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Project Galileo Completing Europa, Preparing for Io

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PROJECT GALILEO: COMPLETING EUROPA, PREPARING FOR IO

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Abstract

Galileo has completed the Europa leg of the Galileo Europa Mission, and is now pumping down the apojove in each succeeding orbit in preparation for the Io phase. Including three encounters earlier in the primary mission, the total of ten close passes by Europa have provided a wealth of interesting and provocative information about this intriguing body. The results presented include new and exciting information about Europa's interactions with Jupiter's magnetosphere, its interior structure, and its tantalizing surface features, which strongly hint at a watery subsurface layer. Additional data concerning Callisto, and its own outlook for a subsurface ocean are also presented.

In addition the engineering aspects of operating the spacecraft during the past year are explored, as well as a brief examination of what will be the challenges to prepare for the Io encounters. The steadily increasing radiation dosage that the spacecraft is experiencing is well beyond the original design parameters, and is contributing to a number of spacecraft problems and concerns. The ability of the flight team to analyze and solve these problems, even at the reduced staffing levels of an extended mission, is a testament to their tenacity and loyalty to the mission. The engineering data being generated by these continuing radiation-induced anomalies will prove invaluable to designers of future spacecraft to Jupiter and its satellites. The lessons learned during this arduous process are presented.

1. Introduction

Galileo is now on the verge of completing its first decade in space, and well on the way to completing its fourth year in the Jovian system. Figure 1 shows the trajectory of the spacecraft during this decade, both during interplanetary cruise and during its extended stay in the Jovian environment. Since entering the Jupiter system in December of 1995, Galileo has completed its prime mission of four Ganymede, three Callisto, and three Europa encounters, and has gone on to complete the Europa and Callisto portions of the Galileo Europa Mission (GEM). Figure 2 shows the details of Galileo's Prime Mission and GEM orbits, including how the flyby of one Galilean satellite targeted the spacecraft for the next encounter.

Galileo closes out the past year with a mixed record on Europa encounters, and an ongoing record of complete success on Callisto. As of this writing, the GEM team was able to successfully complete two of three Europa encounters, and then followed it with four successful Callisto encounters. The Europa portion of the GEM was concluded with Europa 19 playback, ending May 1, 1999. The Callisto portion, designed to lower Galileo's periapsis down to the orbit of Io, began May 2, 1999 and will continue until the Io 24 encounter on October 10, 1999.

Radiation exposure during this extended mission continues to be the prime concern, as the spacecraft is expected to accumulate a total dose above the original design. This appears to have shown itself in several anomalies that have affected data return during the Europa portion of the mission. How the GEM flight team has successfully learned to deal

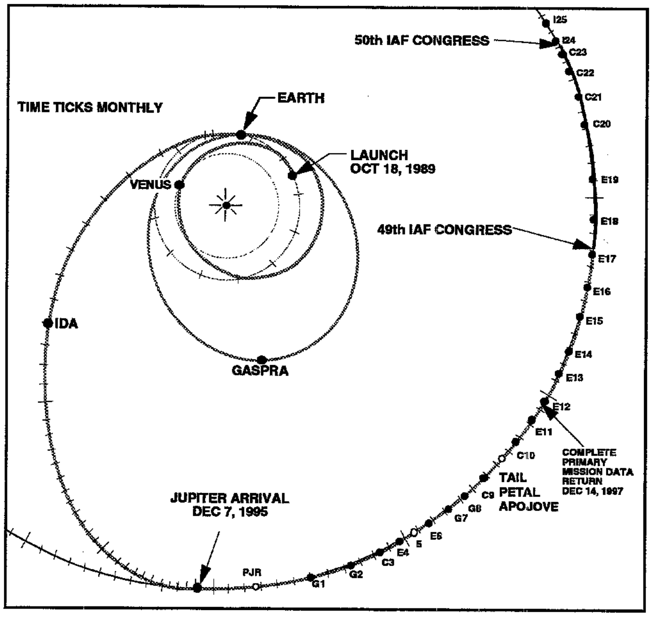

Figure 1. Heliocentric Progress

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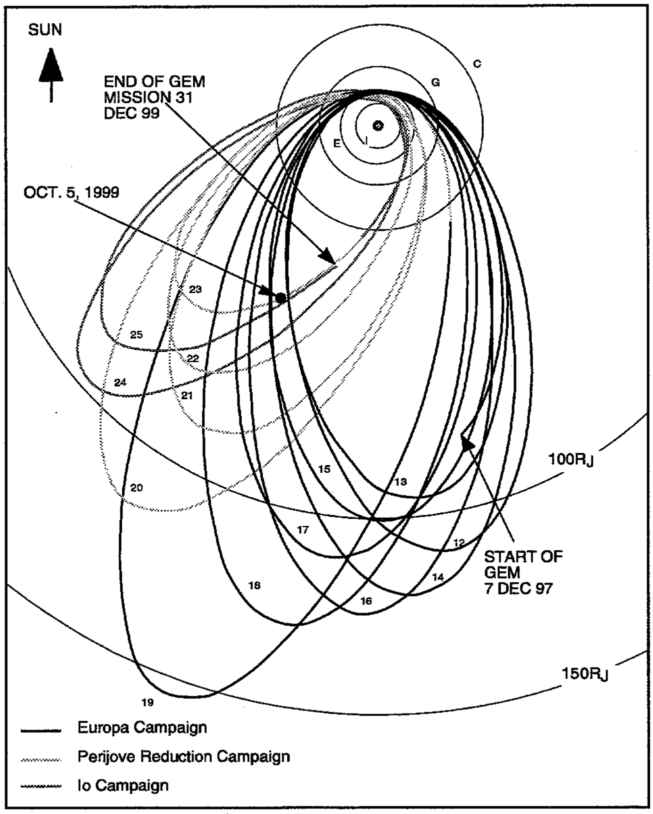

Figure 2. Galileo Europa Mission Tour

with these problems are detailed later in section 3, followed by what challenges are looming for the upcoming Io encounters. The successful completion of the remaining Callisto encounter and the two Io encounters is not assured, as further radiation exposure will be occurring with each succeeding perijove pass. However, the bottom line so far is that the spacecraft is back into a strong position to complete the planned GEM extended mission.

After the successful completion of the GEM mission, what is the next challenge for Galileo? Discussions are underway with NASA Headquarters on a variety of possible further extensions. The health of the spacecraft will figure heavily in the planning, but exciting plans are available for many different situations, including one outlined later. This workhorse spacecraft will almost certainly be asked to get back in harness again.

2. Orbiter Performance Overview

2.1 Attitude and Articulation Control Subsystem (AACS)

The Attitude and Articulation Control Subsystem hardware and software have continued to perform well during the second year of the Galileo Europa Mission, with continuing workarounds for the gyro electronics problem (see section 3 for more details). The gyro electronics problem first surfaced in December of 1997 and was characterized by the middle of 1998 as a disproportionate gyro output problem that appears to be radiation related. Initially, health and safety precautions were put in place to minimize gyro variation until the problem could be diagnosed further. A software workaround was implemented in the summer of 1998 in which a scale factor is applied by software that compensates for the incoming gyro electronics input. More recently, the gyro electronics problem has shown itself to have a further component in that there appears to be a maximum rate at which the gyros can operate (see section 3 for more details).

Aside from the gyro electronics problem, the only other radiation related degradation problems appear to be in the star scanner and in the spin detector. It was anticipated that certain stars in the star catalog might eventually become dimmer in the view of the star scanner as time progressed, radiation increased, and star scanner browning increased. The star dimming has not caused any operational impacts or changes but it is something for the flight team to watch, particularly with regards to the Io encounters. The spin detector began to experience some variation after the C22 encounter and analysis and operational workarounds are being developed at this time.

2.2 Command and Data Subsystem (CDS) and Tape Recorder Subsystem (DMS)

The Command and Data Subsystem is the central computer of the spacecraft and it has performed well during the second year of GEM. The major issue for the CDS team this year has been the continued occurrence of the transient bus resets. Last year was the first incident of a bus reset since 1993 and they have continued into this year. In the past, the bus resets have occurred on one of the computer strings or the other. This year, the spacecraft experienced the first simultaneous bus reset—meaning a reset occurred at the same time on both flight strings. The flight team will continue to analyze this new situation. Meanwhile, a flight software patch has been implemented that allows the response to a bus reset to be less severe so the science data taking continues even in the presence of this fault (see anomaly section 3.2 for further details). In other areas, the CDS lifetime usage has remained constant and thermal cycles on electronics within Bay A (where the CDS is located) have been less than predicted by the models.

The Tape Recorder is continuing to function nominally with no unexpected occurrences, although the tape stoppage seen in C22 may be the first indication of a problem (see section 3.2 for details). The number of tape stop/start cycles continues to exceed the lifetime specification, but the DMS appears to be suffering no ill effects. The start/stop cycles are still monitored carefully and all tape recorder safeguard rules are still followed diligently—including a tape recorder end-to-end conditioning approximately every 30 days.

2.3 Power/Pyrotechnic Subsystem (PPS)

All power for the Galileo spacecraft and its instruments comes from the Power/Pyrotechnic Subsystem (PPS). Last year, the Radioisotope Thermoelectric Generators (RTG) power output dropped from 475 watts to 467 watts and this year decayed further to 463 watts. This continues to match the modeled RTG decay rate. As anticipated, heater configurations were modified this year to account for the drop in available power. In addition, the available power margin increased since the AC Bus Imbalance experienced a large shift. It is anticipated that Galileo will be able to operate for the foreseeable future within its available power by modifying engineering configurations without having to impact any spacecraft capabilities.

2.4 Rocket-Propulsion Module (RPM)

The Rocket Propulsion Module is continuing to operate well. From August 18, 1998 through September 20, 1999, the spacecraft has performed a total of 17 Orbit Trim Maneuvers (OTM 52 through 72—not including the cancelled OTM-54, OTM-60, OTM-62, and OTM-71). These maneuvers occurred from the Europa 16 orbit through the Callisto 23 orbit. These OTMs are typically performed three times during an orbit to keep the spacecraft on its designed trajectory. The RPM continues to be a robust system and has had no problems in performing all the other required activities such as spacecraft attitude maintenance turns, thruster maintenance flushes, and corrections to the spacecraft's angular momentum vector. Some of these activities consume some portion of the remaining spacecraft propellant and the current predict for the propellant margin (amount of propellant expected to be available at the end of the nominal GEM Io 25) is 37.0 Kg (at the 90% confidence level).

2.5 Temperature Control Subsystem

The Temperature Control Subsystem must maintain the normal temperatures of the spacecraft despite its distance from the sun. This subsystem has been operating well since launch. This year, there were a few minor situations that normally produce changes in the spacecraft thermal condition (such as large science turns and minor occultations) and they were handled without incident. Also, there are temperature control monitors on board that autonomously maintain the temperature of fast cycling components, and none of these monitors appear to be adversely affected by any radiation spacecraft effects. In addition, certain components are operating at temperatures that are better than the models predicted, such as Bay A (which houses the CDS electronics). There is an ongoing concern with Bay A maintaining its temperature. Power limitations now require that all Despun Bay heaters be off, which creates a risk that the temperature of Bay A could decrease and potentially expose the CDS electronics to further thermal cycles. However, the Bay A temperature is holding steady and is well within design parameters.

2.6 Telecommunications Subsystem

The Telecommunications Subsystem is the vital link from the spacecraft to the Earth. It is clearly essential that this subsystem continues to operate without incident and it has throughout the mission. As mentioned in previous years, there continues to be an ongoing slow decline in the LGA drive telemetry (which is still not correlated with any loss of transmitted power) and a slowly changing ultra-stable oscillator frequency. The spacecraft and the RFS weathered an expected 28-day conjunction period where there was no communication with the earth due to solar corona interference. When communications were reestablished, there was no change in RFS performance. All indications are that the RFS remains quite healthy.

3. Non-Instrument Anomalies

3.1 AACS Anomalies

3.1.1 Further Gyro Electronics Anomalies

The gyro electronics problem that first showed itself in December of 1997 continues to exist, but the gyros appear to have stabilized and the flight software work around is operating nominally. The leading theory is that a malfunctioning JFET switch is causing the gyro -1X axis to respond disproportionately to the number of input pulses being received—i.e. the gyros receive input rates that indicate the spacecraft attitude has changed by some amount or the scan platform has moved, and when this information is processed through the gyro electronics, the attitude change is incorrectly magnified. The flight software patch in place to compensate for this basically takes the outgoing rate and scales that number using a parameter that can be set from the ground. This way the operations team can evaluate to what extent the gyros are misbehaving and uplink a parameter to compensate for the mismatch. To facilitate this, there is a gyro test during the playback period of every orbit that exercises the gyros and determines the performance of each axis, and then a new scale factor is developed.

