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Farewell to the Major Moons of Jupiter

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PROJECT GALILEO: FAREWELL TO THE MAJOR MOONS OF JUPITER

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Abstract

After a six-year odyssey, Galileo has completed its survey of the large moons of Jupiter. In the four years since the end of the primary mission, Galileo provided new insights into the fundamental questions concerning Jupiter and its moons and magnetosphere. Longevity, changing orbital geometry, and multiple flybys afforded the opportunity to distinguish intrinsic versus induced magnetic fields on the Galilean moons, to characterize the dusk side of the magnetosphere, to acquire high resolution observations supporting the possibility of subsurface water within Europa, Ganymede, and Callisto, and to monitor the highly dynamic volcanic activity of Io. In January 2002, a final gravity assist placed the spacecraft on a two-orbit trajectory culminating in a Jupiter impact in September 2003.

With the successful completion of the Io encounters, plans are being made for the final encounter of the mission. In November 2002, the spacecraft will fly one Jupiter radius above the planet's cloud-tops, sampling the inner magnetosphere and the gossamer rings. The trajectory will take Galileo close enough to Amalthea (a small inner moon) to obtain the first gravity data for this body. Because a radiation dose of 73 krads is expected on this encounter, which will bring the total radiation dose to greater than four times the spacecraft design limits, the command sequence has to account for the possibility of subsystem failure and the loss of spacecraft control after this perijove passage.

One of the primary objectives this year has been to place the spacecraft on a trajectory to impact Jupiter on orbit 35. Galileo's discovery of water beneath the frozen surface of Europa raised concerns about forward contamination by inadvertently impacting that moon and resulted in an end of mission requirement to dispose of the spacecraft. A risk assessment of the final two Io encounters was performed to manage the project's ability to meet this requirement.

Radiation affected the extended mission through damage to electronic parts in the attitude control subsystem, the computer memory and some science instruments and by causing transient bus reset indications. Software patches and changed operating strategies were implemented to work around most of the radiation effects. Recovery efforts to enhance the robustness of the Solid State Imaging camera paid off in the acquisition of images at both Io 32 and Io 33. Data on spacecraft performance in the harsh jovian environment may be useful to designers of future missions to Jupiter and its moons.

1. Introduction

After a thirteen-year journey of discovery, the Galileo Spacecraft is now completing its seventh year in orbit around Jupiter and is nearing the end of its mission. Figure 1 shows Galileo's path through interplanetary cruise to arrival at Jupiter and its subsequent progress travelling over halfway around the Sun as it orbits the giant planet. Figure 2 shows the details of the orbital tour around Jupiter including the prime mission[1, 2], the Galileo Europa Mission (GEM)[3, 4], and the Galileo Millennium Mission (GMM)[5, 6]. Each flyby targets the spacecraft for the next encounter.

During its five years in extended mission, Galileo has achieved a total of 19 (out of 22) successful encounters,

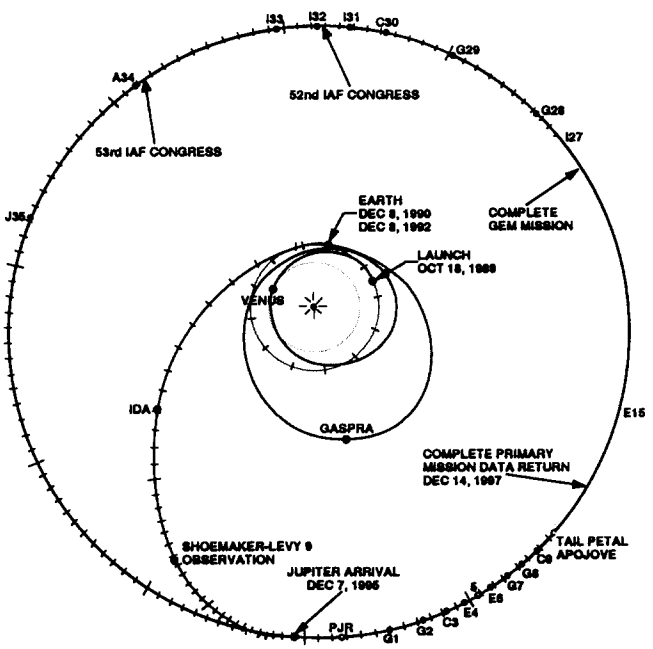

Figure 1. Heliocentric Progress

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exploring the four Galilean satellites (Io, Europa, Ganymede, and Callisto); Jupiter's atmosphere, magnetosphere, and rings; and some of the minor satellites. Section 8 summarizes significant science results. Observations spanning a total of seven years provided time histories and varying sampling geometries to characterize the dynamic processes of the Jovian system. Multiple passes by the major moons as the orientation of Jupiter's magnetic field changed revealed the existence of induced magnetic fields, and the possibility of subsurface water layers, on Europa, Ganymede and Callisto. Progression of the orbit allowed sampling the dusk and afternoon sectors of the magnetosphere (Figure 2) and joint observations with the Cassini spacecraft enroute to Saturn provided unique insight into the dynamic relationship between the solar wind and Jupiter's magnetosphere. Close flybys of Io, culminating in the Io 32 encounter, contributed to identification of more hotspots and to monitoring volcanic activity.

This past year has seen the completion of the survey of Jupiter's major moons with the final two Io flybys, Io 32 and 33 (See Section 5). A complete set of observations was acquired at Io 32. Designed for both science observations and to set up the end of mission trajectory, Io 33 was unsuccessful in acquiring high priority science (See Sections 3 and 5.2) but did achieve the required gravity assist to place the spacecraft on a Jupiter impact trajectory two orbits later, in September 2003. It was important to assure the spacecraft be on a ballistic impact trajectory prior to the upcoming Amalthea flyby because of the expected severity of the radiation environment as the spacecraft passes within one Jupiter radii above the cloud-tops in November 2002. In the event of significant damage to the electronics and loss of spacecraft control, the end of mission

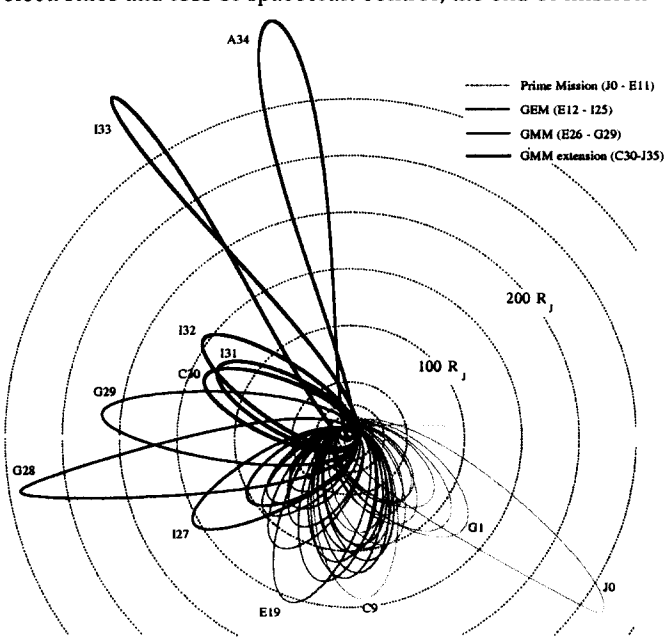


Figure 2. Detail Orbital Tour

plan would still be achieved (See Section 7).

With the completion of the exploration of Jupiter's major moons and the end of remote sensing experiments, the mission focus turns to fields and particles survey of the inner magnetosphere and the gossamer rings and measurement of Amalthea's gravity. The latter will be the first density determination of one of Jupiter's small inner moons. The radiation environment presents challenges to the design of the science observation sequence as discussed in Section 6.

Aging and continued exposure to radiation, with the cumulative dose rising to four times the design expectation, has taken its toll on the spacecraft components. Effects are manifested in degraded performance of some of the engineering subsystems and science instruments as discussed in Sections 2 and 4. This year saw the continuation of the Solid State Imaging camera problem and a slightly different behavior of the despun bus resets[7,8,9]. The latter proved to be particularly costly, resulting in spacecraft safe mode shortly before the closest approach at Io 33 and the loss of Io science.

2. Orbiter Performance Overview

2.1 Attitude and Articulation Control Subsystem (AACS)

The AACS subsystem has functioned nominally in the past year. The gyros continue their pattern of degradation during encounter and annealing during the cruise portion of an orbit.[4] Updated gyro scale factor parameters are uplinked to the spacecraft as needed to offset the discrepency in gyro output determined by regularly scheduled gyro performance tests. The maximum discrepency was seen one day after Io 33 perijove when gyro output on the worst case axis was 98.4% more pulses than expected when sensing motion. This axis has since annealed to 79.2% during the long cruise portion of the orbit. One theory proposed during the gyro anomaly investigation in 1998 predicted that 100% degradation, which means the gyros are putting out twice as many pulses as they should, would be the maximum reached. The raw gyro drift rates do appear to be leveling off somewhat. The 2 R_J approach at Amalthea 34 (A34) should ensure that the 100% mark is reached; a gyro test is planned one day after the encounter. The gyros are required for orbit trim maneuvers (OTMs), none of which are planned after A34. A final attitude turn is planned after A34; if the gyros are non-operational, this can be accomplished by one-degree pointing corrects not using the gyros.

Background radiation noise inside Io's orbit is strong enough to swamp out the signal from the star scanner. A single bright star (OSAD—one-star attitude determination) is used for perijove passages inside 8 R_J, as dimmer stars are lost in the radiation-induced noise. During the spacecraft's initial entry to the Jupiter system in 1995, it used a gyro-based attitude reference during the period when even the OSAD star was expected to be lost. The continuing gyro degradation has resulted in OSAD alone being used for attitude determination

for all GEM orbits since Callisto 22 in August 1999. However, the radiation during A34 is expected to be strong enough to obscure the OSAD star for a period of 7 to 9 hours. (Due to geometry, this is also a dimmer star than the 1995 OSAD star). Work is ongoing to choose the safest method to maintain attitude during this period. (See Section 6)

2.2 Command and Data Subsystem (CDS) and Data Memory Subsystem (DMS)

The command and data subsystem performed well this year. The only software patch necessary was to allow memory copy commands to write into high-level memory in support of data collection during the DMS anomaly (See Section 3.2).

Transient bus resets, presumably induced by radiation exposure, have plagued the spacecraft since 1991. A software patch[4] now allows the spacecraft to autonomously handle these without interrupting the sequence. Io 32 was the first encounter since Europa 19 in early 1999 in which no bus resets occurred.

However, Io 33 was not as fortunate. A new type of bus reset was not recognized by the patch as such (See Section 3.1), and thus spacecraft safing was called, which cancelled the sequence. This incident happened 28 minutes before Io 33 closest approach. These bus resets normally only occur near Jupiter; the furthest out had previously been at 29 R_J in Io 27. However, during the cruise portion of the Io 33 orbit in February 2002, a bus reset occurred at 180 R_J. As playback was active, the patch that allows the spacecraft to autonomously detect and recover from bus resets was disabled, since the playback process is incompatible with the patch. After verifying that the spacecraft entered safing due to a bus reset, the standard recovery procedures were followed.

The DMS' tape recorder successfully recorded all Io 32 data, and Io 33 data outside of the safing incident (See Section 5.2). However, two incidents of the tape sticking were seen; one during Io 32 playback in November 2001, and a second after Io 33 playback was completed, in April 2002. See section 3.2 for more details.

2.3 Power/Pyrotechnic Subsystem (PPS)

The RTG (Radioisotope Thermoelectric Generator) output has continued to decay at the predicted rate (about 7 Watts a year), dropping to 442 Watts in June 2002. To accommodate the decrease in available power, the power management strategy has been to cycle heaters around activities with increased power draw. As the number of heater cycles necessary was increasing, it was decided to permanently turn off two heaters (the 400N engine heater and the Ultra Violet Spectrometer (UVS) supplemental heater). This resulted in gaining 9.4 W of power. No further reconfigurations should be necessary through end of mission.

2.4 Rocket-Propulsion Module (RPM)

The RPM subsystem has performed nominally in the past year. Standard activities included attitude turns, thruster maintenance, pointing and spin rate corrections, and OTMs. From September 2001 through August 2002 the spacecraft performed six OTM's (OTM-100 through OTM-107) to stay on the desired trajectory. Both the pre- and post-encounter maneuvers for Io 33 (OTMs 105 and 106) were cancelled as unnecessary; this was the first time in all orbital operations it was possible to cancel both of these maneuvers.

The propellant margin at the end of mission (post A34) is currently predicted to be 2.4 kg.

