every “superstar,” every “supreme leader,” every saint and sinner in the history of our species lived there—on a mote of dust suspended in a sunbeam.
>
> The Earth is a very small stage in a vast cosmic arena. Think of the rivers of blood spilled by all those generals and emperors so that, in glory and triumph, they could become the momentary masters of a fraction of a dot. Think of the endless cruelties visited by the inhabitants of one corner of this pixel on the scarcely distinguishable inhabitants of some other corner, how frequent their misunderstandings, how eager they are to kill one another, how fervent their hatreds.

> Our posturings, our imagined self-importance, the delusion that we have some privileged position in the Universe, are challenged by this point of pale light. Our planet is a lonely speck in the great enveloping cosmic dark. In our obscurity, in all this vastness, there is no hint that help will come from elsewhere to save us from ourselves.
>
> The Earth is the only world known so far to harbor life. There is nowhere else, at least in the near future, to which our species could migrate. Visit, yes. Settle, not yet. Like it or not, for the moment the Earth is where we make our stand.
>
> It has been said that astronomy is a humbling and character building experience. There is perhaps no better demonstration of the folly of human conceits than this distant image of our tiny world. To me, it underscores our responsibility to deal more kindly with one another, and to preserve and cherish the pale blue dot, the only home we've ever known.

If we as a species don't destroy ourselves and our original home, and are able to make it out into the Cosmos, then our starting inconsequential position and condition will make the accomplishment all the sweeter, and all the more satisfying.

Afterword

Following the success of the 1989 Voyager 2 Neptune Encounter, culminating in the 1990 Family Portrait of the solar system observation, and still basking in the warm afterglow of victory, in the summer of 1990, Kosmann suggested to Sagan and Hansen that the three of them write a paper on the unbelievable history of how the Family Portrait came to be. All three agreed to a paper organization. Kosmann wrote a first draft of the "Evolution of the Observation" and "Obstacles" sections combined. Hansen wrote a first draft of the "Geometrical and Timing Constraints, Phase Angle and Scattered Light Considerations, and Resulting Observation Design" portions of the Observation Implementation section. Sagan was to write the Introduction and Conclusions sections, and to aid in proofing the entire paper for historical accuracy. In September 1990, Kosmann moved to northern Virginia, and did not remain involved in further writing of the paper. Sagan and Hansen continued to work on the paper, along with comments from Porco, through most of 1992, then stopped all work on it. Sagan passed away in December 1996.

In the summer of 2018, after reading yet another book on the Voyager Grand Tour, containing a chapter on the Family Portrait of the solar system that bore little resemblance to what had actually happened, Kosmann decided it was long past time to complete this paper. A paper needed to be in the literature on the history and design of the Family Portrait observation, to provide an accurate story in print for history, and for future Voyager Grand Tour paper and book authors. Kosmann unearthed the first drafts of the 1990 paper and contacted Hansen, who agreed to help complete the paper. The first drafts were updated by reviewing information related to the VPLANETS observation that both Hansen and Kosmann had saved, across the decades. Kosmann added the Project Constraints and Spacecraft Constraints and Resources subsections to the Observation Implementation section, downloaded the various VPLANETS observation image products from the online JPL image website, managed the creation of the rest of the graphics, and retyped all the tables in the IAC format. Hansen had written an Introduction, in either 1991 or 1992, and this section was added. Hansen wrote a first draft of the Results section, and Kosmann added in the VPLANETS images and mosaics. No Conclusions section had ever been written.

As Sagan is regrettably no longer with us, it was left to Hansen and Kosmann to attempt to provide a pale cast moon shadow of the conclusions that Sagan would have provided, had this paper been completed while he was still alive. Fortunately, rather than trying to guess at what Sagan would have written for the Conclusions section, Hansen recalled that Sagan had written about his motivation for proposing the Earth image in 1981, in chapter one of his 1994 book *Pale Blue Dot.* The salient paragraphs from that chapter are reproduced, with permission, from his wife and collaborator Ann Druyan, in the Conclusions section of this chapter.

Kosmann submitted the abstract of the paper to the 2019 International Astronautical Congress (IAC). The IAC accepted the paper, for both presentation and publication. And now the literature contains an accurate description of what it took to create mankind's first Family Portrait of its home solar system.

Acknowledgments

This entire chapter describes the history and motivations that led to the Family Portrait of the solar system. The chapter provides acknowledgment throughout. A number of people generously gave of their time to read, review, and offer "suggestions for improvement" to the chapter. Reviewers include Ann Druyan, Ed Stone, Charley Kohlhase, Randii Wessen, Rex Ridenoure, Chris Potts, Suzzane Dodd, Craig DeForest, and Robert Cesarone. The authors express gratitude to each and every one of them. The chapter ended up better as a result of their efforts.

Further gratitude must in addition be paid to Ann Druyan. Ann participated in two telephone conversations and one in-person meeting on the topic of this chapter. She not only graciously gave permission to quote the one paragraph from chapter one of *Pale Blue Dot* originally requested, and permission to use Sagan's name, posthumously, as a co-author, she suggested that much more of what Sagan and she had written in the first chapter of that book should be quoted in the Conclusions section of this chapter, a suggestion the authors gladly accepted.

Last, but certainly not least, acknowledgment must be paid to Todd Pruetz for laying out the entire chapter in Microsoft Word, in the required IAC format, and to Julie Dao, for recreating Figures 7–5, 7–6, and 7–7, from original artwork created at JPL in 1990.

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