Since the initial identification of the gyro electronics problems, some additional twists have surfaced. During the science data taking in Europa 15 (see reference 1), there were a number of science slews that took the scan platform to unusually high angles of observation. While at these high angles (known as the "cone-pole" region) the scan platform is under the control of a different software algorithm. During the transition from the normal scan platform controller to the cone pole region controller, the attitude estimate is recalculated. This recalculation is sensitive to gyro errors. In addition during Europa 17, certain axes of the gyros demonstrated a "maximum" rate, i.e. a point at which gyro output increased precipitously. Operational workarounds for both of these issues involve planning to enter the cone pole region in ways that minimize built-up gyro error and controlling the highest speed achieved by the gyros. Finally, certain AACS fault protection is now disabled to prevent false trips based on erratic gyro behavior.

3.1.2 Star Mis-Identification Anomalies

During both the Europa 12 encounter (December of 1997) and the Callisto 21 encounter (June 1999), there were incidents in which the attitude determination software mistook a background radiation spike for a star being used for attitude determination. Since the distance from Jupiter was different in each case, it does not appear distinctly tied to radiation levels at a certain Jupiter radius.

There are two types of radiation related star problems (separate from actual hardware degradation). One is the inability of the star scanner to detect stars against the background of radiation (i.e., saturation)—this results in sequential loss of the star set (similar to star dropouts). The other is the misidentification of a star due to a specific background spike in radiation. The latter scenario mean an incorrect location for the star was used by the attitude determination software, resulting in a shift of the basic attitude. This persists until the star scanner (presumably in the next few revolutions) re-identifies the star in its correct location—which again shifts the basic attitude. These attitude shifts can result in torques on the attitude control system that may cause fault responses—which was what happened in both the encounters mentioned above. The E12 problem initially looked like a gyro or SBA related problem, but further flight experience and analysis now show it to be a star related problem. Operational workarounds are being evaluated to mitigate this problem in the Io encounters (see section 4.0).

3.2 Transient Bus Reset Anomalies

The Transient Bus Resets that were first seen during the Europa 16 encounter also occurred again in November 98, during the Europa 18 period. As before, the Despun Bus Resets resulted in a power on reset signal that invoked spacecraft fault protection and canceled the on board sequence. These resets were first seen during the prime mission in 1991 and lasted until 1993. The standing theory is that the bus resets are caused by the accumulation of debris from the slip rings that eventually results in a short that causes a spurious signal. During the prime mission, all the despun bus resets occurred on only one string at a time. The two Europa 18 resets both occurred on the two Galileo CDS strings simultaneously. The simultaneous reset does have one operational advantage in that neither string actually goes down thus minimizing the recovery process.

A great deal of analysis has been done to determine how it is possible for a simultaneous bus reset to have occurred given the current theory of its cause. Basically, enough slip ring debris would have had to accumulate on both strings and shorted at exactly the same time. Or, assuming the current theory is not correct, something either had to go wrong on both strings at exactly the same time or there had to be a common component between those strings that experience the failure. The analysis showed no compelling mechanism to answer how this could have occurred.

A flight software change was uplinked to the spacecraft in April of 1999 to address this issue. The patch monitors for a power on reset signal that indicates a problem in the Despun Low-Level Modules. If the signature does not indicate a problem only in the Low-Level Modules, then the normal error routines are executed; however, if only the Low-Level Modules appear to be affected, then a new error routine is called in which those modules are reset without invoking spacecraft fault protection. This allows spacecraft health and safety to be maintained while also not canceling on-board sequences without reason. This patch was in place for the C20 encounter during which there were two bus resets. The patch worked as expected—the on-board sequence was not cancelled and science collection continued. The C21 encounter had one simultaneous bus reset and, again, the patch worked as expected. The C22 encounter had what appeared to be three simultaneous bus resets. The flight software patch continued the sequences in all three cases but, in one of the bus resets, the tape recorder stopped. The C23 encounter had one bus reset and the patch worked successfully. Analysis is ongoing in this area.

3.3 Europa 19 Incomplete Sun Acquisition

In the final Europa encounter of the Galileo Europa mission, the spacecraft failed to complete a sun acquisition turn designed to bring it back to the nominal Earth point attitude and this halted the science data taking for the orbit. During the E19 encounter in the beginning of February 1999, it was necessary to turn the spacecraft to an off-earth attitude of approximately 60 degrees to eliminate obscuration from the Magnetometer Boom and substantially increase science data taking opportunities. Given the gyro electronics anomaly, turning the spacecraft through such a large angle using gyro control was something that had to be planned carefully. The turn was occurring near the period of close approach to Europa, which is also a period of high radiation given the moon's proximity to Jupiter. Therefore, it was deemed conservative to assume that radiation might again change the gyro performance. So a technical strategy was developed wherein the turn out to attitude was broken into two smaller turns, with time in between for gyro performance to "settle". After the science data taking period, the turn back to earth attitude was done through a sun acquisition as opposed to a turn using the stars and gyros for attitude reference. This way in case the gyros deteriorated during the high radiation period of the encounter the turn back to attitude would not depend on gyro performance. A sun acquisition depends only on the ability of the sun sensor to detect the sun. This operational strategy was intended to maximize the chances of success for the E19 encounter. The first turn to attitude would rely on the gyros and the post-radiation second turn would rely on the acquisition sun sensor.

The sun acquisition did not complete, because the spacecraft failed to detect the sun as it passed through an angle of approximately 45 degrees. As with many operational strategies adopted in GEM to compensate for anomalies, the use of the sun acquisition as a planned activity during an encounter was an unusual approach. In general, sun acquisitions are used for fault responses and if commanded in the earlier part of the mission, were done at a greater distance from Jupiter. However, in this case, it was necessary to plan to use a sun acquisition during an encounter to minimize dependence on the gyros. The sensor upon which the sun acquisition maneuver depended looks for the sun based on an incoming light pulse that persists for a certain duration above a set threshold. These thresholds are typically increased when the spacecraft is making repeated close passes by the Jovian moons so that the acquisition sun sensor will not mistake the brightness of one of the Jovian moons for that of the sun. These two requirements—keeping the thresholds set at a safe level versus not depending on the gyros—were difficult to satisfy at the same time. The sun acquisition was able to proceed as expected until it reached an angle of 45 degrees where the sun pulse no longer exceeded the threshold. The sun acquisition sensor has three detectors with marginally overlapping field of views. One of the two overlap regions is located at 45 degrees and was causing the dip in the output signal. The sun acquisition did not proceed beyond this point, so spacecraft fault protection was invoked and the spacecraft remained at that attitude until ground commanding was able to return the spacecraft to nominal attitude a few days later. Fortunately, the bulk of the expected science data was already on the tape recorder at this time and later played back to the ground. The gyros performed admirably in their turn to attitude and all science pointing during E19 encounter was nominal. The E19 sun acquisition maneuver is the only planned use of the sun acquisition capability in GEM.

4. Expected Engineering Challenges at Io

In the fall of 1999, Galileo will return to Io for two close passes in October and November. This will be the first time Galileo swings by Jupiter's innermost moon since December 1995. As before, when the spacecraft is near Io, there are special engineering challenges due to the higher radiation environment at that distance from Jupiter. Io is the most volcanically active body in the solar system and those volcanoes supply gases to Io's tenuous atmosphere, which are ionized by incoming ultraviolet radiation and charged particles in the magnetosphere. These particles are then picked up by the moving magnetic field of Jupiter and accelerated resulting in belts of high radiation. From experience based on the Van Allen Belts and on previous Jovian flybys, these radiation belts are known to create havoc with spacecraft electronics. Just what kind of spacecraft failure modes are created by long term exposure to high radiation is not known; Galileo is the first spacecraft to spend an extended period of time in a high radiation environment. However, these failure modes can be postulated to fall into three categories—errors due to single event upsets, errors due to high incoming dosage rates, and errors due to cumulative radiation effects. The flight team is currently trying to anticipate the types of errors caused by these three failure modes and to take reasonable precautions to protect the spacecraft during the two passes by Io.

There are three major areas of concern for the Io flybys—the ongoing problem with the gyro electronics, the ability to identify stars against the radiation background, and any other radiation issues created by the failure modes described above. Despite the limited resources of the GEM flight team, one approach being used is to identify possible problems with the Io flybys and determine if there is any reasonable flight software change that can be made to alleviate the problem. At Io, the problem with the gyro electronics and the ability to identify stars come together into the same issue. The bottom line is the need to operate in this high radiation environment safely and to still maximize the ability to accurately point the scan platform at the desired target of Io. There are two major ways the spacecraft maintains an attitude reference that allows it to point the scan platform—by using the gyroscopes or by using stars. Under normal circumstances, a combination of both is used in what is known as "inertial" mode.

Given the increasingly erratic performance of the gyros, I24 will be flown in "cruise" mode. This means the spacecraft will rely on stars to maintain attitude reference. Analysis is currently underway to try to provide a backup method of utilizing the sun sensor for attitude reference should the stars drop out or be misidentified. The mode of operation for I25 will be selected based on performance at I24.

In addition, every effort is being made to locate a star set for the Io encounters that uses stars whose brightness has the greatest chance of being seen by the star scanner against the background radiation. Given that the spacecraft made an earlier pass by Io (Dec. 7, 1995) when it came within four Jupiter radii of Jupiter, it is possible to compare the star scanner's performance from that time to the upcoming Io encounter during which the spacecraft comes within 5.4 radii of Jupiter. Precautions are also being taken to insure that should stars be lost during the encounter, the spacecraft autonomous fault protection as well as the attitude determination spin sources will also be configured for the greatest chance of success.

Finally, during the prime mission of Galileo in 1997, a study was done to examine the spacecraft components and determine which parts of the spacecraft were most susceptible to long-term radiation damage or to single event upsets. In the extended mission, this information, as well as any new information that has been gathered, is being used to evaluate the ability of the spacecraft to fly through the radiation environment. In particular if certain autonomous fault protection routines appear to be more susceptible to radiation damage than other routines, then that algorithm is analyzed to determine if the protection afforded by the routine is more important than the chance of a false trip based on a radiation.

As expected, the current analysis shows that in most cases, the faults that these routines protect the spacecraft from are important enough to keep the fault protection enabled for the encounter.

5. Instrument Status

There have been no significant changes in the capabilities of the instruments from the last report of Galileo's activities. Previously, three instruments had anomalies during Galileo's prime mission and the GEM: the Energetic Particles Detector (EPD), the Near Infrared Mapping Spectrometer (NIMS), and the Plasma Wave Subsystem (PWS). As reported earlier, the EPD instrument experienced two transient problems in the E12 and E16 orbits. Over the past year, the EPD has performed nominally.

The NIMS instrument continues to perform well despite the failure of two of its 17 detectors, which occurred in the prime mission. In addition, analysis of the NIMS data in GEM has revealed a change in wavelength range of its detectors. These changes are not yet understood and additional analysis continues. Tests to characterize these changes have been incorporated into the C20 and C22 orbits. The change in wavelength associated with these detectors presents no health and safety issues or degradation of the science return at this time. The NIMS instrument continues to experience periodic software halts during the encounter data taking periods, which is believed to be attributed to radiation effects. To ameliorate this problem, the NIMS team inserts instrument software reloads prior to each of their observations. This has proven to be an effective approach in minimizing the impacts associated with the software halts.

As reported previously, data from the PWS low-frequency (5 Hz to 3.5 kHz) magnetic search coil became severely degraded during the C10 encounter. In GEM, the PWS team has reported that the coil completely failed and is no longer producing usable data. Loss of this capability does not significantly degrade the ongoing science goals of the PWS instrument.

One new anomaly has occurred in GEM associated with the Plasma Subsystem (PLS). The electric field detectors in the PLS experienced anomalous behavior following the E18 and E19 safings. In both cases the detectors experienced long periods of a cessation in counts but eventually returned to normal operation. As of the Callisto 20 encounter, three of the 6 electric field detectors are performing nominally, the other three have not returned to normal operation. The PLS team is investigating options to try to revive these detectors prior to the C21 encounter.

Another new problem involved the Photopolarimeter/ Radiometer (PPR). During the C20 encounter, the instrument showed no signal from its radiometer channel. Possible causes could involve the detector bonding failing, solder joint cracking, or radiation damage to a JFET in their pre-amplifier. Early in the C21 encounter, the instrument was warmed up beyond normal ranges, and valid data was restored. As of the C22 encounter, the radiometer channel was still performing well.

The ultraviolet spectrometer (UVS) experienced a memory corruption during Callisto 22. The memory was restored for Callisto 23 with no permanent effects.

6. Sequence Operations Status

Sequence operations, the task of designing, building, and executing command sequences for the Galileo spacecraft, has functioned well in the GEM, exceeding expectations. In the past year, the flight team has generated 15 stored or background sequences to control the spacecraft for days to weeks at a time (usually there are two such sequences per orbit, one for data collection during the encounter period and the other for data playback during cruise), 16 maneuver sequences, 9 mini-sequences for focused, usually short-term, activities, and 189 real-time command packages containing over 750 commands. In addition to the overriding priority of maintaining a high level of fidelity in commanding the spacecraft, the major concerns for sequence operations in the second year of GEM were responding in a timely manner to faults and to changing spacecraft performance due to aging and radiation dosage, preparing for the upcoming Io encounters, and maintaining the high performance of the team as individual members leave the project.