2.5 Temperature Control Subsystem

The +X thruster cluster, which has 2 heaters and 8 RHU's (radioisotope heater units), dropped in temperature due to degrading RHU's and came close to its lower limit. The cluster heaters were reconfigured in March 2002 to raise the temperature. The Bay A temperature, which affects the computer electronics' lifetime via temperature cycles, also continues to decrease due to RHU degradation, but no heater reconfigurations have been necessary. The heaters turned off for power management did not adversely affect the temperature of any operating systems.

2.6 Telecommunications Subsystem

The communications subsystem, which allows the spacecraft to send data to the ground and receive commands performed nominally this year. A standard strategy to vary signal carrier power and ground receiver loop bandwidth was implemented to boost link performance during a 21-day period of solar conjunction, in which the sun interferes with the earth-spacecraft communications link.

3. Non-Instrument Anomalies

3.1 Io 33 Bus Resets

Transient despun bus resets continued to plague the Galileo spacecraft. Of the three occurrences during Io 33, a flight software patch loaded in 1999 successfully identified the second one and allowed the background sequence to continue. The first event, a non-standard despun bus reset, occurred inbound to Io 33 encounter and resulted in spacecraft safe mode and cancellation of the science sequence. The final reset happened when data playback was active and the patch was disabled and, again, the spacecraft entered safe mode. The unusual aspect of this event was that it occurred at 180 R_J, well outside the Jovian radiation environment.

The flight software patch to "ride through" transient bus resets relies on certain bits in memory being set in conjunction with detection of a bus parity error signal to recognize the bus parity error as being spurious. At 28 minutes before Io 33 closest approach, a new type of bus reset occurred in which these bits did not get set, and thus the patch was not invoked. The spacecraft then responded as if a real bus parity error had occurred, and called spacecraft safing. The patch is being

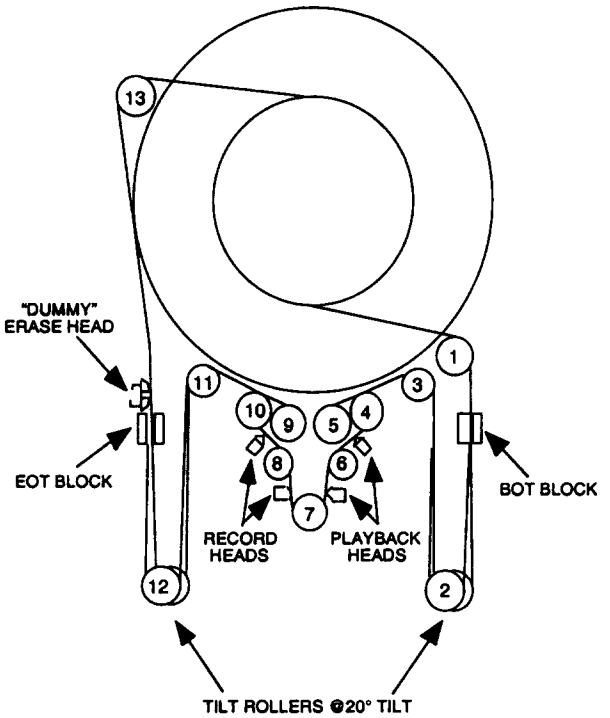


Figure 3. Tape Path

modified to not check these bits in the future but rely solely on the bus parit error signal, in case Amalthea 34 also experiences this new type of bus reset.

3.2 DMS Tape Recorder Sticking

The tape recorder was first observed to stick in 1995 during the approach to Jupiter.[1] It was determined at that time that the stick was occurring at a "dummy" erase head used as a tape guide (See Figure 3). After recovery from that stick, new Data Management Subsystem (DMS) usage rules were implemented. Fault protection routines were added to detect sticking and send the tape into "lockout" mode to prevent further tape commands from being acted on. In addition, an end-to-end tape conditioning was designed and has been performed on average every 30 days during orbital operations. These actions probably helped get the DMS through 6 years of operations with no known sticking events. However the tape continues to age, and "gunk" is likely building up on each pass through. The first indication of a new tape stick problem came on November 13, 2001, when the tape tripped the stick monitor fault protection and entered lockout mode during a DMS conditioning. A subsequent small forward motion executed successfully. The DMS conditioning sequence was redesigned to no longer stop at the same location on the tape, as it was surmised that that location might have become damaged after stopping there regularly for six years. No further action was taken before Io 33.

Due to the Io 33 safing event, less data was recorded than was planned, and playback finished on March 30, 2002, several months earlier than expected. When the tape is not moving, it is preferred to park it at the center of the tape to minimize tension on a negator spring. On April 5, the tape was slewed to the center. The next tape motion was a standard DMS conditioning on April 12. The tape manager entered lockout mode at the same relative point in the sequence as in the November 2001 event, despite the change in landing position. The same small forward motion as before was attempted on April 17, but the tape did not move. This is known, because in playback mode, the tape synchronizes with timing data embedded on the tape. If the DMS software does not show the tape being in lock, it is not moving, even though the position counter did increment one tic (a measure of position on the tape; one tic = 3.14 inches). The tic counter incrementing indicates the motor was turning (i.e., not stalled). The capstans were rotating, but the tape was just slipping on them; there was not enough friction to pull the tape off the heads that it was stuck to.

The small forward motion was again attempted on April 26, this time storing very high-rate diagnostic data on the tape's current draw and status during the motion in CDS memory and then reading it out. The data showed the motor and capstans were moving at the commanded speed. Further characterization tests were performed (slewing the tape forward and backward) on May 7, 17, and 22, allowing the DMS engineer to refine his model of the tape. He found that the tape was most likely sticking to both the dummy erase head and one or both of the playback heads. His recommendation for unsticking the tape was to move in the forward direction at the highest possible speed. He surmised that the greater torque may be enough to pull the tape free immediately, or, if not, that the rotating capstans would heat up the tape and increase the coefficient of friction enough to allow the capstans to grip the tape and pull it free from the heads. A high-speed test was designed, saving high-rate data, with a monitor to stop tape motion if it indeed pulled free (to minimize distance traveled along the tape, as the motors have the greatest pulling authority at the beginning of the tape). This test was performed on June 8 and succeeded in pulling the tape free within four seconds of commanding tape motion (See Figure 4).

An unknown amount of tape position error had accumulated during the preceding activities. In addition, it was undesirable to leave the tape sitting (not in motion) for an extended period of time after unsticking it. The DMS engineer continued studying flight and ground test data to design a new DMS conditioning sequence, and recommended starting out with short (200 tic or less) tape movements. Ground tests suggested that longer periods of tape motion, which heat up the tape more, might lead to resticking the tape. On June 18, two short tape slews were commanded to zero out accumulated position error. The high rate data saved during the start-up of each slew showed that the tape was lightly to moderately stuck at the beginning of the first motion. However, it did pull free even at the slow commanded speed. All subsequent motions were nominal. This light stick was observed after the tape had

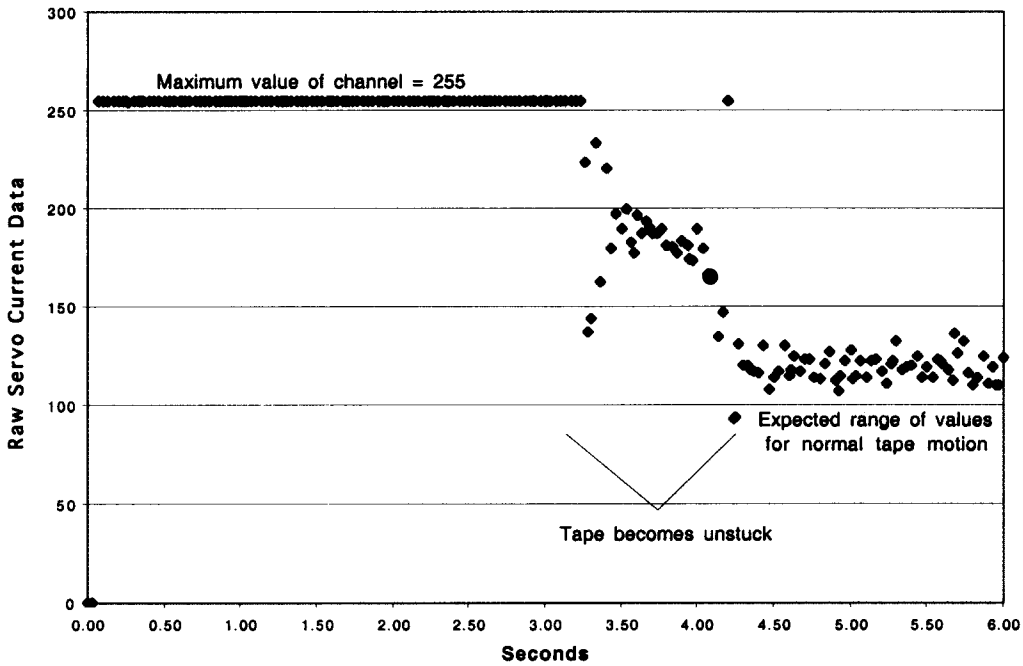


Figure 4. Raw Tape Servo Current (Channel Maximum Value is 255). During Tape Run-up Time, The Channel Pegged at 255, indicating A Stuck Tape

sat without moving for 10 days. The next planned motion was not until 17 days later, so an additional short slew was commanded at 12 days and executed as expected; no high rate data was saved, so it is unknown if the tape was stuck at all. The tape was put in motion, 200 tics at a time, starting July 5 for a 24-day period during the solar conjunction in July. During this time, a strategy to keep the tape healthy through Amalthea 34 was designed.

4. Instrument Status

4.1 SSI Recovery

The SSI instrument's problem characterized by increased baseline stabilization (BLS) voltage and increased SSI input current[6] was solved by redesigning the power cycle/software reload (PCR) process to permanently disable instrument erase mode, which reduced the maximum signal level seen by the suspect amplifiers. In addition, a check was added so that the PCR did not happen if the instrument was in the nominal state. None of the 13 possible PCRs allowed for in Io 32 were necessary, as the instrument never entered the anomalous state. During Io 33 most of the SSI images were lost due to the spacecraft safing event; however, all images subsequent to safing recovery were obtained and none of the 21 sequenced PCRs were necessary.

4.2 Other Instruments' Status

NIMS's grating remained stuck[5], and memory reloads continued to be sequenced to preclude loss of data due to memory corruption. A single software halt was observed in I32, but no data was lost. No halts were seen in I33. The other science instruments had no change in their operating status in the past year.

5. Summary of Encounters in the Past Year

5.1 Io 32

The seventh encounter of the GMM and sixth Io flyby for the entire mission occurred on October 16, 2001 at 01:23 UTC, when the spacecraft flew within 184 km of the satellite surface (Figures 5a, 5b). This south polar pass was the second closest flyby of Io by the Galileo spacecraft, and the next to last for the GMM tour. The flyby was less than 3.5 km off target (78.6 deg S. latitude, 224.3 deg W. longitude) in the B-plane, and 0.7 seconds off in time of flight. This aimpoint delivery within approximately one sigma of the target resulted in a smaller post-encounter maneuver than had been planned, thereby increasing the end-of-mission propellant margin to 2.4 kg. The Io 32 encounter sequence began at 02:00 UTC on October 14, 2001, continuing for 15 days until October 29, 2001 at 02:00 UTC. This longer encounter period was designed to allow fields and particles instruments to collect continuous real-time science for 12 days. Perijove range for this encounter was a mere 5.8 R_J.