The anomaly recovery process, starting with diagnosis of the problem and ending with spacecraft reconfiguration and resumption of the planned background sequence, has been streamlined by reviewing encounter timelines to identify recovery strategies from the most likely faults and pre-generating contingency commands to do a wide range of activities from reading out diagnostic data and resetting fault flags to bringing up a CDS string and restarting the Science Virtual Machine. Flight team engineers modify the grouping of contingency commands in real-time depending on the specific nature of the problem, available DSN track time to both send the commands and receive the telemetry, and to avoid conflicts with the on board sequence. Recovery packages that were built during the prime mission to respond to faults that invoked spacecraft fault protection and canceled the stored sequence were reviewed prior to use in Europa 16. In Europa 18 and Europa 19 the recovery process and associated real-time commanding were modified based on experience and greater autonomous checking was built into the commands to reduce the need for ground in the loop verification. To reduce the impact of known faults on science acquisition, flight software patches have been implemented as discussed in sections 3.1.1 and 3.2 and some contingency commands included in the stored sequences.

The recovery process from a known fault case such as a transient bus reset is estimated to be about 24 hours if a new background sequence does not have to be generated, i.e. the spacecraft is reconfigured to match the assumed incoming state of the next planned sequence. This may be the case if the fault occurs part way through an encounter and the next restart point is the beginning of the cruise sequence. Additional time is required if the pre-planned sequence needs to be adapted either to start at a different time or to incorporate science changes and engineering workarounds to accommodate changed spacecraft performance such as the gyroscope scale factors. In some cases, up to three squads work concurrently to recover the spacecraft; one focuses on diagnosis and near-term commanding, the second builds a set of commands to match the spacecraft state expected by the next stored sequence, and the third to adapt a planned stored sequence for a new start time.

Recovery from the AACS gyroscope faults and star mis-identification problems which do not cancel the on-board sequence involves reading out fault counters and diagnostic information, clearing fault flags, and re-enabling science data processing within the AACS processor. These commands are pre-generated and checked by subsystem analysts so that at the time of the fault, a limited number of people have to be involved in the command process. A system engineer, in consultation with an AACS analyst and the fault protection engineer can verify the nature of the fault and submit commands for uplink approval. Depending on the science-observing plan subsequent to the fault, the gyroscope and inertial mode may be commanded back on.

The second concern for Sequence Operations has been preparing for I24 and I25 and a possible post-GEM mission. Early planning for Io was not as extensive two years ago as it was for the Europa and Perijove Reduction phases of GEM because of the recognition that the spacecraft capabilities likely would change before these encounters and that the closest approach aim point could change, particularly if a post-GEM trajectory was patched to the GEM trajectory. Also a longer development time, more like the prime mission, to allow tighter integration to maximize science acquisition was deemed appropriate because of the high priority of these encounters. I24 will be the first opportunity to acquire remote sensing observations close to this volcanically active moon since the prime mission encounter was severely limited due to a DMS tape anomaly prior to Jupiter Orbit Insertion. Section 4 discusses many of the engineering strategy changes being considered for the Io encounter. A particular challenge has been to accomplish this work while continuing the ongoing sequence development required for the Perijove Reduction orbits. A science working group laid out the general plan of observing time and distribution of other resources such as space on the tape recorder and bits to ground. Science coordinators then took the overall plan and implemented the designs down to the command level and corrected conflicts between observations and with rules and operating guidelines. This implementation work was a concentrated effort by the science teams requiring 100% of their resources. To accommodate this planning effort, ongoing sequence generation for the Perijove Reduction phase was shifted around and non-standard development schedules were used.

The third concern for sequence operations this year, the loss of personnel to other projects, has not materialized to the extent expected. Flight team morale remains high, possibly because the anomalies and Io planning present challenges which offset the routine, standard operations of a long-lived mission. There is also the long anticipated goal of getting the Io science that is yet to come and which continues to motivate the team. Where early departures have occurred, other team members have cross-trained to fill the gap or work schedules have been adjusted.

7. Summary of Encounters in the Past Year

7.1 Europa 17

The sixth flyby of Europa in the Galileo Europa Mission, E17, occurred on September 26, 1998, at a close approach altitude of 3,582 km at 03:54 UTC. The encounter sequence was 4 days long and began on September 24, 1998, 04:00 UTC and lasted until September 28, 1998, 02:00 UTC. The E17 encounter, like the E16 encounter, was a south polar pass, making it possible to get good views of many of the E16 targets that were lost when the spacecraft experienced a bus reset event that resulted in spacecraft safing and termination of the E16 encounter sequence. The E17 encounter was the final south polar pass of the Europa campaign; therefore the last chance to see the previously missed E16 targets in high resolution. Figures 3a and 3b show the trajectory plot and encounter geometry with key science observations highlighted.

The Radio Science team measured changes in the

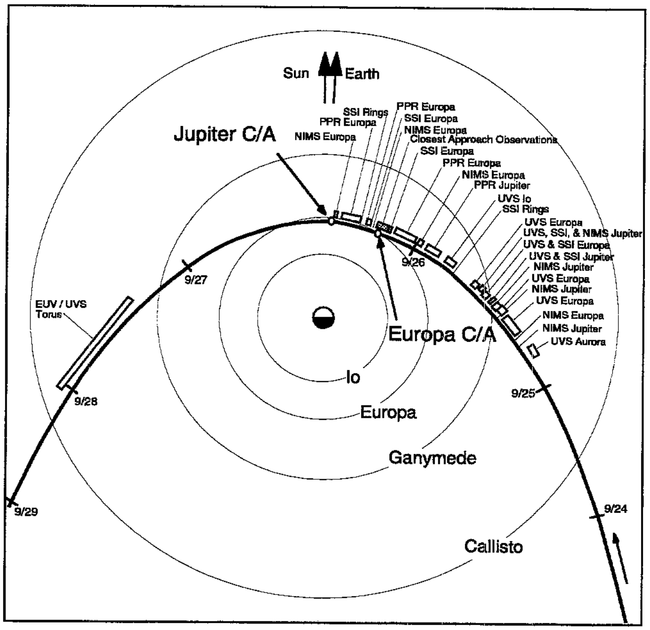

Figure 3a. E17 Encounter Trajectory

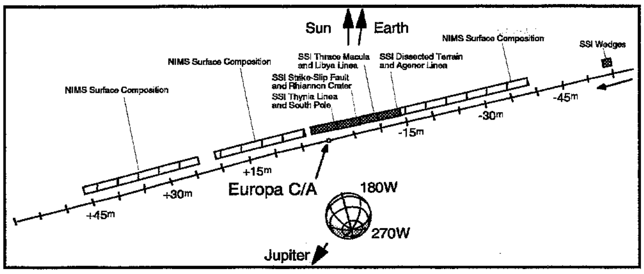

Figure 3b. E17 Flyby Geometry

frequency of Galileo's radio signal for 20 hours, centered on the close approach to Europa. Using the Doppler effect, scientists improved their knowledge of the gravity field produced by Europa.

Low-rate, real-time magnetospheric data, symmetrical about perijove, is obtained in each of the GEM orbits to provide background and contextual data for the recorded, high rate measurements. In orbits where no recorded magnetospheric data are taken, the real-time survey provides data on spatial and temporal variations of the innermost and more active portion of the magnetosphere. For E17, there was no magnetospheric recording.

The NIMS E17 observation objectives included, 1) Europa high resolution surface composition observation to determine non-ice components on the surface, 2) Europa global compositional mapping designed to extend and complement prime mission coverage and, 3) distant Europa global observations at –20 hours of the Jupiter facing hemisphere designed to collect spectra outside the high radiation environment. Three new Jupiter observations were added to observe a possible merged white oval area. In the history of observing Jupiter's white ovals (~50 years), this situation has never been seen before; the white oval observations were also observed by SSI and UVS.

PPR E17 objectives included two south hemisphere wave structure observations covering 3 to 35 degrees south and as much as possible longitudinally. Four Europa dark maps and one Europa night side polar observations were taken pre-dawn to ensure the coldest temperatures and therefore the greater possibility of detecting hot spots. One Europa south hemisphere day side thermal observation, covering the same longitudes as in G7, but a different time of the day. The dark maps, night side, and day-side observations were part of a campaign to map Europa thermally and were taken to complement and enhance prime mission data.

SSI observed both Europa and Jupiter during the E17 encounter. The SSI Europa imaging included, 1) a single full disk image for shape measurements at 4 km/pixel, 2) a near terminator mapping of the pull-apart zone, mottled terrain, densely banded region, cycloidal band and dark spots to look for evidence of large scale shifting that may be due to a liquid sub-layer, 3) a campaign of high resolution imagining of the Agenor Linea-Thrace Macula region, 4) dissected terrain, 5) regional scale color of the wedges region for high spectral resolution compositional information, 6) Libya Linea, 7) strike-slip fault zone, 8) high resolution of Rhiannon Crater, Thynia Linea, and 9) a sample of south polar terrain for comparison with E4 and E6 equatorial terrain. The SSI Jupiter imaging included the first SSI feature track of GEM, a rare opportunity to view a white oval produced by two that merged in early 1998, and first time imaging measurements of the ring brightness at various phase angles (30, 60, 80).

UVS observations included 1) Europa atmospheric emissions and possible out-gassing episodes on the body, 2) observations to compliment prime mission data to derive phase curves for several Europa locations, 3) ride-along observations with NIMS to compliment NIMS surface composition data, 4) real-time observations to characterize long term changes in the Io plasma torus as coupled with the Jovian magnetosphere, 5) observe southern Jupiter region Lyman-alpha and H2 emissions in an attempt to capture the Io flux tube footprint, and 6) the feature campaign to observe merged white ovals.

7.2 Europa 18

The seventh flyby of Europa in the Galileo Europa Mission, E18, occurred on November 22, 1998, at a close approach altitude of 2,273 km at 11:38 UTC. The encounter sequence was scheduled to be 4 days long and began on November 21, 1998, 12:00 UTC. During the execution of the E18 encounter sequence, about 2 hours before Jupiter close approach and 6 hours before Europa close approach, the spacecraft experienced a despun bus reset event that resulted in spacecraft safing and termination of the science sequence. The E18 encounter was to have been the seventh encounter with Europa and the second to the last Europa encounter during GEM. Due to spacecraft safing, the primary data collected during the Europa close approach period was the radio science Doppler data. This was the second encounter sequence missed by Galileo during all of its orbital operations to date. The original science objectives for E18 were to observe Europa "features" (South Pole pits and plateaus), Europa "terrain's" (massifs, bright and dark plains), Europa global and regional polarimetry maps, surface composition maps, and gravity field measurements. Jupiter observations were planned by NIMS (longitudinal spectral scans) and by UVS (upper atmosphere energy). In addition, Ganymede (polarimetry), Io (polarimetry, surface monitoring and torus), and Jupiter system inner magnetosphere survey.

With the termination of the E18 encounter sequence, a revised E18 cruise sequence was developed to play back the encounter data that was recorded prior to safing which included UVS observations, a PPR RTC calibration, and one NIMS observation of Jupiter's white oval storm system. The revised sequence began on December 11, 1998, 14:30 UTC and continued until January 31, 1999, 02:00 UTC. Recording during the cruise phase of the E18 orbit was provided to collect one SSI "Family Portrait" calibration (targeting Titan, Saturn,

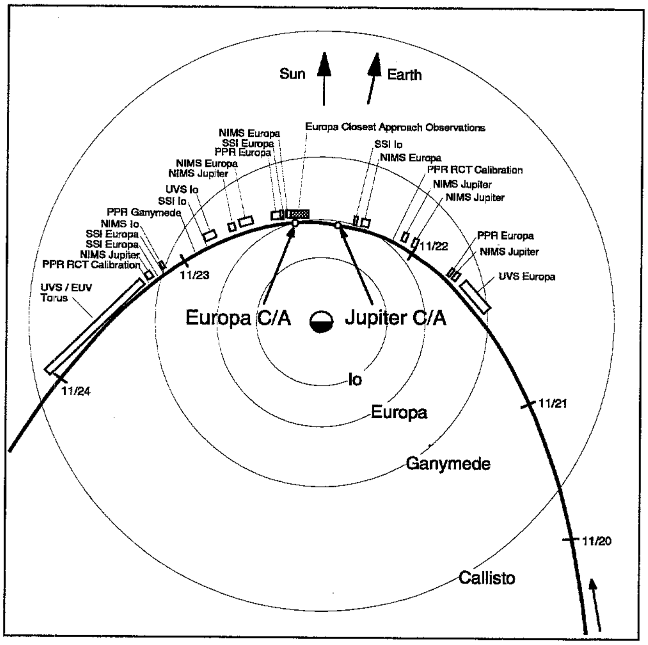

Figure 4a. E18 Encounter Trajectory

Neptune, and Uranus), one NIMS calibration (targeting Sirius), and recording MWG data for a half Jupiter rotation (covering a plasma sheet crossing). The details of the orbit geometry and observations that had been planned in the E18 encounter period are shown in Figures 4a and 4b.