The encounter activities began with a standard calibration activity for the Photopolarimeter Radiometer (PPR) instrument, followed shortly by a 5-hour long series of observations of the turbulent north polar vortex region of Jupiter's atmosphere, along with an additional observation of the remaining white oval in the southern hemisphere. This storm has been the lingering result of several white ovals, which have merged

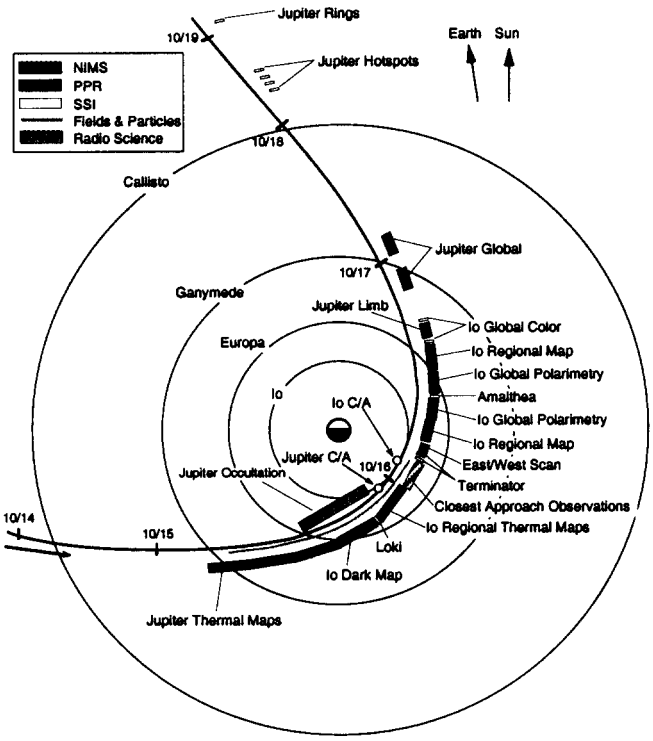


Figure 5a. Io 32 Encounter Trajectory

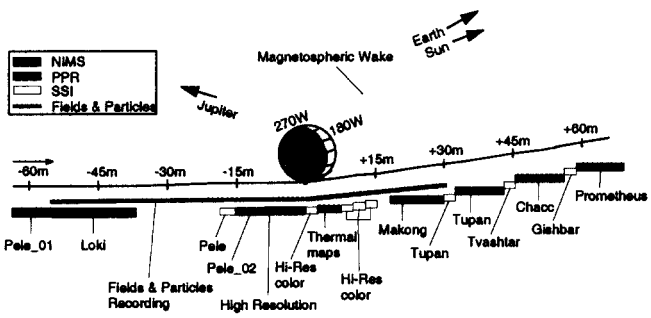


Figure 5b. Io 32 Flyby Geometry

together during the life of the Galileo mission, and has been a focus of repeated study in each encounter. PPR began collection of Io data while viewing the dark side of Io (in eclipse) to map surface temperatures. While still in the dark, PPR captured several hour-long high-resolution temperature maps of the northern hemisphere, including the Colchis Caldera, Loki, Daedalus, and Amatarasu, and Babbar Patera and Ra Patera in the southern hemisphere. During the closest approach to Io, PPR looked directly down on the satellite capturing temperature data for ten minutes, while the spacecraft flew by at 7.72 km/sec. Approximately one and one-half hours later, PPR performed a scan of Io's equatorial region and mapped a small portion of Io just south of the equator, looking at the polarization of light reflected from the surface. Three and one-half hours after Io closest approach, PPR conducted a global polarimetry map of the surface of Io, and wrapped up their observing for this encounter with two Jupiter limb scans and a global look at Europa in the dark. As done in most previous encounters, PPR finished with another calibration activity—however, this time tested the use of full radiometry mode for the first time since the filter wheel anomaly at Ganymede 1[2]. The use of this mode was a complete success, and it was employed in the Io 33 encounter.

Approximately one hour before Io closest approach, NIMS began to observe Io in the dark—looking at temperatures of the Pele and Loki hot spots and the surrounding areas. During the closest approach time frame, NIMS conducted several observations of thermal and SO_2 distributions in the south polar region of Io, as well as the Emakong Caldera, the Chaac Caldera, the Tupan Patera, and a new very large hot spot region discovered in the Io 31 encounter. This new discovery has shown us once again the short time scale in which geologic processes on Io can change the surface in macroscopic ways. The NIMS instrument also performed two longer regional observations of Io, mapping the distribution of SO_2 and hotspots from pole to pole. The final science observations for NIMS in Io 32 were two Jupiter global maps.

The Solid State Imaging (SSI) instrument had a successful encounter as well. With the loss of almost all Io observations by SSI in the previous encounter[6] due to the BLS anomaly (See Section 4.1), the goal was to maximize the chances that SSI would successfully obtain Io images in this encounter, hopefully recovering lost opportunities in previous encounters. A fast version of the SSI PCR was placed as often in the sequence as possible, and the erase mode function was disabled in the flight software. In addition, the fast reload SSI PCR was made conditional in the sequence—meaning it would only occur if in fact the SSI instrument was in an anomalous state. This approach appears to have worked flawlessly, as all SSI images were received during this encounter. These observations included the highest resolution look at Loki on the limb (See PIA02595 in Appendix), eclipse images of the Pele volcano with 30 meter/pixel resolution, and a high resolution look at Telgonus Scarp (See PIA02597 in Appendix), which was planned but lost in the Io 25 encounter. Further observations of Io included high-resolution images of the lava channels in the Emakong region, a look at Tohil Mons near the terminator (to determine relative heights of features due to shadows (See PIA03600 in Appendix)), and broader context imaging at medium resolution of the Telgonus region (See PIA03528 in Appendix). SSI collected a medium-resolution view of the Tvashtar Catena. This site was the focus of activity during the Io 25, Io 27, and Ganymede 29. The loss of the SSI images in Io 31, when the spacecraft passed almost directly overhead, prevented a good look at Tvashtar at the time. Io 32 was the first look at the feature since the last large plume eruption seen late in 2000, and it appeared not to have been active in Io 32 (See PIA03529 in Appendix). Further Io imaging included the Gish Bar region; near-terminator views of Mycenae, Tohil Mons, Culann, Zamama, Volund, and several other newly studied paterae. The final images included a couple of full-disk, low resolution global color images to detect changes in

surface albedo and color patterns as well as plume activity on the limb, and covered several volcanic centers including Loki, Pele, Zamama, Isum, and Prometheus among others. An image was taken of Amalthea to improve the ephemeris for the Amalthea 34 flyby, followed by a Jupiter feature track series focused on the Galileo Probe entry site and a final look at the Gossamer Ring, wrapping up the encounter for SSI.

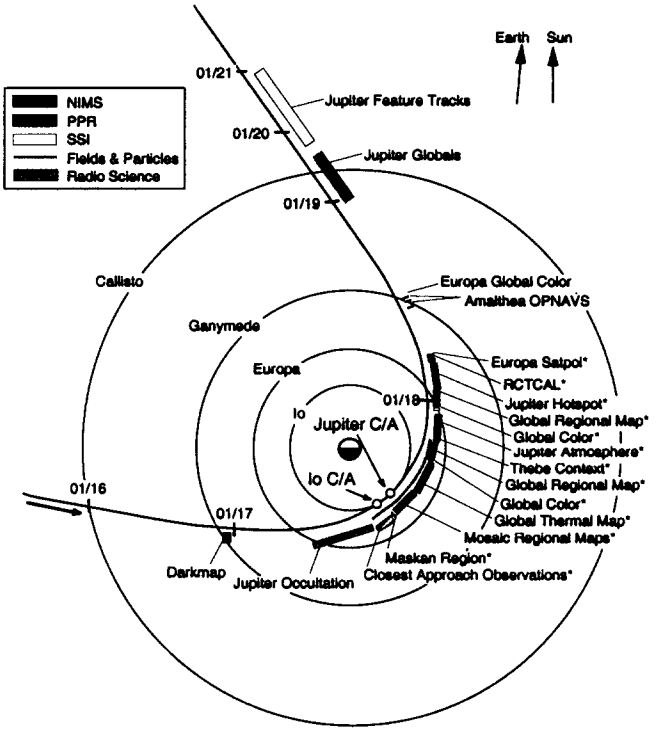
Fields and Particles collected a relatively large amount of data at the Io 32 encounter both on the tape recorder and in real-time. The main science objectives for the fields and particles suite of instruments was to study the inner magnetosphere, the transition region between the magnetosphere and the torus, and the satellite/magnetosphere interactions at closest approach to Io. Twelve days of low rate real-time science data were collected by all six instruments (Energetic Particles Detector—EPD, Heavy Ion Counter—HIC, Plasma instrument—PLS, Plasma Wave Subsystem—PWS, Magnetometer—MAG, and Dust Detector—DDS) and an additional three days were collected by MAG and DDS, in the afternoon sector of the magnetosphere for the first time. The recorded activities in this encounter included a nearly 2-hour transit of a region near the Io torus known as the Ramp region. This region is the transition between the relatively cold plasma of the background magnetosphere and the more energetic Io Torus, where the ion density and temperature of the environment increase sharply, and has not been fully explored. A two-and-one-half hour recording through the Io Torus as well as an additional recording for nearly one-and-one-half hours surrounding closest approach to Io captured higher resolution data of the satellite/magnetosphere interactions, complementing the continuous real-time data being collected simultaneously. Ten buffer dumps of real-time data to tape were needed for continuity in the data set over the twelve days of data collection.

Radio Science measurements for Io 32 included an Io gravity field measurement to better characterize the gravity field and refine models of Io's interior, and a Jupiter occultation experiment, observing the atmosphere of Jupiter and electron density profiles from 25,000 km above the one-bar level.

Playback of Io 32 data began with an initial SSI preview pass through the tape in order to verify that all SSI observations were captured successfully, and was followed by the standard two passes through all of the recorded data. With approximately 270 Megabits of science downlink capability, most of the data from the tape recorder was played back in the months following the encounter. Playback was terminated for approximately 3 days on November 13, 2001 due to the tape sticking (See Section 3.2), and was re-initiated on November 15, 2001. Playback terminated on January 14, 2001 in preparation for the Io 33 encounter activities.

5.2 Io 33

The final Io encounter (eighth flyby of the GMM) took the Galileo spacecraft to 101.5 km above the moon's surface—



* Indicates observations lost due to anomaly. See Section 3.1.

Figure 6a. Io 33 Encounter Trajectory

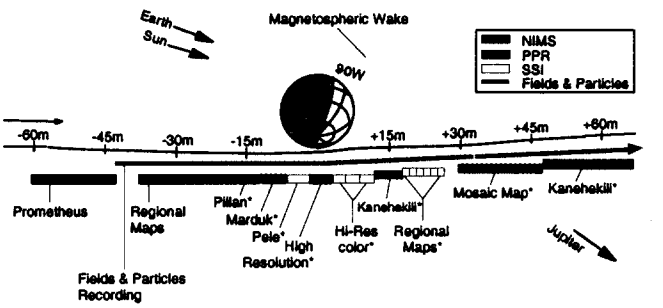


Figure 6b. Io 33 Flyby Geometry

the closest encounter to any Galilean satellite to date. The Io 33 flyby began at January 15, 2002 at 02:00 UTC, continuing for six days to January 21, 2002 at 13:00 UTC. Closest approach to Io occurred on January 17, 2002 at 14:08 UTC, targeting an aimpoint over Io of 43.6 deg S. latitude, 318.2 deg W. longitude (Figures 6a, 6b). The flyby was over the southern hemisphere, coming in on the darkside of Io, moving in the sunward direction. The majority of science activities for this final Io flyby focused on Io, but also included a number of Jupiter observations as well as extended real-time science data collection beyond the encounter period for a total of just over sixteen days. Perijove range for this encounter dove to 5.5 R_J.

After beginning the collection of fields and particles real-time science data at the start of the encounter period, the observations for Io 33 began with a standard PPR calibration activity. PPR then began the first Io observations, looking for thermal emissions from the dark side of the satellite. Following

an Earth occultation by Jupiter, PPR took a thermal map of the Prometheus volcano in the dark, an east/west scan along the equator of Io, and a look in the dark at the Marduk hotspot.

Fields and Particles instruments began what was to be a five-and-one-half hour stretch of continuous recording around the time period of Io's closest approach. It was designed to capture the very active upstream Io torus, including the ribbon region which is very energetic, looking at temporal changes between the cold torus and warm torus—a region very difficult to observe from the ground. Five minutes into this recording, approximately 28 minutes prior to closest approach, the spacecraft experienced a safing event (See Section 3.1), causing the loss of this and all further Io recorded observations. Further Io nightside observations were planned for PPR and SSI prior to closest approach to Io, as well as a large number of medium and high resolution observations of several Ionian features—Kanehekili, Mbali, Tholi, Gish Bar, Masubi and Hi'iaka to name a few. Also lost were two NIMS mosaic observations, several Io global observations for both NIMS and SSI, a view of the small moon Thebe, two Europa PPR observations, and all of the remaining Jupiter PPR observations.

The spacecraft was recovered and a new sequence restarted in time to acquire the second of two planned Amalthea ephemeris update images. Following this, SSI acquired a color image of the Jupiter-facing hemisphere of Europa—the last for the Galileo mission. Due to the recovery efforts of the flight team, the SSI instrument was able to complete a long observation of Jupiter atmospheric features, running 26 hours in duration. Eighteen observations, each 5 minutes in length, captured a turbulent region west of the Great Red Spot, a site of past thunderstorm activity. There was no evidence of any BLS anomalies in this encounter and no SSI PCRs were executed by the onboard sequence.

NIMS was able to salvage three Jupiter global observations—full-disk multicolor maps of Jupiter to study cloud morphology—making up a final global mosaic for the GMM. The EUV experiment began its final Lyman-Alpha sky background study, which will last until the end of the Io 33 orbit, finishing just 11 days prior to the Amalthea 34 encounter. The fields and particles instruments were able to collect further real-time science until January 26, 2002, including buffer dumps of data to tape during times of no downlink coverage.