7.3 Europa 19

The eighth and final Europa encounter in GEM occurred on February 1, 1999, 02:20 UTC, at an altitude of 1,439 km. The encounter sequence was 4 days long and began on January 31, 1999, 02:00 UTC and lasted until February 4, 1999, 01:00 UTC. This was the first and only Europa encounter that required a set of spacecraft attitude turns to support science observations. The initial turn occurred on January 31, 1999, 18:01 UTC, prior to the Europa close approach. The purpose of the spacecraft turns is to allow the camera and the other remote sensing instruments a view of Europa that is unobstructed by the spacecraft's booms and sunshield. The E19 encounter sequence was terminated by on-board fault protection software when the spacecraft entered safe mode (see section 3.3 for details) about four hours after its close approach to Europa and about one hour after its close approach to Jupiter. Prior to safing, all planned close approach observations of Europa and Jupiter were successfully recorded and subsequently returned to Earth for processing, but the planned outbound distant observations of Europa, Io, and Jupiter were lost. Figures 5a and 5b provide details of the E19 encounter.

The Radio Science team measured changes in the frequency of Galileo's radio signal, centered on the close approach to Europa using two-way coherent tracking data for the purpose of improving their knowledge of the gravity field and to probe the internal structure of Europa.

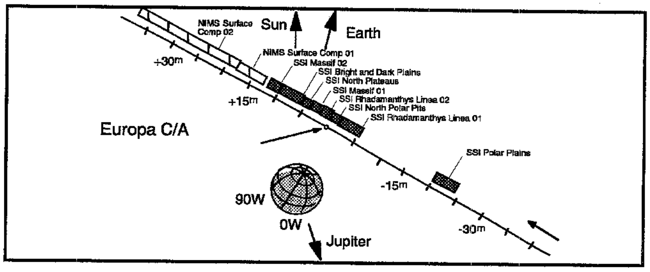

Figure 4b. E18 Flyby Geometry

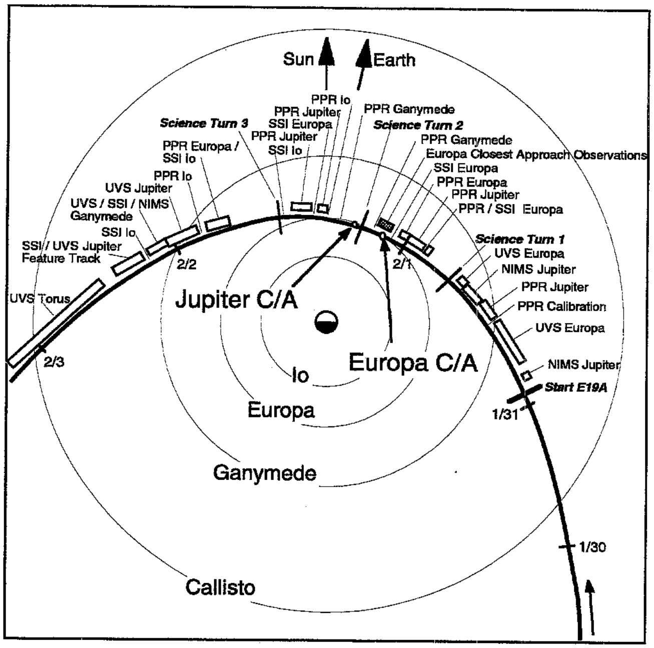

Figure 5a. E19 Encounter Trajectory

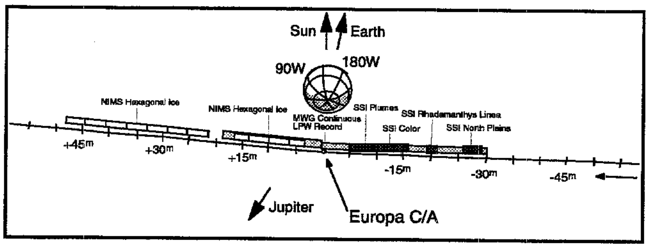

Figure 5b. E19 Flyby Geometry

Magnetospheric science observations for this orbit consisted of high-time resolution recording during the period of close approach to Europa. This high-latitude, relatively low-altitude pass (31°N 1,439 km) provided a unique geometry that was second in priority only to E12 for magnetospheric studies.

The NIMS E19 observations included 1) Europa high resolution surface composition observation to determine non-ice components on the surface, 2) Europa global compositional mapping designed to extend and complement prime mission coverage and, 3) distant Europa global observations at -20 hours of the Jupiter facing hemisphere designed to collect spectra outside the high radiation environment. Three Jupiter observations were included to observe a possible merged white oval area. In the history of observing Jupiter's white ovals (~50 years), this situation has never been seen before; the white oval observations were also observed by SSI and UVS.

The PPR E19 objectives included two south hemisphere wave structure observations covering 3 to 35 degrees south and as much as possible longitudinally. Four Europa dark maps and one Europa night side polar observations were taken pre-dawn to ensure the coldest temperatures and therefore the greater possibility of detecting hot spots. One Europa south hemisphere day side thermal observation, covering the same longitudes as in G7, but a different time of the day was observed by the PPR. The dark maps, night side, and day-side observations were part of a campaign to map Europa thermally and were taken to complement and enhance prime mission data.

The E19 SSI Europa imaging was divided between global-scale mapping, regional-scale mapping, and a series of close approach imaging. The global-scale image was multi-spectral in four filters at 1.5km/pixel. The regional-scale mapping observations included the Tegid Crater at 950 m/pixel, observations to evaluate stratigraphic relationships between plains and triple bands, and observations to characterize north polar plains and plateaus. The close approach observations included 1) Rhadmanthys Linea volcanic features at 65m/pixel, 2) multi-color imaging of a dark spot, mottled terrain, and specular point, and 3) a very high phase limb scan to look for plumes. The additional outbound observations of Io, Ganymede, and Jupiter were lost due to the spacecraft safing. The UVS observations included Europa atmospheric emissions of oxygen, hydrogen, sulfur, etc. and possible out-gassing episodes on the body. In addition, the Europa surface was monitored at various phase angles to derive phase curves and complement prime mission observations and to study surface scattering properties.

7.4 Callisto 20

The next and ninth encounter in GEM was the first Callisto fly-by during the GEM and occurred on May 5, 1999, at an altitude of 1,315 km at 13:56 UTC. The encounter sequence was five days long and began on May 2, 1999, 17:00 UTC and ended on May 7, 1999 at 12:00 UTC. The C20 encounter marks the introduction to the second phase of GEM, the Perijove Reduction Campaign. The Perijove Reduction Campaign, includes four flybys of Callisto. These flybys are designed to incrementally change the spacecraft's orbit to allow for a close flyby of the innermost Galilean satellite, Io. In addition to the trajectory-altering objective, these four orbits also present extensive science opportunities. These opportunities include monitoring volcanic activity on Io, exploration of the Io plasma torus, observations of Callisto, and observations of Jupiter's atmosphere and magnetosphere. The C20 encounter observations are highlighted in Figures 6a and 6b. During the Perijove Reduction Campaign, the spacecraft's Perijove distance, or closest distance to Jupiter for a given orbit, will be to a distance that allows Galileo to fly within the orbit of Io (5.5 Jupiter radii, 393,000 kilometers, or 244,000 miles). With this reduction in the distance from Jupiter also comes an increase in the amount of radiation to which the spacecraft will be exposed.

With the start of the encounter sequence came the resumption of the magnetosphere survey performed every orbit by the Fields and Particles instruments. C20 was the first of four opportunities to sample the Io Torus during the Perijove Reduction Campaign. During this survey, the instruments sample the inner portions of Jupiter's magnetosphere, which will allow scientists to study the long-term variations in the plasma, dust, and electric and magnetic fields that comprise it. Recordings in this region provide important information on the dynamics of Jupiter's magnetosphere. This orbit's recording is centered at closest approach to Jupiter and is performed for two hours.

The PPR conducted a set of Jupiter atmospheric observations aimed at finding subtle longitudinal wave structure in Jupiter's atmospheric temperature field. In two observations, the PPR made observations of Jupiter's clouds, looking for

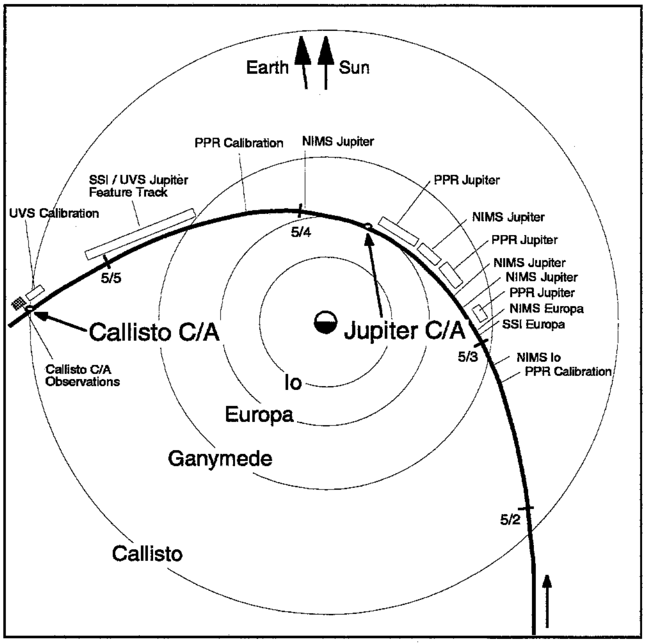

Figure 6a. C20 Encounter Trajectory

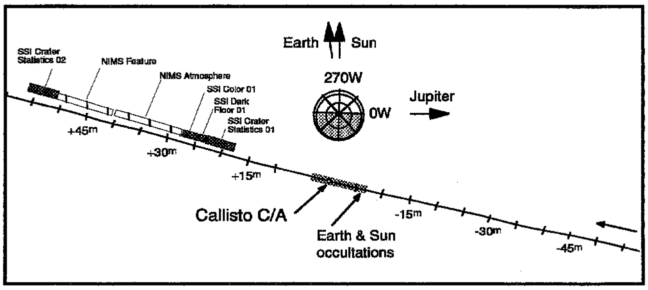

Figure 6b. C20 Flyby Geometry

small temperature variations within cloud bands. In addition, the PPR observed the Great Red Spot as well as two white ovals.

The NIMS observations for C20 included observations of Jupiter, Callisto, Europa, and Io. The NIMS Callisto observations included, 1) a global observation of the trailing side of Callisto, 2) three small "postage stamp" observations that target the same Callisto territory as SSI, 3) a regional observation of the Bran crater, and 4) a Callisto trailing-side limb scan observation. The NIMS Jupiter science observations were designed to detect the dynamics of a small turbulent zone northwest of the Great Red Spot and to determine the height of infrared aurora emissions. The NIMS targeted one high-resolution observation of Io in preparations for the upcoming Io encounters. In addition, NIMS and SSI observed Europa in eclipse to search for evidence of atmospheric signatures and surface emissions.

Throughout the encounter, the SSI observed a variety of cloud features in Jupiter's atmosphere. These observations were designed to determine the dynamics of cloud motion in three dimensions, with high spatial and time resolution. Each feature was observed three to six times as it moves across Jupiter's sunlit hemisphere. Some of the features were also imaged after they had rotated into the night side of Jupiter, to look for lightning flashes which the scientists hope to correlate with clouds seen in the daylight images taken earlier in the same areas. The features covered by this observation campaign are equatorial waves, high speed jets, clouds in the north and south equatorial belts, and white ovals. In addition, the camera also made an observation of Jupiter's aurora to measure its vertical structure at high resolution. The UVS also took advantage of these observation opportunities and made measurements of these features.

In addition to the observations taken along with the SSI, the UVS also performed its own measurements of Jupiter. In one type of observation, the spectrometer measures hydrogen in Jupiter's dark atmosphere. Without sunlight, changes in hydrogen loss are caused by interaction with particles in Jupiter's magnetosphere and mixing of the upper atmosphere with lower cloud levels. In a second type of observation, taken on Jupiter's lit side, the spectrometer measures hydrocarbons in Jupiter's upper atmosphere. Finally, the spectrometer looked at aurora in Jupiter's atmosphere. These observations allow scientists to further study the dynamics of Jupiter's upper atmosphere, and its interaction with Jupiter's magnetosphere.

The NIMS and UVS made observations of the Bran crater to provide information on the chemical composition and variations of the region. The two instruments collaborated on a series of five observations. The first was designed to scan Callisto's bright limb in hopes of detecting and determining the composition of Callisto's tenuous atmosphere. In the remaining four observations, the two instruments looked at different regions of Callisto's surface to obtain measurements of the chemical composition of the regions.

During the close approach period with Callisto, the Radio Science Team conducted its first occultation experiment in the GEM. The Team observed the Ionosphere of Callisto and measured the vertical distribution of free electrons.

7.5 Callisto 21

The second Callisto encounter and the tenth encounter in GEM occurred on June 30, 1999, 07:46 UTC, at an altitude of 1,047 km. The encounter sequence was five days long and began on June 29, 1999, 07:00 UTC and ended on July 3, 1999, 11:00 UTC. During this encounter, Galileo performed the second in a series of four close flybys of Jupiter's moon Callisto. The details of the orbit geometry and observations contained in the C21 encounter period are shown in Figures 7a and 7b.

The start of the encounter marked the resumption of the magnetospheric survey performed every orbit by the Fields and Particles Instruments. Recordings in this region provide important information on the dynamics of Jupiter's magnetosphere. This orbit's recording is centered at perijove and is performed for two hours.

The radio science team measured the changes in the

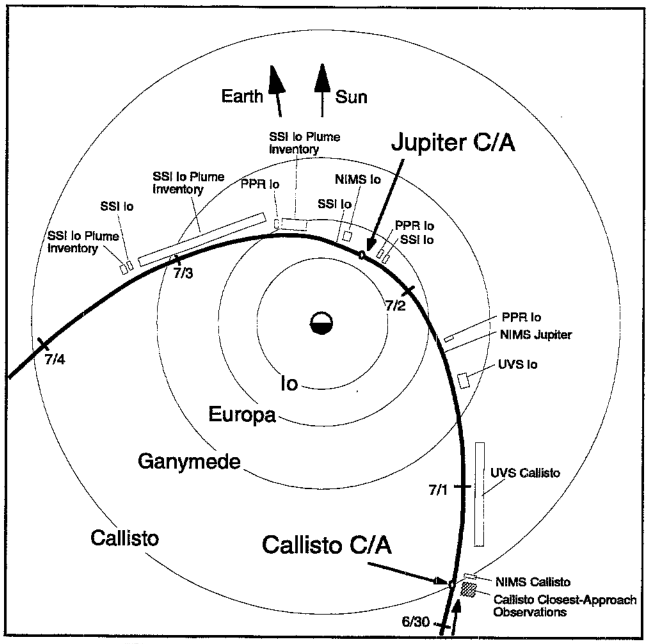

Figure 7a. C21 Encounter Trajectory

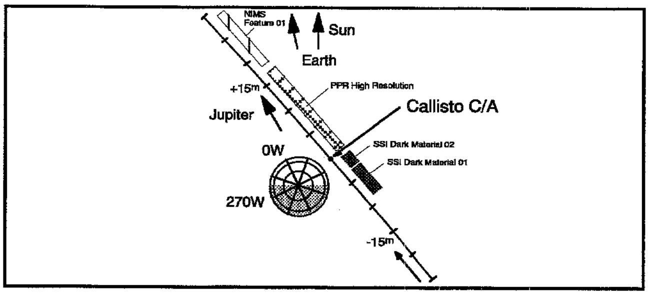

Figure 7b. C21 Flyby Geometry

frequency of Galileo's radio signal, which are caused by Callisto's gravitational pull on the spacecraft, and the resulting Doppler shift in Galileo's radio signals. The team uses the measurements to refine models of Callisto's gravity field and internal structure.

The NIMS observations for C21 included observations of Jupiter, Callisto, and Io. The NIMS Callisto observation was a feature observation of the trailing hemisphere. The NIMS Jupiter observation was designed to search for Jupiter atmospheric composition and thermal variations over time. The NIMS Io observation was the highest resolution mosaic during Galileo Prime Mission and GEM with the objective to obtain a high spatial and spectral map of one hemisphere of Io.

The C21 SSI imaging was devided between Io and Callisto. The Callisto observations targeted dark material found near a ringed feature. The observations were designed to allow scientists to study variations in the appearance of Callisto's surface in hopes of understanding the processes that modify the surface and the apparent deficit in the number of small craters. The first series of Io images formed a regional map at a resolution of 1 to 1.5 kilometers (0.6-0.9 miles) per picture element. The second series of images captured a global view of Io at a resolution of 2.6 kilometers (1.6 miles) per picture element. The SSI then obtained a series of images that will yield stereo images when combined with images expected to be taken later this year. These two image sets will be combined to produce stereo views at a resolution of 1.4 kilometers (0.87 miles) per picture element. The camera's next set of observations were part of a campaign to monitor Io's plume activity in preparation for two close flybys of Io later this year. These observations also allow scientists to compare Io's volcanic activity with magnetosphere measurements made by the Fields and Particles instruments.

The PPR took a high-resolution observation of a region near Callisto's equator. The observation measured the surface brightness temperatures that will provide information about the density and composition of surface materials.

The UVS observations included both Callisto and Io. The UVS observations were designed to study both Io and Callisto atmospheres as well as Io's surface composition.

7.6 Callisto 22

The third Callisto encounter and the eleventh encounter in GEM occurred on August 14, 1999, 08:30 UTC, at an altitude of 2,296 km. The encounter sequence was four days long and began on August 11, 1999, 14:00 UTC and ended on August 14, 1999, 22:00 UTC. The details of the orbit geometry and observations contained in the C22 encounter period are showned in Figures 8a and 8b.

Once again, the start of the C22 encounter marked the resumption of the magnetospheric survey performed by the Fields and Particles Instruments. The in situ instruments will collectively make measurements of the magnetic fields and particles interactions within the region, including waves and radio signals. This orbit's recording was centered at perijove and was performed for six hours.

During the close approach period with Callisto, the Radio Science Team conducted its second occultation experiment during GEM. During the experiment, the Team observed the ionosphere of Callisto and measured the vertical distribution of free electrons.

The NIMS observations for C22 included observations of Jupiter, Europa, and Io. The NIMS Europa observations targeted a global observation of the trailing hemisphere and obtained spectra near Belus Linea with concentrated dark surface materials. The NIMS Jupiter observations were designed to search for Jupiter atmospheric composition and thermal variations over time, the northern Temperate Belt, and White Ovals. The NIMS Io observation was the last planned Io observation prior to I24 and was designed to look for hotspots.

The C22 SSI imaging was devided between Jupiter, Amalthea, and Io. The Amalthea observation was a high-resolution image at 8.5-9.2km per pixel. The Io images are a set of observations that are part of a campaign to monitor Io's plume activity in preparation for two close flybys of Io later

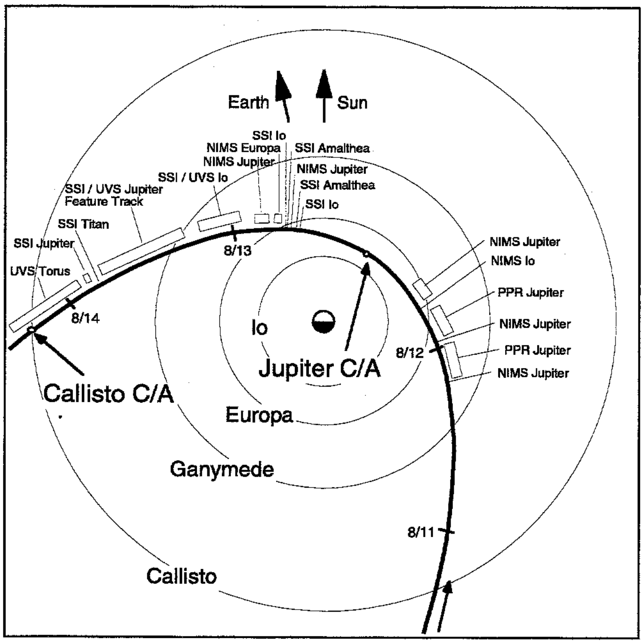

Figure 8a. C22 Encounter Trajectory

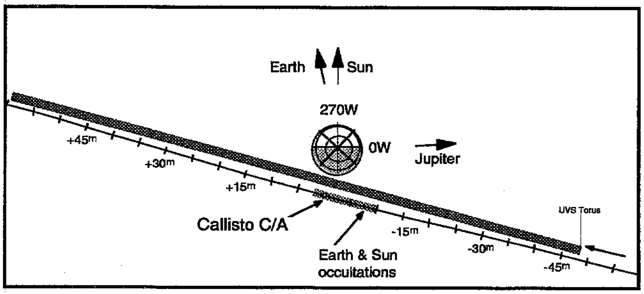

Figure 8b. C22 Flyby Geometry

this year. The Jupiter feature track observations targeted regions of latitude bands from the southern mid-latitudes to northern mid-to-high latitudes looking for hot spots and lighting. In addition, observations were made as each region moved from the lit side through the terminator. Night-side observations were used to search for lighting and dayside observations were focused on understanding three-dimensional dynamics of clouds.

The C22 UVS observations focused on Jupiter, Io, and Ganymede. Jupiter feature track observations were observed targeted regions and obtained data on stratospheric aerosols in each latitude band. In addition, the UVS will also study atmosphere-magnetosphere interactions and will observe Jupiter bright-side acetylene and ammonia emissions. The UVS will observe Io in eclipse and search for auroral emissions. The UVS will also obtain spectra of Ganymede to look for possible auroral glow.

The PPR took three Jupiter regional map observations in C22. Two of these observations were designed to study temperature field and wave structures downwind of the Great Red Spot. The third observation searched for "warm ovals" seen in Keck images and uncorrelated with any visible wavelength features.

7.7 Callisto 23

The fourth and final Callisto encounter and the twelfth encounter in GEM just successfully occurred on September 16, 1999, 17:27 UTC, at an altitude of 1,057 km. The encounter sequence was four days long and began on September 13, 1999, 20:00 UTC and ended on October 19, 1999 04:00 UTC. This orbit is limited to magnetospheric science only (Fields and Particles instruments plus UVS/EUV). No SSI, NIMS, or PPR science observations were planned during C23. Figures 9a and 9b provide details of the C23 encounter observations.

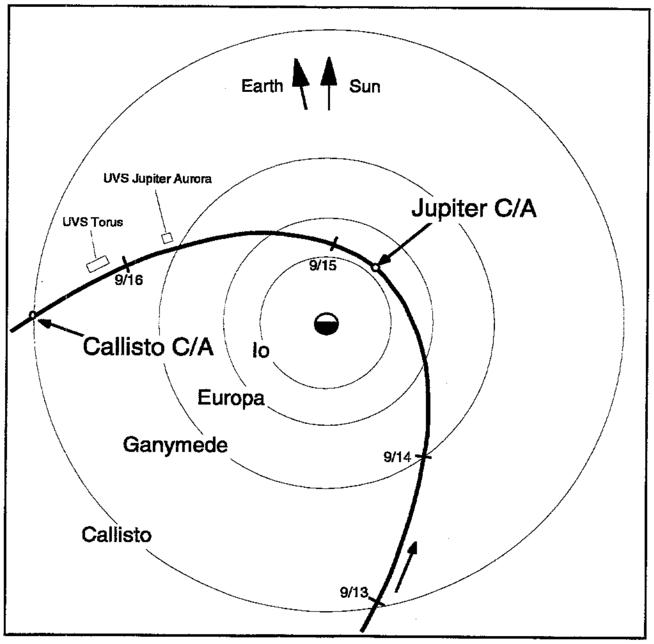

Figure 9a. C23 Encounter Trajectory

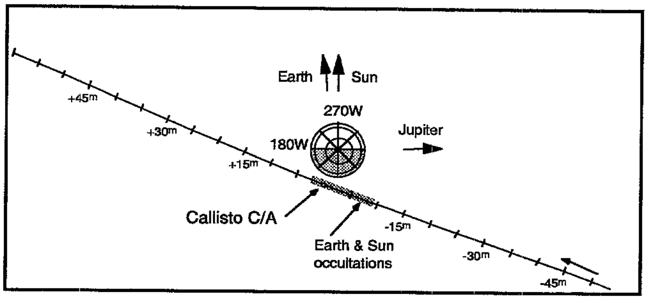

Figure 9b. C23 Flyby Geometry

The start of the C23 encounter signaled the resumption of the magnetospheric survey performed by the Fields and Particles Instruments. Recordings in this region provide valuable high-resolution data on the innermost magnetospheric/torus environment as the perijove is reduced. The in situ instruments will collectively make measurements of the magnetic fields and particles interactions within the region, including waves and radio signals. This orbit's recording is centered at perijove and is performed for seven hours.

During the close approach period with Callisto, the Radio Science Team conducted its third occultation experiment during GEM. During the experiment, the team observed the Ionosphere of Callisto and measured the vertical distribution of free electrons.

The EUV/UVS studied the Io Torus and the Jupiter aurora.