Prior to the earth occultation by Jupiter, the radio science team began a 20-hour long Io gravity field experiment, centered around closest approach to the satellite. The experiment was not affected by the spacecraft safing, and the receivers appear to have remained in lock almost continuously. A Jupiter occultation experiment occurred in the middle of the gravity experiment, with telemetry commanded off for 2 hours and 42 minutes in order to study Jupiter's atmosphere at the northern latitudes.

Playback initiated on January 27, 2002 after completion of the real-time science campaign. With three tracks of recording lost during the Io 33 encounter and nearly 150 megabits of science capability, the playback strategy included the return of additional Io 32 data still remaining on the tape. Two passes were made through the replay of additional Io 32 data, with three passes through the Io 33 data. Due to resource constraints on final processing of remote sensing data, playback was set up to allow only remote sensing data to be played back first. After all the data for Io 32 and Io 33 were downlinked, playback was terminated on March 17, 2002 and a final calibration sequence for SSI and NIMS was executed. These data were then immediately played back between March 20, 2002 and March 31, 2002, when playback was then terminated once again. This marked the completion of remote sensing science operations for the Galileo spacecraft.

6. Preparation for Amalthea

In November of 2002, Galileo will execute a close flyby of the small inner moon Amalthea, and will approach to within 1 R_J of Jupiter's cloud tops. During a nine hour passage inside Io's orbit and through Jupiter's inner magnetosphere, the orbiter will be exposed to levels of radiation almost double those experienced during Jupiter Orbit Insertion in 1995. Given the total radiation dosage absorbed by Galileo and the spacecraft's age, this represents a high-risk endeavor. However, the potential payoff is equally high:

- A high-resolution sample of the inner radiation belts of Jupiter, including possible detection of whistler mode waves. Galileo will be flying through the region where synchrotron emissions are produced and will make measurements in a region of "dusty plasma" which may have similarities to conditions in nascent planetary systems.
- A refined estimate of Amalthea's mass and density and an estimate of its density distribution.
- Direct measurements of dust particles in the gossamer ring.

There are four major challenges posed by the extreme radiation conditions anticipated for the Amalthea flyby. In approximate order of concern these are:

- Maintaining attitude knowledge during the time when the star scanner will be blinded by radiation (up to seven hours) and with gyro electronics that are known to be vulnerable to radiation.
- The potential for multiple despun bus power-on reset (POR) events[4] (See Section 3.1).
- A DMS sticking event, similar to the one in April 2002 (See Section 3.2).
- Hardware subsystem failures caused by SEUs or permanent bit-hits. Such an event occurred in a processing buffer prior to Io 24 and significantly threatened that encounter[5].

The first and third concerns were addressed prior to the Io 24, Io 25, and Io 27 flybys (the first of the extended mission)

in 1999[4] and much of what was learned from investigations then is being applied to the current challenge. However, the state of the spacecraft has changed and the Project budget (and thus its staff and resources) are more constrained. Below, we describe each concern in more detail, along with the strategies that are currently being pursued to mitigate them.

During passages inside of ~15 R_J, standard operating procedure since Io 24 has been to use a single bright star for attitude determination (OSAD) and to minimize damage to gyro electronics by turning them off. These electronics are vulnerable to radiation[3,4], but powering them off appears to minimize the effects. The use of OSAD has been effective, but is limited by the relative intensity of the star as compared to background radiation levels. If those levels are high enough, the scanner can either fail to identify the target star or may recognize a radiation "hit" (i.e. random fluctuation above the background) as the target star. Although protective measures have been put into place to prevent the spacecraft from reacting to erroneous attitude information (e.g., disabling of autonomous pointing corrects), false data could still be fed to the science instruments. Since several instruments use attitude information in their onboard processing for real-time data, this could result in no useful real-time science data. Similar concerns exist with regard to use of gyros only for attitude determination. In addition, the known vulnerability of gyro electronics raises the concern of an outright hardware failure.

We are currently pursuing two strategies to mitigate attitude maintenance concerns. The first is to place OSAD in a "hibernation" mode at some point inside Io's orbit, keeping it there during passage through the region of intense radiation. Hibernation would be accomplished by altering AACS flight software parameters such that (a) the software will fail to recognize the OSAD star or any radiation "hit," and (b) set persistences such that the attitude estimation algorithm simply propagates the spacecraft spin rate and pointing through time. Key remaining issues are the robustness of this method to radiation hits and the accuracy of the hibernated attitude estimate after several hours of recalculation and rounding errors.

The second strategy is the possible use of a gyro-based attitude estimate. Although the electronics are known to be vulnerable to radiation, that issue may be mitigated by keeping the scan platform and stator fixed in an inertial frame. By minimizing torques on the gyros we will also minimize mis-estimation. Remaining issues include the effects of outright failure of the radiation-affected portion of the electronics and the accuracy of gyro-based estimates after several hours.

The final strategy for the flyby may be a two-layered one, in which we plan to fly the encounter on gyros, but have configured AACS such that the hibernated OSAD option is running and available in the event of a fault or failure of the gyro-based estimate. A third potential option is use of the sun acquisition sensor. However, this option has been accorded a lower priority due to resource constraints and the occurrence of an hour-long solar occultation by Jupiter near perijove.

Despun bus PORs were first seen during interplanetary cruise. They resurfaced in a radiation-induced form in 1998[3], but their effects were rendered benign by a flight software patch in 1999[4]. A new manifestation of this type of event cancelled the Io 33 flyby sequence (See Section 3.1). We are working toward a change to the original patch that would allow flight software to recognize an Io 33-like event as it does other despun bus PORs. Implementation and testing of this fix has a priority second only to maintaining Galileo's attitude during the A34 flyby.

Three additional strategies are either in work or being considered for the kind of risk posed by despun bus PORs. The first is to build a nominal command sequence for the encounter that is as robust as possible. The second is to make appropriate preparations for a ground-commanded recovery in response to a safing event. The third is to prepare an autonomous sequence that is stored on board and to be executed only in the event of a safing occurrence. The first two represent standard procedure for all encounters since Io 24. The third is a higher risk/higher payoff strategy that is in line with the extreme conditions of the Amalthea flyby. Each is discussed in the following.

A robust sequence design includes both spacecraft and science instrument commanding. This means using standard commanding (e.g., library sequences), making the sequence as standalone and transparent as possible, minimizing mode changes, and allowing for rapid adaptation. This latter strategy includes consideration of potential late changes to the sequence (within a week or so prior to uplink) as well as truncation, modification, and uplink of a modified command sequence in response to a safing event.

Science strategies for Amalthea 34 were designed with contingency in mind, balancing complexity with the science priorities. The highest science priorities for the flyby are the study of the innermost magnetosphere of Jupiter, capture of whistler mode waves by the PWS instrument, and Amalthea gravity measurements. Those instruments which cannot collect real-time science and recorded data simultaneously, have to balance the risk of a tape recorder failure against the risk of safing in the high radiation environment. Using record mode provides more robustness in the event of safing, because the science data could continue to be recorded without full recovery of the spacecraft. On the other hand, relying on record mode increases the risk of data loss due to a DMS failure. Ongoing discussions of this issue will continue through the summer of 2002. Likely strategies include gathering recorded data on the inbound portion of the flyby, and real-time science only on the outbound part (or vice-versa). An additional strategy built in to the baseline plan is to record more than the available four tracks of tape (i.e., overwrite data recorded earlier in the encounter with higher priority data on the outbound leg). Although the spacecraft tape recorder remains an area of concern, efforts are focused on restoring the recorder to its

nominal operability rather than generating an automated or rapid response to another tape stick event.

Preparations for ground response to safing events involve standard command packages to recover the spacecraft and modified science sequences to acquire a minimal set of observations. In practice, the experienced Galileo flight team has managed to identify breakpoints in command sequences that allow for rapid creation (in real-time) of a truncated sequence and uplink to the spacecraft in time to recover useful science observations—all dependent upon having a safing event occur some number of hours prior to the beginning of the truncated sequence. Such a strategy was successful during the Io 24 and 25 encounters[5]. However, it was insufficient to deal with the timing of the Io 33 safing event, which happened 28 minutes prior to Io closest approach. A potentially more robust strategy is to program an onboard response to a safing event that will execute a standard, simplified set of observations.

In addition to the well-understood conditions that follow a despun bus POR, other potential causes of safing are under consideration. Previous work done in preparation for the 1999 Io flybys[4] was unable to identify any components that were particularly likely to undergo sudden failure due to radiation exposure. A stuck bit somewhere in processor memory or storage (the cause of safing at Io 24) is a possibility, but can occur anywhere and (potentially) at any time. We are currently reviewing the fault protection responses that are in flight software. Those that can be modified or removed without significantly adding to the risk of data loss will be considered. However, the most effective strategies for dealing with unpredictable hardware failure are likely to be robust sequence design, and standard preparations for a ground-based recovery as described above.

7. Risk Management Strategy

A risk management strategy to meet planetary protection requirements for end of mission was developed prior to Io 32 because of dwindling resources, continued radiation soaking, and time criticality of decisions. Successful flybys of Io 32 and Io 33 from a spacecraft health, resources, and navigation point of view allowed the project to meet the nominal end of mission requirements without having to invoke contingencies.

Of significant concern to the ability to meet the nominal mission plan was spacecraft control after the large dose of radiation at the Amalthea 34 perijove passage. Addressing that concern, the planned tour was designed to use the gravity assist at Io 33 to place the spacecraft on a ballistic Jupiter impact trajectory before the Amalthea flyby. If the Io 33 delivery had been significantly off-nominal, a maneuver would have been required to correct the trajectory. As it was, the navigation delivery error was within one sigma at 2.4 km off in B-plane and 5 seconds off in flight time and the post-encounter maneuver was canceled.

The risk management strategy focused on spacecraft failures that could affect the flight team's ability to perform a maneuver to guarantee the impact trajectory. A fault tree analysis was used and risk items ranked in terms of (1) likelihood of occurrence and (2) impact to the ability to control the spacecraft path. Mitigation actions or contingency plans were identified and put in place whenever possible within the available resources and time. Significant faults fell into two broad categories: spacecraft health and remaining propellant.

Spacecraft failures that could preclude a maneuver include loss of hardware required to execute maneuvers such as telecom uplink, command and data control, attitude control electronics and detectors, and propulsion electronics and thrusters. A second area of concern was the possibility of a radiation induced memory cell failure in one string of the onboard computer required to execute a maneuver. In the case of a single-string hardware problem, backup solutions exist but require flight software patches to execute an impact-targeting maneuver. Even in redundant systems, switching to back-up, uncalibrated hardware would require careful analysis before using it. Workarounds to hardware failures would have required the targeting maneuver, if needed, to move later, possibly to a few days before Amalthea 34 closest approach. Resources did not permit a priori preparation of pre-built recovery actions for each failure mechanism.

Propellant margin (PM), defined as the amount of usable propellant remaining at the end of the mission in a 90 percent case, was of concern upon approach to Io 32. For the purposes of this definition, end-of-mission is the final targeting maneuver for an Amalthea 34 gravity experiment. In terms of managing risk, however, the primary concern was to guarantee sufficient propellant to ensure an impact trajectory for Jupiter 35. As of the Io 32 apojove maneuver, PM was not considered a significant risk to accomplishing the nominal mission. If, however, the PM had become negative after Io 33, propellant could be made available by abandoning the Amalthea 34 gravity experiment or by selecting a new trajectory that required less propellant expenditure but which still targeted a Jupiter impact.

8. Summary of Scientific Discoveries from Galileo's Extended Mission

Since the end of Prime Mission in December 1997, Galileo has returned a valuable legacy of data and scientific discoveries. Many of the new findings were the result of careful planning or the extraordinary efforts needed to continue to operate a spacecraft in the harsh conditions of near-Jupiter space. Others were more serendipitous—none more so than the discovery that Delta Velorum (one of the 50 brightest stars in the sky) is a variable star. In June 2000, Delta Velorum was temporarily "lost" to Galileo's star scanner, and later appeared to return to normal. Variable stars are not used for attitude reference, since Galileo's star scanner identifies a given star on the basis of brightness at a given position. Wondering if

Delta Velorum might be mis-identified in standard star catalogs, a member of the flight team forwarded a report of the incident to the American Association of Variable Star Observers. This resulted in a collaboration that showed that the star (actually a tight group of at least five stars) includes a pair of eclipsing binaries that mutually occult one another every 45 days.[10]

8.1 Jovian Atmosphere

Other than the Great Red Spot (GRS), the largest persistent storms seen over the past half-century have been three white ovals (FA, BC, and DE). Like the GRS, these features display anti-cyclonic motion and appear to be storms created by the upwelling of warm gases from deeper inside Jupiter. During 1998, two of the storms merged to form a single, new white oval feature. Again in 2000, the remaining two merged, leaving a single storm. Data obtained by Galileo's remote sensing instruments (SSI, NIMS, and PPR) show the best close-up views of these features before and after their mergers. They have been used to help understand the dynamics of this unusual event.