8. Io Encounter Plans and Beyond

8.1 Io 24

As of this writing, the Io encounters are in the planning stages. The first Io encounter and the thirteenth encounter in GEM will occur on October 11, 1999, 04:32 UTC, at an altitude of 611 km. The encounter sequence will be four days long and begin on October 10, 1999, 03:00 UTC and end on October 14, 1999, 03:00 UTC. Figures 10a and 10b provide details of the I24 encounter observations.

The fields and particles instruments will record for 6 hours during passage through the Io torus, through perijove, and up until 1 hour before Io closest approach. They will then wait for the tape recorder to change tracks, and continue recording for 1 hour, until 15 minutes after the spacecraft makes its close approach to Io.

SSI and NIMS will be concentrating strictly on imaging Io itself, with observations planned for numerous volcanic features and other areas of interest, including the regions around Pele, Pillan Patera, Colchis Montes, Zamama, Prometheus, Tohili, Dorian, Amarani, Skythia, Gish Bar, and the region near the terminator. SSI will finish off with regional stereo observations (to be combined with C21 encounter

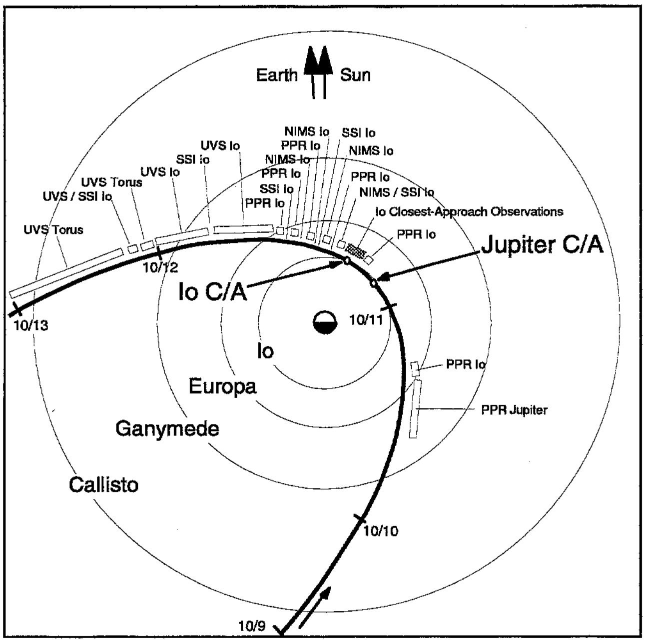

Figure 10a. I24 Encounter Trajectory

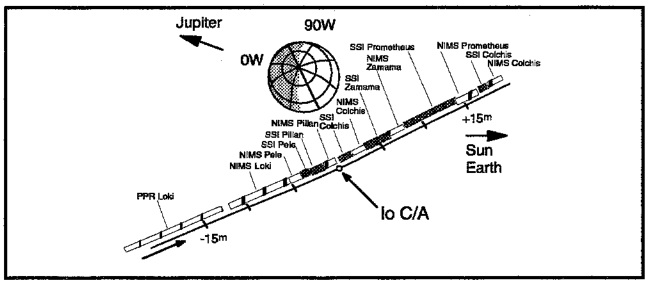

Figure 10b. I24 Flyby Geometry

observations of Io), a global color image, and an eclipse observation. NIMS will finish off with a regional map, a plume image and monitoring of Io for undiscovered hot spots. PPR starts off the encounter recording with a Jupiter atmospheric observation followed by an Io night-side radiometry observation of Acala and Loki before NIMS/SSI recording.

UVS will be collecting Io atmospheric observations, Io eclipse and surface observations, and observations of the noon ansa of the Io torus.

8.2 Io 25

The second Io encounter, and the fourteenth and last encounter in GEM, will occur on November 26, 1999, 04:05 UTC, at an altitude of 300 km. The encounter sequence will be about two days long and begin on November 25, 1999, 03:00 UTC and end on November 27, 1999, 03:00 UTC. Figures 11a and 11b provide details of the C23 encounter observations.

The fields and particles instruments will make recorded measurements that show how Io interacts with Jupiter's magnetic field, and that will help to confirm whether or not Io possesses an intrinsic magnetic field (as does Ganymede). They will also obtain an extended recording during the spacecraft's passage through the Io torus and the near-perijove region.

SSI and NIMS will be observing previously unseen portions of Europa's equatorial region facing Jupiter and at high northern latitudes. However, most of their observations are focused on Io, including a nightside observation of a hot spot called Creidne Patera, Culann, the Emonkong Patera caldera, a series of observations of the giant calderas on the northern hemisphere, the Tupan hotspot, the Prometheus volcanic plume, the Shamsu hotspot, and coverage of the south pole region. SSI also has an observation of Amalthea (one of Jupiter's small icy satellites) planned.

PPR starts off their encounter recording with a series of Europa observations, followed by Io global coverage, and specific observations of the region around the Pele Volcano and different Io hotspots.

UVS plans to ride along with the NIMS observations of Europa, as well as conducting some standalone observations of Io's atmosphere and the noon ansa of Io's torus.

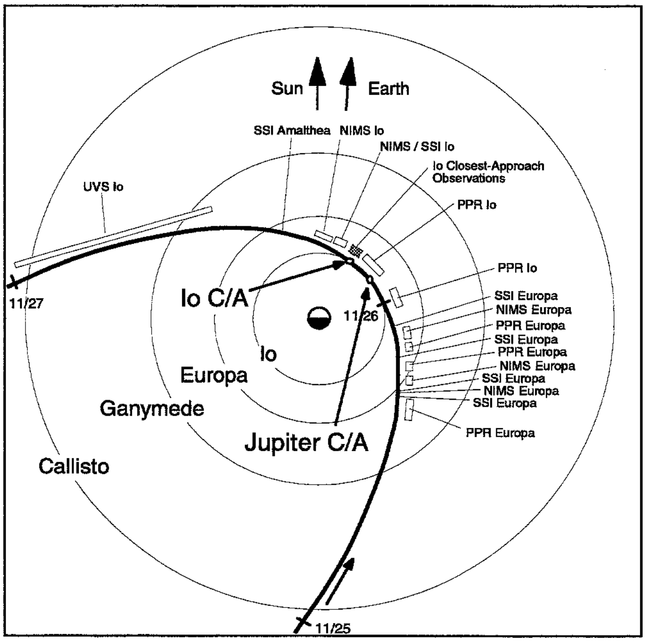

Figure 11a. I25 Encounter Trajectory

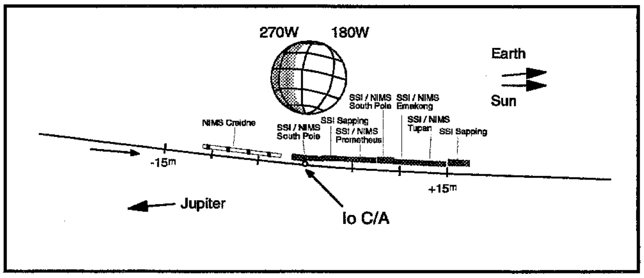

Figure 11b. I25 Flyby Geometry

8.3 Beyond the GEM

Another follow-on mission for Galileo, known as the Galileo Millennium Mission (GMM), is being discussed with NASA Headquarters. As an extension of the Galileo Europa Mission, it follows up on key questions raised during the GEM, and would provide further guidance to follow-on missions to Europa and Io. The GMM would further investigate Europa (including a magnetic field measurement key to the questions of liquid water), add further to our knowledge of Io, and, with the aid of two flybys of Ganymede, perform a joint investigation with Cassini of Jupiter's environment and how it is affected by the solar wind. Figure 12 shows the timeline for the GMM, and Figure 13 shows the trajectory planned for this proposal.

8.3.1 Europa 26

The sole Europa encounter and the first encounter in GMM will occur on January 3, 2000, 18:00 UTC, at an altitude of 374 km. The planned observations for E26 are greatly limited in scope, due to the very limited resources that are available for uplink development. The encounter was chosen specifically to address a measurement of the relationship of Europa's magnetic field to Jupiter's magnetic field. This measurement, in complement to measurements taken in the Galileo Prime Mission and GEM, will provide information to resolve the question of whether Europa's magnetic field interaction fits the preferred induced magnetic field model, or an intrinsically generated field. If there were an induced field, this would be substantial additional evidence for the existence of a subsurface liquid salty ocean on Europa. Additional observations will include remote sensing observations of several small satellites.

8.3.2 Io 27

The sole Io encounter and the second encounter in GMM will occur on February 22, 2000, 13:47 UTC, at an altitude of 374 km. The I27 encounter provides additional Io coverage, both in remote sensing and in fields and particles data, as well as a key backup opportunity for the GEM I24 and I25 encounters.

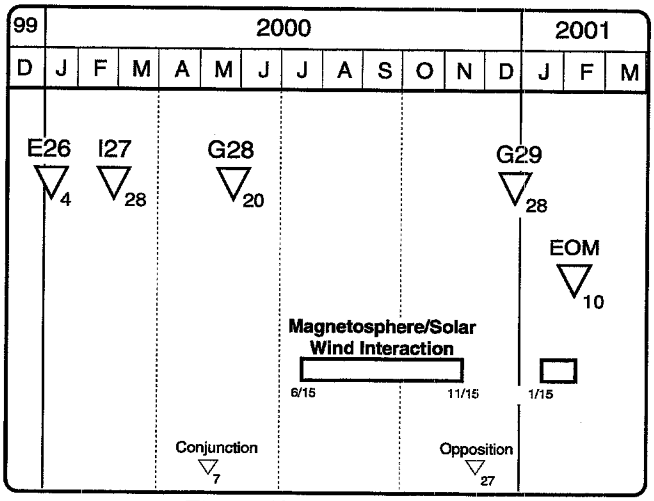

Figure 12. GMM Timeline

8.3.3 Ganymede 28 and 29

The G28 encounter will occur on May 20, 2000, 10:10 UTC, at an altitude of 900 km. The G29 encounter is planned for December 28, 2000, 08:45 UTC, at an altitude of 1,000 km, to coincide with Cassini's Jupiter close approach. G28 and G29 raise Galileo's apoapsis to outside of Jupiter's magnetosphere. Science objectives include magnetospheric measurements of the dusk side magnetosphere, joint observations with Cassini to investigate solar wind effects and nature of magnetospheric dynamics drivers. Galileo in situ data will be compared with Cassini remote sensing and the Galileo solar wind data supports Cassini magnetospheric encounters. In addition, Io volcanic observations will be

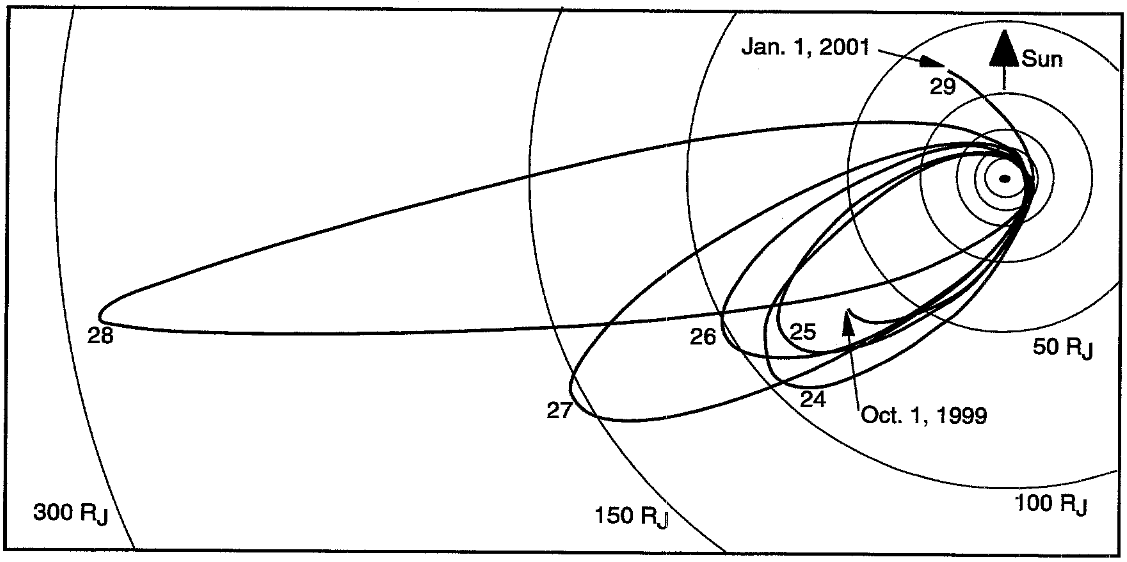

Figure 13. Proposed GMM Trajectory

related to magnetospheric state at Cassini encounter. Other observations will include atmospheric high-resolution dynamics imaging in conjunction with Cassini global movies, G28 Ganymede high-resolution imaging, and G29 Ganymede auroral data.

9. New Scientific Discoveries

There have been some exciting new discoveries from the Galileo data over the past year as a result of analysis of data returned during the prime mission, as well as data returned during GEM. Some of the more interesting results reported by the science teams are related to the formation of the Jovian ring system and surface structure and composition of Europa. It is now believed that we have conclusive evidence of the origin and formation of the Jovian ring system based on comprehensive analysis of the imaging data acquired during the prime mission. The Jovian ring system, which is comprised of a main bright ring, an ethereal gossamer ring, and a cloud-like ring halo, which is interior to the main ring, is formed by dust kicked up as interplanetary meteoroids, or fragments of comets or asteroids smash into the four small inner moons, Amalthea, Adrastea, Metis, and Thebe. The new Galileo data also shows that the gossamer ring is actually comprised of two distinct rings. The thickness of the bright ring and gossamer rings coincides precisely with the inclination of the orbit from Amalthea and Thebe. This is consistent with particles being blasted off of the moon and entering orbits similar to the source satellites. The main ring is believed to be formed by particles coming off of Adrastea and Metis.

For Europa, a significant discovery came from the analysis of spectroscopic data collected by the Near Infrared Mapping Spectrometer (NIMS) instrument. The recent data shows that the chemical hydrogen peroxide exists on the icy surface of Europa. Since hydrogen peroxide is a very reactive chemical it is being formed constantly on Europa as Jupiter's energetic particles smash apart molecules on the surface to produce new chemicals. This process is called radiolysis. Since hydrogen peroxide breaks down rapidly, due to interaction with ultraviolet light or contact with other chemicals, its life span on Europa is only a few weeks to months. In addition to this surface composition discovery, the imaging experiment returned high-resolution data from a Europan fault that rivals the length of the San Andreas Fault in California. The fault, known as Astypalaea Linea is one of the largest strike-slip faults on Europa. These types of faults are a result of two crustal blocks moving horizontally past one another. The new images show that the fault extends about 810 kilometers and has had about 50 kilometers of movement. It is believed that this fault is no longer active since newer crosscutting ridges have been formed on top of this fault.

In GEM, the Galileo instruments were able to observe a unique event on Jupiter - the merging of two "white oval" storms. For half a century three cold storms or "white ovals" have been observed on Jupiter in a band around Jupiter's mid-section. Sometime prior to the Europa 17 orbit, two of the three white ovals merged into one. The merging event actually occurred during superior conjunction when Jupiter was behind the sun; therefore no direct viewing of the merge was possible. During the Europa 17 orbit, observations of the merged white ovals were added to the plan. Prior to the merger, the white ovals were about two-thirds the diameter of the Earth, when combined they formed a feature as large as the Earth. The new white oval has some unique characteristics that the parent ovals did not. The new white oval cannot be seen at certain infrared wavelengths indicating that the white oval is not as deep as the previous storms. The previous ovals had upwelling winds in the center and downwelling around it. The new white oval has a very cold center temperature of -157°C, and is about one degree colder than its surroundings.

For Io, the first-ever color picture in visible light of the aurora on Io was released. This image was produced from data acquired during the prime mission as well as the Europa 15 orbit. The collision of Io's atmospheric gases and the energetic particles trapped in Jupiter's magnetic field produce the vivid colors seen in the image. The blue emission areas in the image are sites of plume vapor from Io volcanoes and the red and green emissions are probably produced in a process similar to the Earth's aurora.

10. Summary

As the Project looks forward to the Io encounters and the future, it is important also to look back on the successes of the past. The Galileo Project has been able to rack up an outstanding series of space "firsts", ranging from the first images of an asteroid, first images of an asteroid moon, through first entry and sampling of an outer planet's atmosphere. The real legacy of the Galileo Project though, is the scientific treasures that will be left to our grandchildren. The data that Galileo returned will be used for decades, if not hundreds of years. The long delayed Io data will be added to that treasure trove, and passed on to the coming generations.

11. Acknowledgements

The success of the Galileo Europa Mission is due to the efforts of a large number of people, all of whom deserve recognition for their contributions. A special recognition is due to the GEM team itself, which has been able to accomplish this ambitious undertaking with only the significantly reduced resources available.

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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.

12. References

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A View From The Galileo Orbiter—
Selected Images Since The Last IAF

Historic Merger of Storms on Jupiter

Jupiter's white oval storms before (top) and after (bottom) their historic merger. The smallest resolved features are tens of kilometers in size. The three classic white ovals which formed in the 1930's have occupied the band from 31 to 35 degrees south planetocentric latitude ever since. The top panel shows the two of the ovals with a pear-shaped region between them. Winds around the white ovals are counterclockwise (anticyclonic), indicating they are high-pressure systems. Winds around the pear-shaped region are clockwise (cyclonic), indicating that it is a low-pressure region. The two white ovals were named BC (right) and DE (left) shortly after they formed. The lower panel shows the merged oval, named BE. The pear-shaped cyclonic region is absent. The merger took place in February 1998 when Jupiter was behind the Sun and could not be seen from Earth.

PIA01650

Mitten Shaped Region on Europa

This view of Jupiter's icy moon Europa shows a region shaped like a mitten that has a texture similar to the matrix of chaotic terrain, which is seen in medium and high resolution images of numerous locations across Europa's surface. Development of such terrain may be one of the major processes for resurfacing the moon. North is to the top and the sun illuminates the surface from the left. The material in the "catcher's mitt" has the appearance of frozen slush and seems to bulge upward from the adjacent surface, which has been bent downward and cracked, especially along the southwest (lower left) margins. Scientists on the Galileo imaging team are exploring various hypotheses for the formation of such terrain including solid-state convection (vertical movement between areas which differ in density due to heating), upwelling of viscous icy "lava", or liquid water melting through from a subsurface ocean.

PIA01640

Double Ridges, Dark Spots, and Smooth Icy Plains on Europa

This mosaic of a region in the northern hemisphere of Jupiter's moon, Europa, displays many of the features which are typical on the satellite's icy surface. Brown, linear (double) ridges extend prominently across the scene. They could be frozen remnants of cryovolcanic activity which occurred when water or partly molten water ice erupted on the Europan surface. A geologically older, smoother surface, bluish in tone, underlies the ridge system. The blue surface is composed of almost pure water ice, whereas the composition of the dark, brownish spots and ridges is not certain. One possibility is that they contain evaporites such as mineral salts in a matrix of high water content.

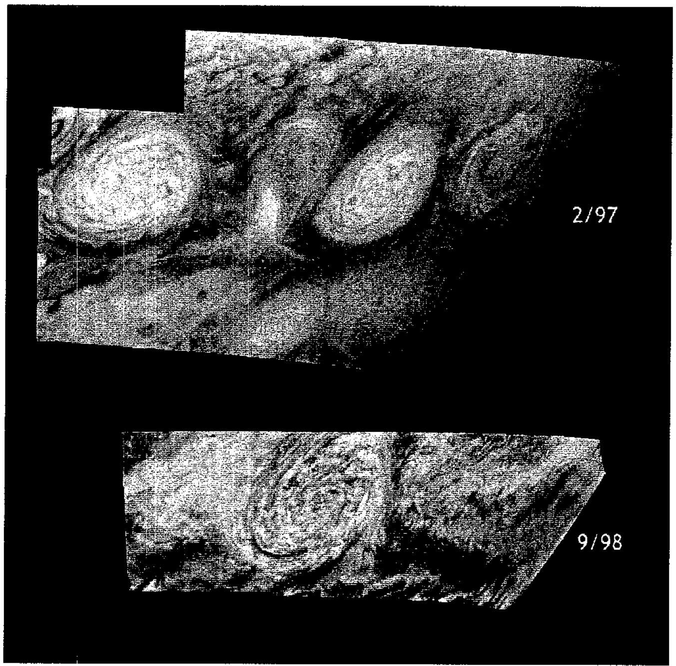
PIA01641

The San Andreas Fault and a Strike-slip Fault on Europa

The mosaic on the right of the south polar region of Jupiter's moon Europa shows the northern 290 kilometers (180 miles) of a strike-slip fault named Astypalaea Linea. A strike-slip fault is one in which two crustal blocks move horizontally past one another, similar to two opposing lanes of traffic. The overal motion along the Europan fault seems to have followed a continuous narrow crack along the entire length of the feature, with a path resembling steps on a staircase crossing zones which have been pulled apart. The images show that about 50 kilometers (30 miles) of displacement have taken place along the fault. Opposite sides of the fault can be reconstructed like a puzzle, matching the shape of the sides as well as older individual cracks and ridges that had been broken by its movements. The entire fault is about 810 kilometers (500 miles) long, the size of the California portion of the San Andreas fault on Earth which runs from the California-Mexico border north to the San Francisco Bay.

The left mosaic shows the portion of the San Andreas fault near California's San Francisco Bay that has been scaled to the same size and resoltion as the Europa image. Each covers an area approximately 170 by 193 kilometers (105 by 120 miles). The red line marks the once active central crack of the Europan fault (right) and the line of the San Andreas fault (left).

PIA01645



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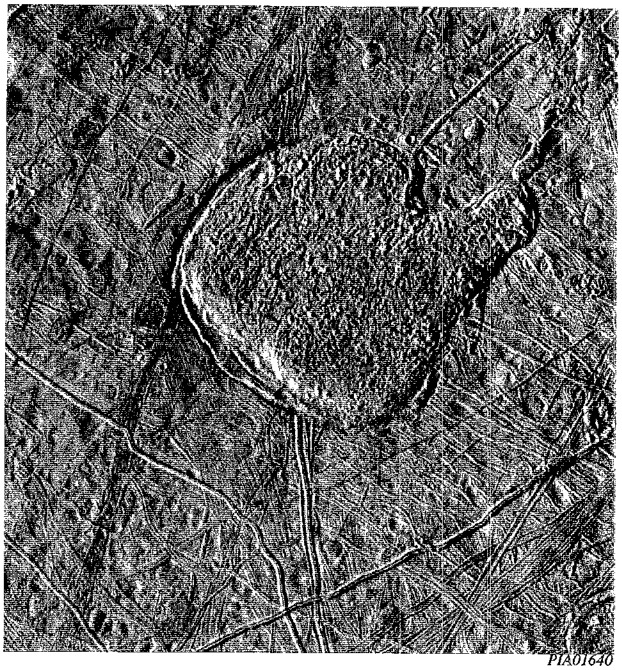

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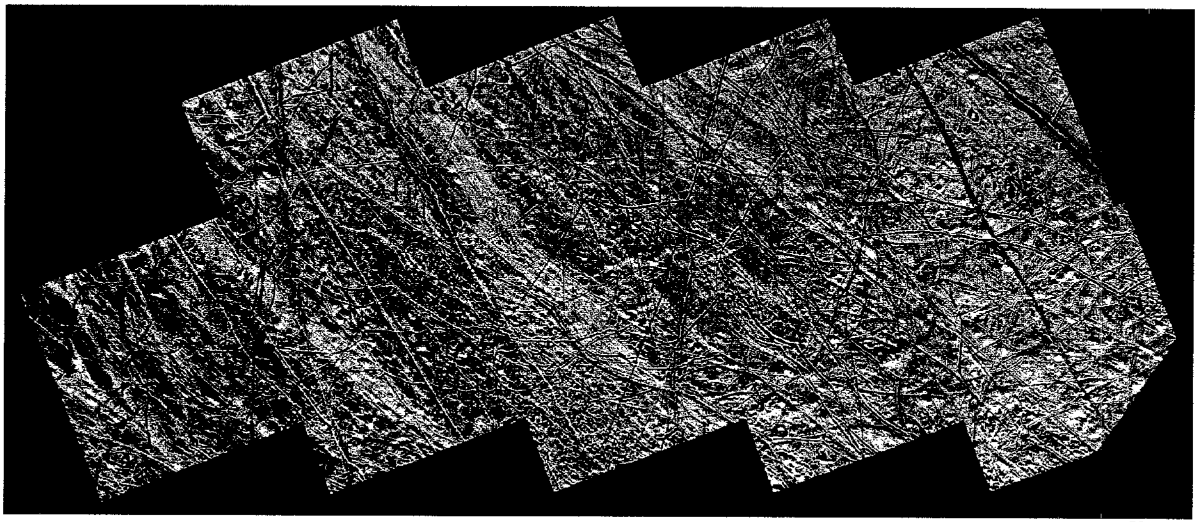