8.2 Rings and Dust

While it has been known since the Voyager flybys in 1979 that Jupiter possesses a ring, Galileo images of the ring system have demonstrated the full structure of the system and allowed scientists to unravel its origin[11]. In addition to a main ring, the rings include two faint gossamer rings and an inner halo region. The two gossamer rings and the main ring are strongly linked to the presence and characteristics of the four inner moons of Jupiter (Metis, Adrastea, Thebe, and Amalthea). The impact of meteorites and comets onto the surfaces of these moons supply the small dust particles that make up the associated ring. Tiny Adrastea's gravitational field is too weak to prevent most ejecta from any impact from escaping, providing the main ring with its primary source of material. Metis is located slightly inward from Amalthea; its orbit matches a gap in the main ring. The two gossamer rings also owe their natures to their associated moons, Thebe and Amalthea. The outer edges of the gossamer rings are associated with the radius of Thebe's and Amalthea's orbits, while the thickness of each ring matches the furthest excursion of each moon to the north and south of Jupiter's equatorial plane.

A different dust-related phenomenon was observed during Galileo's approach to Jupiter in 1995. Jovian dust streams are intense bursts of sub-micron-sized particles that are charged via interactions with UV light and then accelerated out of the Jovian system by Jupiter's magnetic field. They were first observed by the dust detector instrument on the Ulysses spacecraft in 1992 and were subsequently detected by Galileo's DDS for over a year prior to arrival at Jupiter. Over the past four years of Jupiter observations, DDS has patiently collected data in order to constrain the source of the streams; both Io and Jupiter's gossamer ring considered as potential sources. Careful analysis of data collected throughout Galileo's tour[12] reveals peaks in dust activity, which correspond with Jupiter's rotation (10 hours) and Io's orbital period (approximately 42 hours), demonstrating that the particles originate at Io and may reflect variations in volcanic activity.

8.3 Io

Io has represented the greatest challenge of Galileo's extended missions (thus far) and arguably its greatest success. Images, spectra, and fields and particles data have begun to elucidate the broad variety of phenomena ranging from styles of ultramafic volcanism and the SO_2 cycle to the structure and dynamics of Io's core and mantle to the varied and complex interactions between Io and the Jovian magnetosphere.

8.3.1 Io's Interior

Repeated flybys of Io in 1999-2002 permitted collection of Doppler acceleration data from which models of Io's gravity field have been created[13]. Io is confirmed to possess a metallic core and is at hydrostatic equilibrium. A metallic core is a potential source for an internally generated magnetic field (such as Earth's or Ganymede's). Measurements made by fields and particles instruments during the 1995 flyby of Io were inconclusive. In late 1995, a near-polar flyby (Io 25) was designed to test for the presence of an internally generated field. Due to a spacecraft anomaly, the required data were not obtained. Polar flybys in August and October 2001 (Io 31 and Io 32) showed that Io does not possess a significant internal field[14, 15]. This result has important implications for the state and dynamics of Io's interior, particularly the tidal heating mechanism that powers Io's volcanism.

8.3.2 Volcanism on Io

The ability to repeatedly visit Io and to monitor its activity has begun to make clear the extraordinary abundance of Ionian volcanic activity. From the estimates of a dozen or so hotspots based on Voyager data, to the dozens seen during Galileo's Prime Mission, we now know that there can be upwards of 100 actively erupting volcanic centers on Io at any given time. The abundance of this volcanism suggests that Io's crust is not primarily composed of sulfur and sulfur compounds, even though images and spectra show a surface dominated by these materials. Instead, Mg-rich (ultramafic) silicate rocks must also make up at least a substantial fraction of the crust.

Repeated close flybys allowed Galileo to collect data showing that lava temperatures may reach as high as 1,370°–1,650° C (2,600°–3,000° F). Such temperatures indicate the presence of ultramafic lavas not seen on Earth for at least 2 billion years. Lava temperatures today on Earth are typically 1,100°C (2,000°F) or less. Such temperatures are another indication that Io's interior is strongly heated by the gravitational tides caused by Jupiter. Such conditions may be more like the Earth's mantle two or three billion years ago, when the interior was much hotter. Io thus represents an

opportunity to study styles of volcanism that only exist on Earth in remnant form, as highly altered ancient volcanic rocks.

Perhaps the best single illustration of our new understanding of Io's volcanism is the series of observations made between 1999 and 2001 of the series of eruptive activity at Tvashtar Catena, near Io's north pole. The first high-resolution Galileo images of this feature were obtained during the Io 25 (November 1999) flyby. They show an active "curtain of fire" eruption occurring along a 20 km (12 mile) fissure, with lava reaching heights of a kilometer or more above the surface. Three months later, images of the same region taken during the Io 27 flyby showed deposits from November's activity as well as a fresh, 60 km long flow emanating from a separate eruptive center. Then during the Ganymede 29 flyby (December 2000), distant images obtained by Galileo and the Cassini spacecraft revealed an active plume eruption launching gas and dust as high as 400 km above Io's surface and centered on Tvashtar.

Such a sequence of volcanic events and styles would have been difficult to reconcile with our understanding of Io before Galileo's extended mission. The Voyager-era paradigm was that Ionian volcanism was due to melted and/or vaporized sulfur, which has a much lower melting temperature than do silicates. Volcanic plumes were thus the result of heating and vaporization of sulfur, which powered jet-like geysers of gas and dust. Io's plumes were thought to be most analogous to terrestrial geysers, where groundwater circulation near a subsurface magma body has created an extensive plumbing system, and eruptions occur at a single, stationary conduit. Earth-based observations and distant Io observations during Prime Mission had begun showing temperatures that seemed too high for molten sulfur; close flybys by Galileo demonstrated that the lavas were silicates and were at extremely high temperatures. In the same manner, observations of plumes by Galileo showed that our previous understanding was incomplete.

The key observations were made on the Prometheus plume, which had apparently moved 75 to 95 km to the west of its Voyager-era location[16]. High-resolution Galileo images made it apparent that the center of the plume had moved, but the eruptive center of high temperature lavas had not. This observation led to the understanding that plumes can be the result of lavas that have flooded and thus overlie sulfur-rich surface layers. The heat from the silicate lavas melts and/or vaporizes the sulfur substrate, while also capping and pressurizing it due to its weight. Plumes may occur as the high-pressure S and SO_2 erupt through rootless conduits[17], similar to eruptions that occur on Earth when molten lava interacts with surface or near-surface water or ice layers.

At both Prometheus and Tvashtar (as well as many other plume centers), significant outpourings of lava appear to be the cause of plume eruptions. In the case of Prometheus, volcanism appears to have been relatively steady over long periods, resulting in constant or near-constant plume activity. At Tvashtar, both the volcanism and plume activity appear to have been more episodic. The most recent observations of the region were obtained in August and October 2001. They show little or no additional lava flow activity and no evidence of ongoing plume eruptions (See PIA03529 in Appendix).

8.3.3 Ionian Mountains

The origin of Io's mountains is a long-running puzzle. These features rise as much as 16 km above the surrounding terrain, rivaling mountainous features on the terrestrial planets Earth, Mars, and Venus. They are distributed throughout Io's surface and do not appear to have been formed tectonically. It is clear that some dynamic process is responsible for their formation, however. Many of these high-elevation features display numerous faults and deposits indicative of slumping and gradual mass wasting into adjacent low areas (See PIA02597 and PIA03528 in Appendix).

On the terrestrial (rocky) planets and moons, mountains are formed either by volcanism (e.g., Olympus Mons on Mars, Hawaii on Earth), by convergent tectonic motion (e.g., Himalayas on Earth, Maxwell Montes on Venus), or by divergent tectonics (e.g., Basin and Range Province on Earth). However, the latter two of these are common only on Earth and Venus, where there appear to have been relatively large-scale horizontal movements of the crust. Io, in contrast, shows none of the signs of such motion.

Observations made by Galileo have begun to suggest an answer to the puzzle. The large amounts of material erupted onto Io's surface every year tend to create a compressional stress regime in Io's crust. In addition, there appears to be a correlation between volcanic paterae and mountains (See PIA03600 in Appendix). Paterae are oval-to-irregularly shaped depressions that display associated volcanic flows (either inside or emanating from them). Paterae near Ionian mountains are often associated with faults, as evidenced by linear rim segments. One possibility is that the paterae either create weakness in the crust, or take advantage of pre-existing faults to form. Such weak regions may represent the places where the crust fails under Io's compressional stresses, forming thrust faults and uplifting large crustal blocks to form mountains.

8.3.4 Io/Magnetosphere Interactions

Io's extraordinary volcanic activity is responsible for shaping more than just the surface of Io. It is also responsible for a tenuous atmosphere and exerts significant influence on the magnetosphere of Jupiter. The gases emitted in plume eruptions can rise as much as 400-500 km above Io's surface, where they become susceptible to charging by UV photons. These ions can then be swept up by Jupiter's powerful magnetic field, joining the plasmas resident in the Io torus. Plume gases also glow as they are struck by charged particles spiraling along Jovian field lines, creating the auroral glows observed

by Galileo and Cassini during several of Io's transits through Jupiter's shadow.

Measurements of the torus and the near-Io environment by Galileo's six fields and particles instruments have yielded detections of a variety of ionic species and have begun to reveal details of the transport of ions from near-Io space throughout the torus and the magnetosphere. Detections of intense cyclotron wave activity near Io have been seen in a number of flybys. These appear to be due to a variety of ionic species (SO_2+ and SO+, and possible detections of H_2S+, Cl-35(+), and Cl-37(+)) as they are being picked up and accelerated by the Jovian field. Variations in flyby geometry with respect to Io, the Io torus, and the Sun as well as variations in volcanic activity are all thought to influence measurements made during a given flyby. One striking result was that the size the pickup region extended to ~20 Io radii. This region was expected to extend only two Io radii from the moon. The large size of this interaction region helps to spread Ionian material throughout the Io torus and the magnetosphere in general. Normally, exospheric particles become ionized and are accelerated by the magnetic field, but remain trapped within a relatively narrow zone. Charge exchange with Io-derived neutrals allows these fast-moving particles to again move on ballistic trajectories until re-ionization occurs, spreading Ionian material over a much broader region of the Io torus.

One of the most unusual observations in near-Io space occurred during the I31 flyby (August 2000), when the spacecraft flew over the recently active Tvashtar region. Measurements by the PLS instrument indicate that Galileo flew through tenuous gases at or near the top of an active plume. With a flyby altitude of 194 km at closest approach, it was thought that the spacecraft might fly through the recently discovered Tvashtar plume (see above). However, images and spectra revealed that the Tvashtar plume was probably quiescent, and the source was a new (or previously unobserved) volcano some 600 km to the south and west of Tvashtar (See PIA03602 in Appendix). This represents the first in-situ measurement of an actively erupting volcano on a planetary body (other than Earth).

8.4 Europa

The primary goal of Galileo's first extended mission was the study of Europa. The multiple flybys of this moon have yielded a wealth of data on the surface morphology, composition, and surface properties. The primary finding for Europa—that it may contain a liquid water layer beneath its icy surface—was first suggested on the basis of images and magnetic field data obtained during Prime Mission. Data obtained during the extended mission have greatly strengthened the case for that proposition, and represent an archive of data that will help to both pose and answer the wide variety of scientific questions about Europa that will arise in the coming decades.

In one of the first significant moments in science for the 21st century, Galileo flew past Europa on January 3, 2000. Data obtained by the spacecrafts magnetometer definitively showed that Europa possess an induced magnetic field. The field is a response of a conductive material somewhere in the outer hundred kilometers or so of the moon. Although there are many possible conductive materials, most (e.g., gold, iron) are implausible in the amounts required. A good match to the observation is produced by a layer of water containing dissolved salts (e.g., similar to seawater). This observation is the strongest piece of evidence to date for the current presence of a liquid layer inside Europa.

Spectral observations have also revealed unusual chemistry in Europan surface materials. Both hydrogen peroxide and sulfuric acid and other sulfur compounds are present in detectable amounts. These compounds are likely to be the result (in part) of the radiation bombarding Europa's surface. In particular, the sulfur compounds are of interest because they appear to be associated with brownish deposits on the surface. Many of these are found in close association with linear faults and fractures, leading to the speculation that they could represent the products of water volcanism, and thus are indicative of the chemistry of a putative liquid layer.

8.5 Ganymede

With only two encounters in the extended mission (Ganymede 28 and 29), there is only one major discovery to report for Ganymede. Of the Galilean moons, Ganymede is perhaps most remarkable for its internally generated magnetic field, making it unlike Callisto, Europa, or Io. However, like Callisto and Europa, Ganymede also possesses an induced field. Magnetometer data from the Ganymede 28 flyby, when combined with data from earlier flybys, revealed two distinct signatures in Ganymede's overall field. One is due to the internally generated field, and the other to a conductive layer located within 300 km of Ganymede's surface. In addition, like measurements for Callisto and Europa, the data are consistent with a conducting layer composed of water and dissolved salts.

8.6 Magnetospheres

A major component of Galileo's study of the Jovian magnetosphere is its low resolution real-time survey. In the course of its 35 orbits of Jupiter, the six fields and particles instruments will have gathered tens of thousands of hours worth of data that map out nearly all sectors of the magnetosphere. During Prime Mission, data were obtained in the dawn sector through the midnight (magnetotail) sector at distances between 4.5 R_J and 150 R_J. The extended mission has allowed for coverage to continue from midnight through local noon (i.e., the region directly between Jupiter and the Sun), with several orbits crossing out of the magnetosphere's region of influence and into the solar wind. Analyses of this data are anticipated to contribute significantly to understanding the dynamics of the magnetosphere, the mechanisms by which

plasmas are transported throughout the system, and the mechanisms by which Io and the solar wind affect the system.

A major contribution toward these ends was presented by the results of joint studies obtained during Cassini's flyby of Jupiter in December 2000. The presence of two spacecraft with a full complement of fields and particles instruments allowed for unique measurements that have yielded the first clear picture of the interaction between a solar wind shock event and the Jovian magnetosphere. During the joint flyby, both spacecraft encountered the magnetopause just hours apart on the same day, despite being separated by over 100 R_J. Cassini was receding from Jupiter, and was "downwind" from Galileo, which was on its way outbound from its close approach to Jupiter. Careful comparison of the data from the two probes with magnetospheric models indicated that the magnetosphere at Cassini's location was significantly larger. Further, data from the probes indicated that a shock front in the solar wind had passed Galileo, but had not yet reached Cassini's position. Thus the measurements taken by the two probes allow for quantitative estimates of the response of the magnetosphere to changes in the solar wind.

During its approach to Jupiter, Cassini had previously measured earlier interplanetary shock events in the solar wind. Correlation with Galileo data has revealed that these shock events led to magnetopause crossing for Galileo once the shock events reached Jupiter. As seen by Galileo, the shock events compress the Jovian magnetosphere. Moreover, each compressional event is associated with distinct brightening of Jupiter's aurora and hectometric radio emissions that are generated by the aurora. These observations settle the question of the effect of interplanetary shocks on Jupiter's aurora.

9. End of Mission Plans

As the Galileo spacecraft is nearing the end of its illustrious career, it will continue to investigate key outstanding science questions concerning Amalthea and the inner Jupiter system before it is properly disposed of by a controlled impact into Jupiter. Figure 7 shows a timeline for the final phase of the Galileo mission.

The Galileo Millennium Mission concludes with the Amalthea flyby on November 5, 2002 06:19 UTC. No remote sensing is planned for this orbit. Mission operations will end January 2003 with the return of the Amalthea recorded data.

The end of Galileo's historic journey is scheduled for September 21, 2003 as the spacecraft plunges into the atmosphere of Jupiter (Figure 8). Disposal of the spacecraft, as mutually agreed upon by the Project and NASA Headquarters, is necessary for planetary protection purposes: a result of the mission's own success. Evidence supporting the existence of liquid water on Europa raises the possibility of life on that frozen moon. The planned destruction of Galileo removes any risk of forward contamination of Europa by an inadvertent impact of that moon if the spacecraft were left in

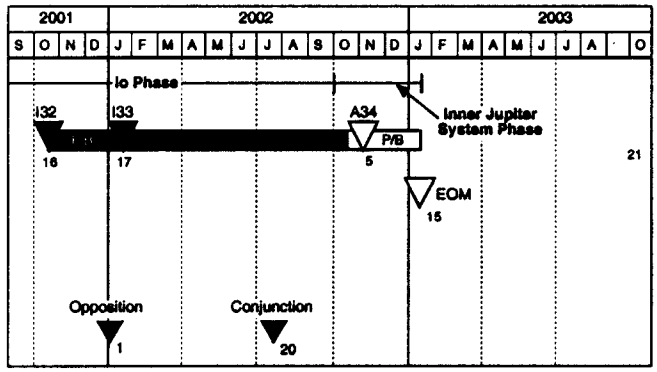


Figure 7. Galileo Final Phase Timeline

orbit.

If resources permit before the end of operations in January 2003, a science command sequence will be loaded onboard. This sequence will activate on approach to Jupiter and sample the inner magnetosphere for the last time as the spacecraft traverses the region inside Io's orbit down to the point it passes into the shadow of Jupiter.

10. Summary

Having already achieved outstanding success during its primary mission, Galileo continues to expand our horizons with world class science despite aging parts, diminishing resources, and absorbing a total radiation dose four times the design specification. The ability of the experienced and seasoned flight team to respond to anomalies and design workarounds is a major factor in the success of the past year

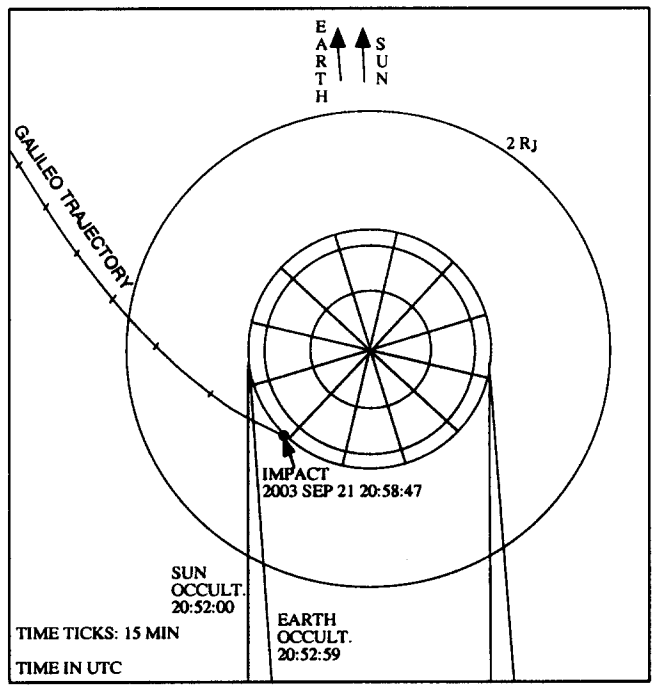


Figure 8. Galileo Jupiter Impact Trajectory

as the spacecraft performed its final two flybys of Io. Io 32 completed monitoring of the dynamic volcanism on that moon, whereas Io 33 achieved its navigation objective. Attention is now focussed on the final encounter of this historic mission as we prepare for the Amalthea 34 flyby and passage through the gossamer ring and inner magnetosphere.

11. Acknowledgments

The success of the Galileo Project results from the individual efforts of a large number of people. The Galileo Europa and Millennium Mission teams have persevered through many challenges to accomplish outstanding science results within limited resources. The work of the current team would not be possible without the efforts of team members from the past and of the science teams.

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Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

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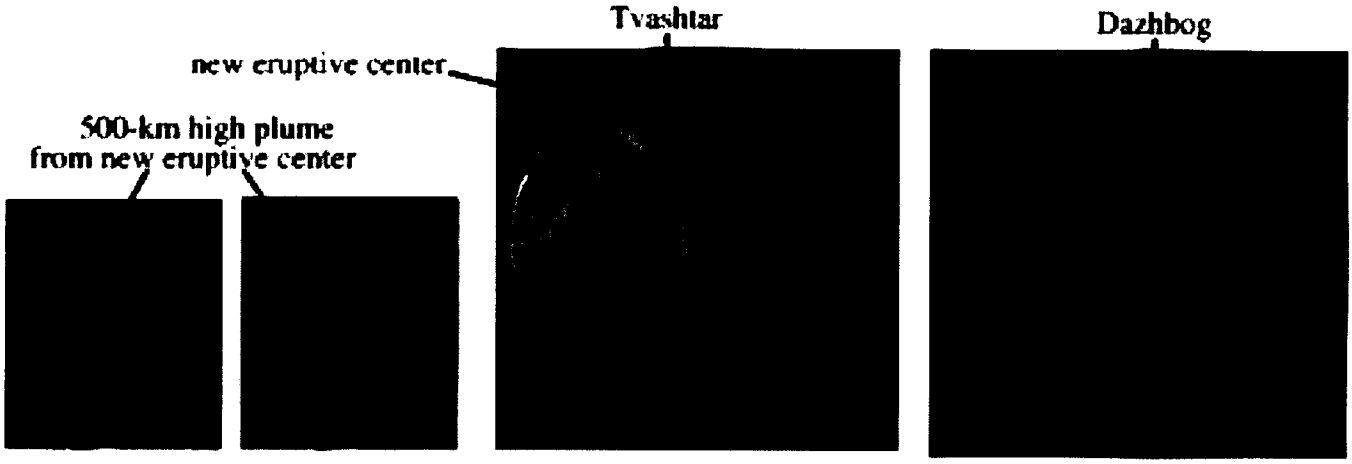

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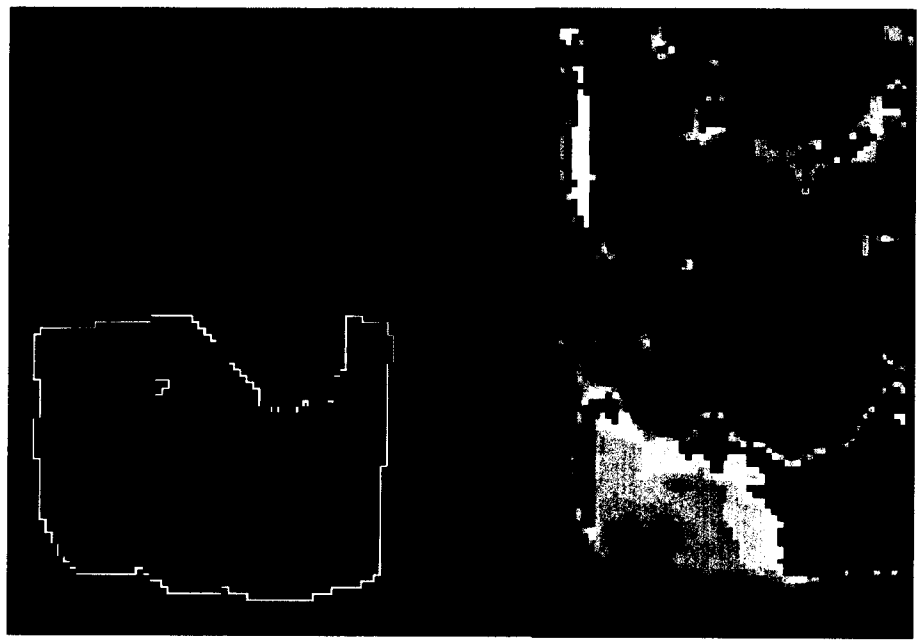

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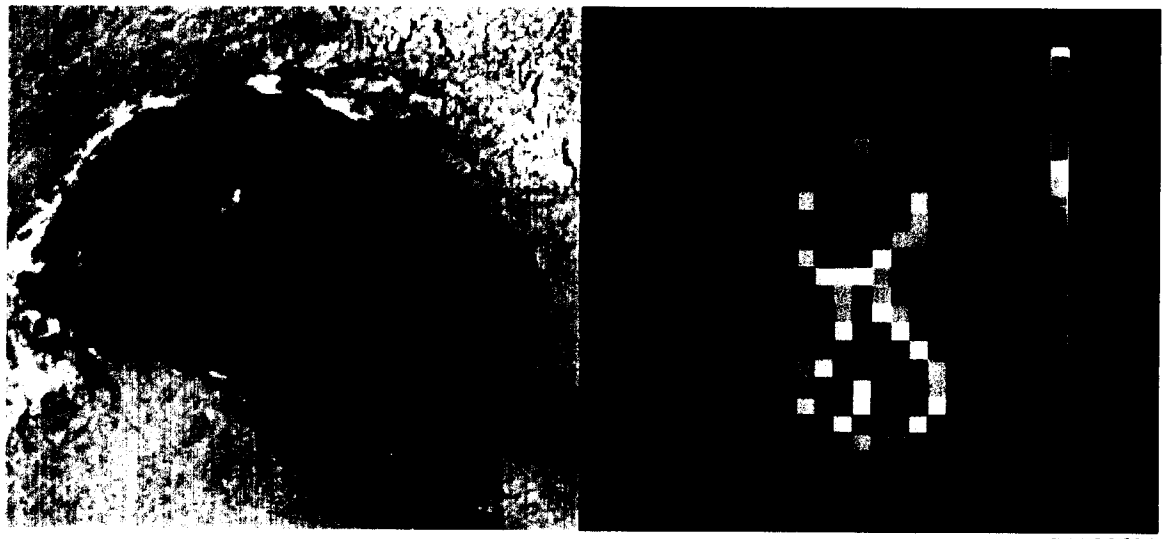


PIA03601

Northern Plume and Plume Deposits on Io

Io is about the same size as Earth's Moon. All four images have resolutions of 18 to 20 kilometers (11 to 12 miles) per picture element. Backlit views (left pair) show a giant volcanic plume as a bulge on the crescent edge of Jupiter's moon Io, and more fully lit views (right pair) reveal rings where sulfur-rich plume material has fallen back to the ground, in images captured by NASA's Galileo spacecraft in early August 2001.

During its Aug. 6, 2001, close encounter with Io, Galileo flew right through a space where a plume from the Tvashtar volcano near Io's north pole had been active when Galileo and Saturn-bound Cassini imaged Io seven months earlier. To see if the Tvashtar plume was still active in August, scientists used Galileo's camera to acquire images when the spacecraft was nearly on the opposite side of Io from the Sun, so that Io appears as a backlit crescent.

Tvashtar's plume did not show up, but another one did, rising from a previously undiscovered and still unnamed volcano about 600 kilometers (370 miles) south of Tvashtar. The left two images are color coded to reveal the faint outer plume. The bright inner plume rises about 150 kilometers (90 miles) high, and the top of the faint outer plume can be detected at 500 kilometers (310 miles) above the surface, making this the largest plume ever detected on Io. A portion of the plume with intermediate brightness extends north of the eruption's source vent. (The vertical lines, bright spots and short streaks in these two images are noise.)

One of the more fully illuminated color images of Io (second image from right) reveals a bull's-eye ring of new dark and light materials marking the eruption site. No obvious volcanic center had previously been seen at this location, 41 degrees north latitude and 133 degrees west longitude. The bright material of the new plume deposit overlies the red-ring plume deposit encircling the Tvashtar volcano at 63 degrees north, 123 degrees west. Tvashtar's ring deposit was first seen in Galileo images taken in late December 2000. Another new full-disc color image of Io (far right) reveals yet another new plume deposit near Io's north pole, encircling the Dazhbog Patera volcanic site. This red ring has a diameter of about 1,000 kilometers (620 miles), suggesting a plume height of about 300 kilometers (190 miles). This plume deposit was not present in January 2001, so it is evidence of a new eruption.

PIA02592

Io's Loki in Infrared: Hot Edge

High temperatures observed by NASA's Galileo spacecraft along the western edge of the Loki volcano on Jupiter's moon Io may indicate freshly exposed material at the shore of a lava lake.

Two temperature maps of the southern portion of Loki show hot (lower right) and hotter (upper right) features based on infrared-wavelength observations during an Oct. 16, 2001, flyby of Io. For context, they are shown beside a visible-wavelength picture (left) of the area taken during an earlier flyby.

Loki is the most powerful volcano on Io. It has been active since at least 1979, when it was discovered by NASA's Voyager mission. Loki's dark volcanic crater, called a caldera, surrounds a light-colored island, as seen in the camera image (left). Previous observations by Galileo's instruments have shown that active lavas and still-cooling lava flows cover the floor of the caldera. In contrast, the island is cold and has no volcanic activity except in a narrow dark region that may be a crack or valley. Current volcanic activity appears in the two temperature maps from Galileo's near- infrared mapping spectrometer instrument. The lower right image shows where the surface is glowing at an infrared wavelength of 4.4 microns, with the yellow-orange coding correlated to temperatures of about 360 degrees Kelvin (188 Fahrenheit) and the reddish coding correlated to temperatures of about 430 Kelvin (314 Fahrenheit). The upper right image is at a wavelength of 2.5 microns, with the white streak correlated to temperatures of roughly 840 Kelvin (1,052 Fahrenheit). Each picture element averages the characteristics of an area about 2 kilometers (1.2 miles) across; smaller patches may be hundreds of degrees higher.

PIA02595

Io's Tupan Caldera in Infrared

Tupan Caldera, a volcanic crater on Jupiter's moon Io, has a relatively cool area, possibly an island, in its center, as indicated by infrared imagery from NASA's Galileo spacecraft.

A thermal portrait of Tupan collected by the near-infrared mapping instrument on Galileo during an Oct. 16, 2001 flyby is presented on the right, beside a visible-light image from Galileo's camera for geographical context. The infrared image uses false color to indicate intensity of glowing at a wavelength of 4.7 microns. Reds and yellows indicate hotter regions; blues are cold.

The hottest areas correspond to the dark portions in the visible-light image and are probably hot lavas. The central region in the crater may be an island or a topographically high region. Parts of it are cold enough for sulfur-dioxide to condense.

Tupan, an active volcano on Io since at least 1996, was named for the Brazilian native god of thunder.

PIA03601

Collapsing Cliff at Telegonus Mensa, Io

These images of an area called Telegonus Mensa on Jupiter's moon Io, taken by NASA's Galileo spacecraft on Oct. 16, 2001, reveal a complex interplay of geologic processes.

Small, high-resolution frames (see below) have been set into the larger context mosaic, which has a resolution of 42 meters (140 feet) per picture element. The illumination is from the upper right and north is to the top of the mosaic.

A fracture runs northwest from the lower right corner of the mosaic into the amphitheater in the center of the frame. A high-resolution image along this fracture reveals that lava has erupted from it.

The amphitheater itself is the site of extensive erosion, as the cliff has slumped southeastward under the influence of Io's gravity. High-resolution frames (box) directly south of the amphitheater show another slumping cliff in detail (below). Flat tops of massive slump blocks — up to 6 kilometers (3.7 miles) long and 0.5 kilometers (0.3 miles) across — are illuminated by the Sun and cast shadows down the face of the cliff. Based on these shadows, Galileo scientists estimate that the cliff is 1 to 2 kilometers (3,300 to 6,600 feet) high. Just to the left of center, a series of landslides can be seen, the longest of which extends 4 kilometers (2.5 miles).

The mosaic is centered at 21.45 degrees south latitude and 124.8 degrees west longitude and is 67 kilometers (42 miles) across.

PIA03528

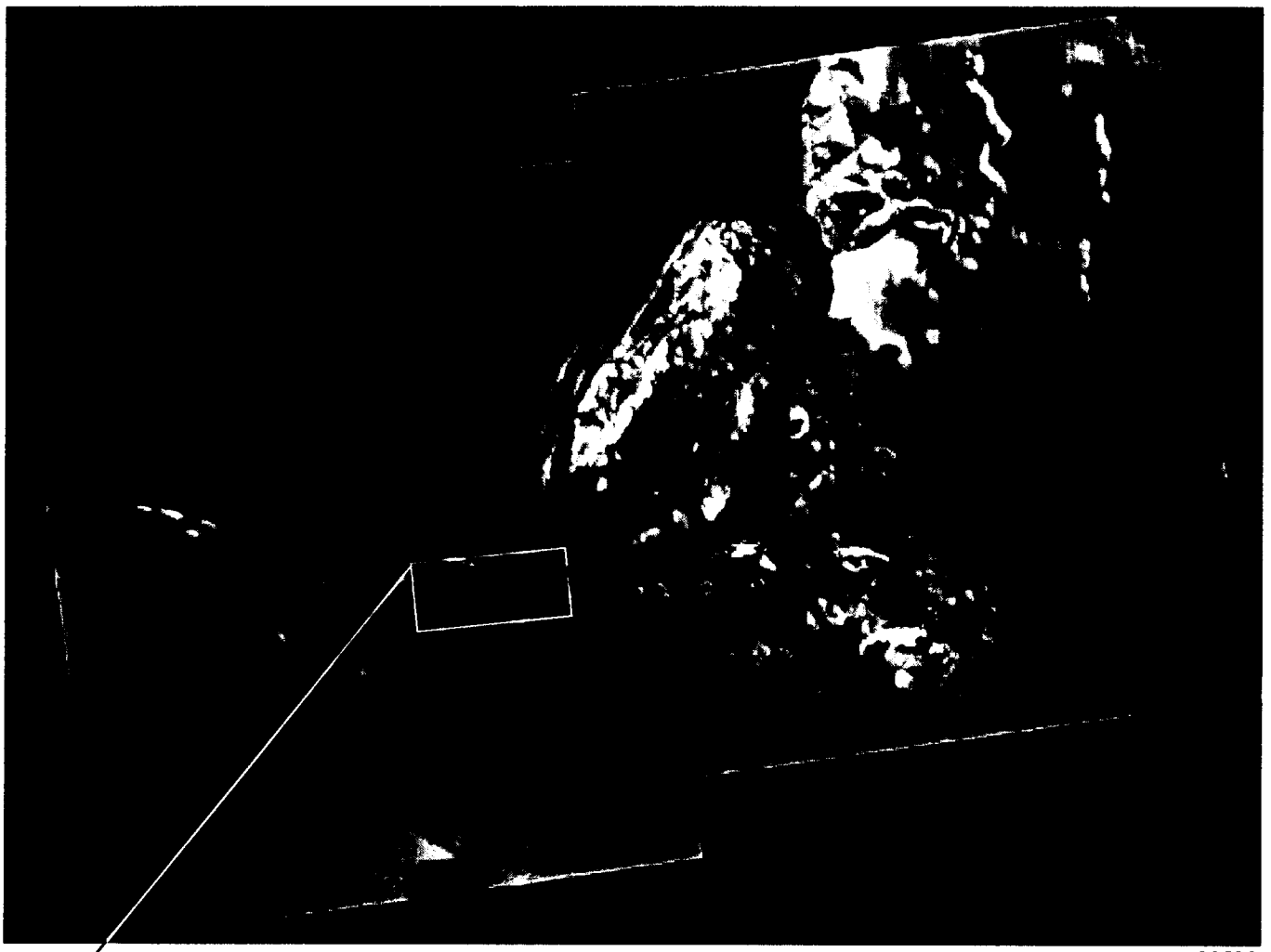
Slumping Cliff on Io in High Resolution

A cliff slumps outward in these high-resolution views that NASA's Galileo spacecraft captured of the edge of a mountain named Telegonus Mensa on Jupiter's moon Io.

When Galileo flew near the south pole of Io in October 2001, scientists targeted this cliff to study the process of erosion. Water and wind cause most erosion on Earth, but Io has neither surface water nor an atmosphere. The cliff is slumping due to gravity.

This image has a resolution of 10 meters (33 feet) per picture element. Galileo's camera took it from a distance of about 1,000 kilometers (620 miles). The larger image (top) sets context with a resolution of 40 meters (131 feet) per picture element and was taken from a distance of about 4,200 kilometers (2,600 miles). North is to the top and the Sun illuminates the surface from the upper right.

PIA02597



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PIA02597

Tall Mountain, Tohil Mons, on Io

Dramatic shadows across a mountainous landscape on Jupiter's moon Io reveal details of the topography around a peak named Tohil Mons in this mosaic created from images taken by NASA's Galileo spacecraft in October 2001.

Tohil Mons rises 5.4 kilometers (18,000 feet) above Io's surface, according to analysis of stereo imaging from earlier Galileo flybys of Io. The new images, with a resolution of 327 meters (1,070 feet) per picture element, were taken when the Sun was low in the sky, producing informative shadows. North is to the top and the Sun illuminates the surface from the upper right. The topographic features revealed include a very straight ridge extending southwest from the peak, 500- to 850-meter-high (1,640- to 2,790-foot-high) cliffs to the northwest and a curious pit immediately east of the peak.

Major questions remain about how Io's mountains form and how they are related to Io's ubiquitous volcanoes. Although Io is extremely active volcanically, few of its mountains appear to be volcanoes. However, two volcanic craters do lie directly to the northeast of Tohil's peak, a smaller dark-floored one and a larger one at the very edge of the mosaic. Furthermore, the shape of the pit directly east of the peak suggests a volcanic origin. Galileo scientists will use these images to investigate the geologic history of Tohil Mons and its relationship to the neighboring volcanic features.

The image is centered at 28 degrees south latitude and 161 degrees west longitude.

PIA03600

Galileo's Last View of Tvashtar, Io

This mosaic of Tvashtar Catena on Jupiter's moon Io, taken by NASA's Galileo spacecraft on Oct. 16, 2001, completes a series of views depicting changes in the region over a period of nearly two years. A catena is a chain of volcanic craters.

Streaks of light and dark deposits that radiate from the central volcanic crater, or "patera," are remnants of a tall plume that was seen erupting in earlier images.

This image and the others from November 1999, February 2000, December 2000, and August 2001 were all taken to study aspects of this ever-changing, extremely active volcanic field.

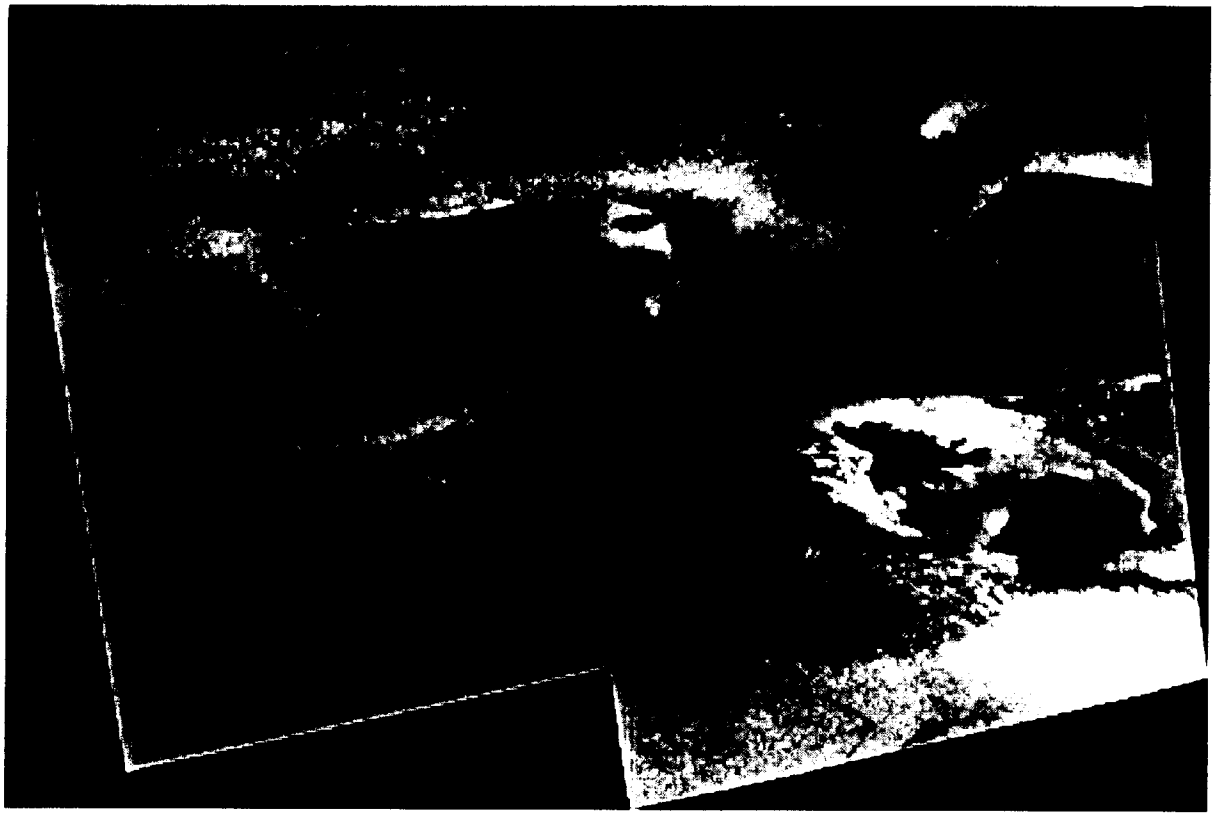
Tvashtar is pictured here just 10 months after both the Galileo and Cassini spacecraft observed the eruption of a giant plume of volcanic gas emanating from it. The plume rose 385 kilometers (239 miles) high and blanketed terrain as far as 700 kilometers (435 miles) from its center.

Tvashtar has erupted in a variety of styles over the course of almost two years: (1) a lava curtain 20 kilometers (12 miles) long in the center patera, (2) a giant lava flow or lava lake eruption in the giant patera at far left, and (3) the large plume eruption. Therefore Galileo scientists expected that the lava flow margins or patera boundaries within Tvashtar would have changed drastically. However, the series of observations revealed little modification of this sort, suggesting that the intense eruptions at Tvashtar are confined by the local topography.

North is to the top of the mosaic, which is approximately 300 kilometers (186 miles) across and has a resolution of 200 meters (656 feet) per picture element.

PIA03529

PIA03600



PIA03529

Io in Infrared with Giant Plume's New Hot Spot

Nine previously unknown volcanoes have been discovered from this infrared image of Jupiter's moon Io, acquired by NASA's Galileo spacecraft on Oct. 16, 2001. The infrared image, on the right, serves as a thermal map to a section of Io's surface from pole to pole. An image from Galileo's camera showing the same face of Io (left) is included for correlating the heat-sensing infrared data with geological features apparent in visible wavelengths. The infrared image uses false color to portray the intensity with which the surface glows at the invisible wavelength of 5 microns, as observed by Galileo's near infrared mapping spectrometer instrument. White, reds and yellows indicate hotter regions; blues are cold. The resolution varies from 24 to 39 kilometers (15 to 24 miles) per picture element.

Some of the hot spots visible in this image were not seen in a similar infrared image taken just 10 weeks earlier of an overlapping section of Io. Three sites of major activity in the images are Prometheus, which is a bright spot at center left; Amirani, which is an elongated feature in the upper right; and the site where a giant plume was erupting in August, which is the bright spot near the top of the image.

PIA03528

A New Hot Spot on Northern Io

NASA's Galileo spacecraft has returned infrared imagery of a new hot spot on Jupiter's moon Io that was the source of a towering plume in August 2001, indicating a sulfur-dioxide concentration that may have been fallout from the plume.

Galileo's near-infrared mapping spectrometer captured the image on the left during an Oct. 16, 2001 flyby of Io. The resolution is 15 kilometers (9 miles) per picture element. Coloring indicates the intensity of glowing at a wavelength of 4.1 microns. Yellow, red, and white represent high temperatures. Black is where the near-infrared glow was so intense the image was saturated. Greens and blues are cold. The visible-light image on the right was obtained by Galileo's camera in 1999, before any volcanic activity was seen at this site. The first sign of activity came in August 2001, when Galileo detected an infrared hot spot and the tallest volcanic plume ever seen at Io.

The dark blue band north of the hot spot in the new infrared image represents a concentration of sulfur-dioxide, which has a strong signature in the infrared. The sulfur-dioxide is thought to be from the fallout of the plume. The image shows high temperatures corresponding to yellow flows in the center of the visible-light image, and from a small caldera at the 8 o'clock position.

PIA03602

Nighttime Temperatures on Southern Io

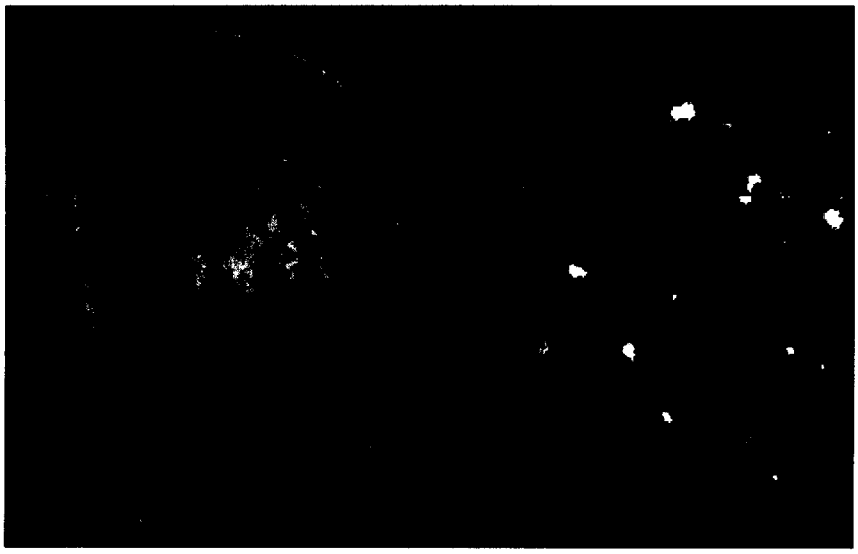
Nighttime temperatures in the southern hemisphere of Jupiter's moon Io, mapped here with data from NASA's Galileo spacecraft, give hints about the textures of surface materials, as well as the locations of volcanic hot spots.

The photopolarimeter/radiometer instrument on Galileo collected the information during an Aug. 6, 2001 flyby of Io, yielding the most detailed temperature map yet for this region. Features are visible as small as 150 kilometers (93 miles) across. The temperature map is superimposed here on images from Galileo's camera, covering volcanoes Pele (Pe), Pillan (Pi), Babbar (Ba) and others. It extends southward almost to Io's south pole. The contour interval is 2.5 degrees Kelvin (4.5 degrees Fahrenheit), but contours above 110 Kelvin (minus 262 Farenheit) have been omitted to reveal the volcanic hot spots that produce these relatively high temperatures.

Some of the most interesting features on this map occur in the regions between the hot spots. The hot spot of the Pele volcano is surrounded by concentric temperature patterns that echo Pele's concentric rings of volcanic plume debris, which can be seen in full-color visible-light images. Close to the volcano, temperatures drop below 87 Kelvin (minus 303 Fahrenheit, among the coldest on Io), corresponding to a yellowish inner portion of material ejected from the volcano. A ring of higher temperatures, up to 105 Kelvin (minus 271 Fahrenheit), surrounds this cold area and coincides with an orange ring of volcanic debris seen in full-color visible- light images.

These concentric temperature patterns probably reflect variations in the texture of the deposits from Pele's volcanic plume, because textures affect the surfaces' ability to retain heat through the night. The yellow material may be exceptionally fluffy, so it cools quickly at night, while the orange material is more compact and better at retaining heat. Also of interest is the strange fact, first noted on Galileo's February 2000 Io flyby, that nighttime temperatures do not drop off significantly between the equator and the poles. Because the nighttime temperatures away from the volcanoes are probably largely determined by sunlight absorbed during the previous day, and the poles receive less sunlight than the equator, lower nighttime temperatures are expected at high latitudes, just as on Earth. Temperatures between the volcanoes are typically in the range of 90 to 100 Kelvin (minus 298 to minus 280 Fahrenheit) regardless of latitude.

PIA03603



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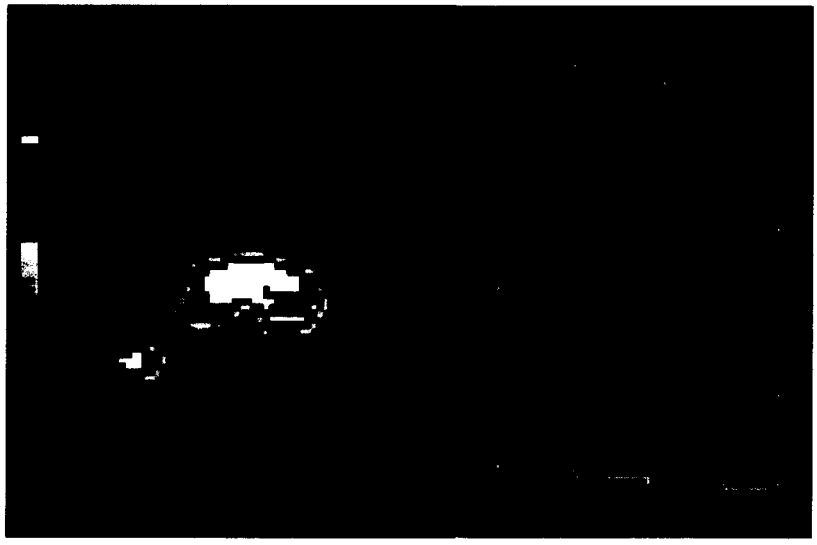

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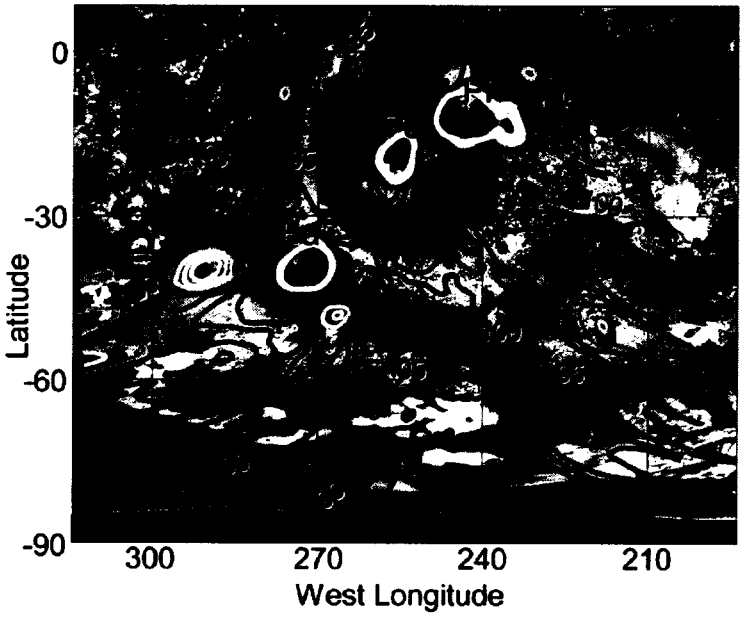

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