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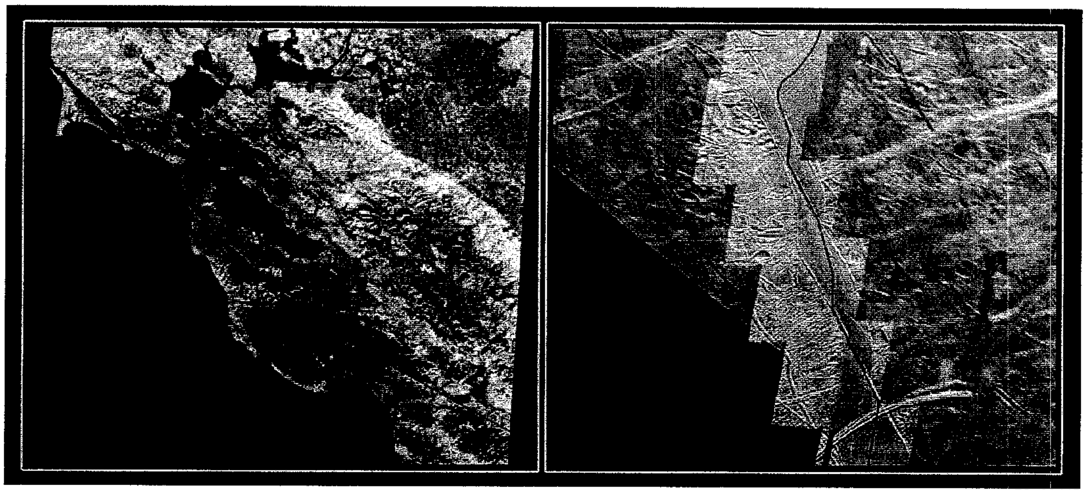

PIA01645

Three Dimensional View of Double Ridges on Europa

These images reveal the dramatic topography of Europa's icy crust. North is to the right. An east-west running double ridge with a deep intervening trough cuts across older background plain and the darker wedge shaped band. The numerous cracks and bands of such terrain may indicate where the crust has pulled apart and sometimes allowed dark material from beneath the surface to well up and fill the cracks. A computer generated three dimensional perspective (upper right) shows that bright material, probably pure water ice, prevails at the ridge crests and slopes while most dark material (perhaps ice mixed with silicates or hydrated salts) is confined to lower areas such as valley floors. The northernmost (right) slope which faces north, however, has a larger concentration of dark material than south facing slopes. The model on the lower right has been color coded to accentuate elevations. The red tones indicate that the crests of the ridge system reach elevations of more than 300 meters (330 yards) above the surrounding furrowed plains (blue and purple tones). The two ridges are separated by a valley about 1.5 kilometers (0.9 mile) wide.

The Stereo perspective combines high resolution images obtained from two different viewing angles. Such a three dimensional model is similar to the three dimensional scenes our brains construct when both eyes view something from two angles.

PIA01664

Rugged Terrain on Europa in 3-D Stereo

This three dimensional effect is created by superimposing images of Jupiter's moon, Europa, which were taken from two slightly different perspectives. When viewed through red (left eye) and blue(right-eye) filters as with red-blue glasses, the product shows variations in height of surface features.

This stereo view is of an area just southeast of the Tyre multi-ring structure on Jupiter's icy moon Europa. The circular to oval shaped pits that contain dark material are secondary craters formed by debris which was tossed from the site of the impact which formed Tyre, then reimpacted some distance away. Ridges appear as high-standing features and troughs as low-standing features. Regions of chaotic terrain also have topographic expression; for example, the one with large rafts and blocky material (upper right) appears lower than the surrounding terrain.

PIA01654

Thera and Thrace on Europa

Thera and Thrace are two dark, reddish regions of enigmatic terrain that disrupt the older icy ridged plains on Jupiter's moon Europa. North is toward the top of the mosaic. Thera (left) is about 70 kilometers wide by 85 kilometers high (43 by 53 miles) and appears to lie slightly below the level of the surrounding plains. Some bright icy plates which are observed inside appear to be dislodged from the edges of the chaes region. The curved fractures along its boundaries suggest that collapse may have been involved in Thera's formation. In contrast, Thrace (right) is longer, shows a hummocky texture, and appears to stand at or slightly above the older surrounding bright plains. Thrace abuts the gray band Libya Linea to the south and appears to darken Libya. One model for the formation of these and other chaos regions on Europa is complete melt-through of Europa's icy shell from an ocean below. Another model is that warm ice welled up from below and caused partial melting and disruption of the surface.

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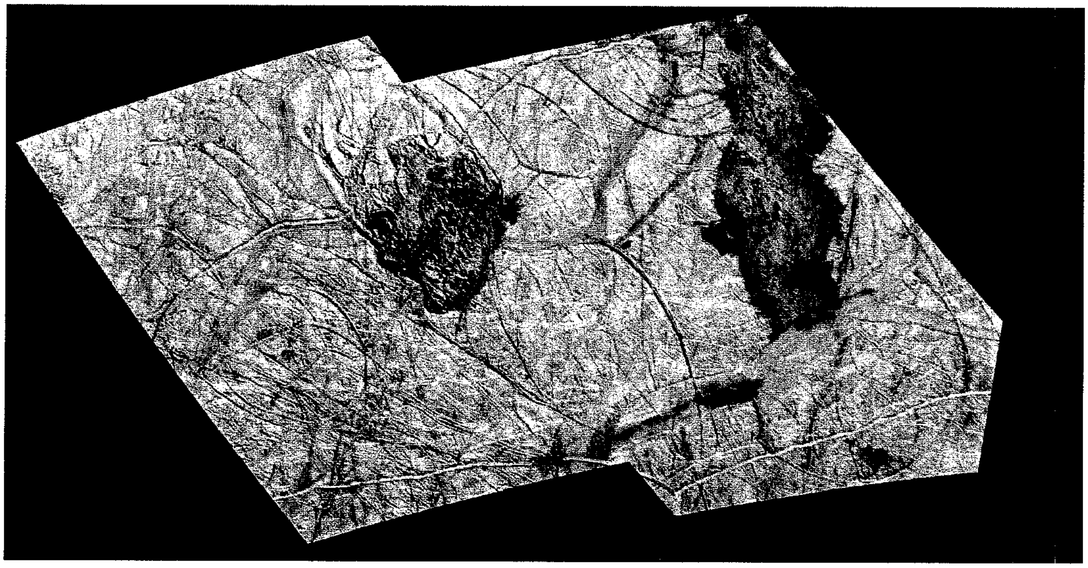

PIA02099

Closeups of Io (False Color)

This color mosaic is the highest resolution Io image taken by the Galileo spacecraft. It uses the near-infrared, green and violet filters (slightly more than the visible range) of the spacecraft's camera, processed to enhance more subtle color variations. Most of Io's surface has pastel colors, punctuated by black, brown, green, orange, and red areas near the active volcanic centers.

This improved resolution reveals small-scale color areas which were not recognized previously and which suggest that the lava and sulfurous deposits are composed of complex mixtures (close-up A). Some of the bright, whitish, high-latitude (near the top and tottom) deposits have an ethereal quality like a transparent covering of frost (close-up B). Bright red areas were seen in previous images only as diffuse deposits. However, they now appear as both diffuse deposits and sharp linear features like fissures (close-up C). Some volcanic centers have bright and colorful flows, perhaps due to flows of sulfur (rather than silicate) lava (close-up D). In this region of Io, bright, white material can also be seen to emanate from linear rifts and cliffs.

Comparison of this mosaic to previous Galileo images reveals many changes due to ongoing volcanic activity. Galileo is scheduled to make two close passes of Io in october and November. Most of the high-resolution targets for these flybys are seen on the hemisphere shown here.

PIA02319

Io's Aurorae

This eerie view of Jupiter's moon Io in eclipse (left) was acquired by NASA's Galileo spacecraft while the moon was in Jupiter's shadow. Gases above the satellite's surface produced a ghostly glow that could be seen at visible wavelengths (red, green, and violet). The vivid colors, caused by collisions between Io's atmospheric gases and energetic charged particles trapped in Jupiter's magnetic field, had not previously been observed. The green and red emissions are probably produced by mechanisms similar to those in Earth's polar regions that produce the aurora, or northern and southern lights. Bright blue glows mark the sites of dense plumes of volcanic vapor, and may be places where Io is electrically connected to Jupiter.

PIA01637

Sequence Showing Active Volcanic Plumes

These four views of Io clearly show airborne plumes of gas and dust from two of Io's active volcanoes. Zamama and Prometheus. The bottom row consists of enlargements of the plume areas. The first view (left) depicts the tops of both plumes on Io's bright limb or edge. In the second image, an excellent view of Zamama on the bright limb reveals the umbrella-shaped structure. The third image also shows both plumes as bright spots against Io's illuminated crescent. In the fourth view (right) where the volcanic centers lie beyond the terminator (day-night boundary), the tall plumes are visible because they extend up into sunlight. The plumes have a height of about 100 kilometers (60 miles). Both plumes have been active throughout the Galileo tour of the Jovian system which began in 1996. Zamama, however, is considerably larger and brighter in these images from the spacecraft's eleventh orbit of Jupiter than when imaged previously. Prometheus was also active during 1979 flybys of NASA's Voyager spacecraft.

PIA01652

Io's Pele Hemisphere After Pilan Changes

In this enhanced color composite of Io, deposits of sulfur dioxide frost appear in white and grey hues while yellowish and brownish hues are probably due to other sulfurous materials. Bright red materials, such as the prominent ring surrounding Pele, and "black" spots with low brightness mark areas of recent volcanic activity and are usually associated with high temperatures and surface changes. One of the most dramatic changes is the appearance of a new dark spot (upper right edge of Pele), 400 kilometers (250 miles) in diameter which surrounds a volcanic center named Pillan Patera. The dark spot did not exist in images obtained 5 months earlier, but Galileo imaged a 120 kilometers (75 miles) high plume erupting from this location during its ninth orbit.

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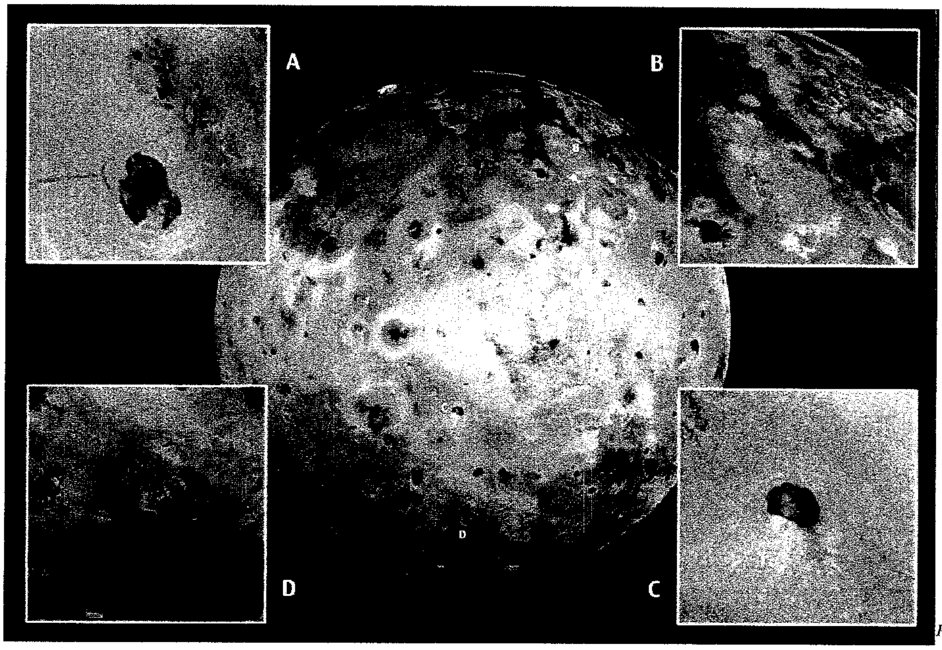

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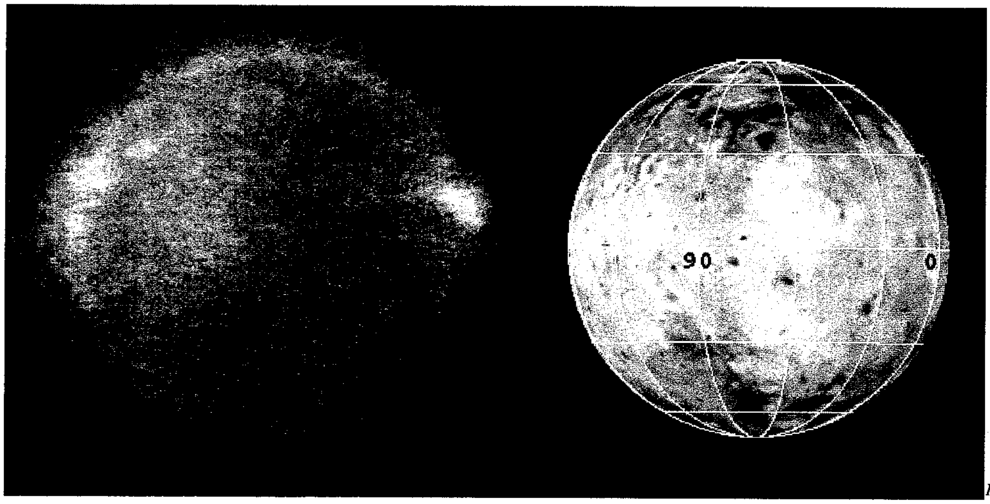

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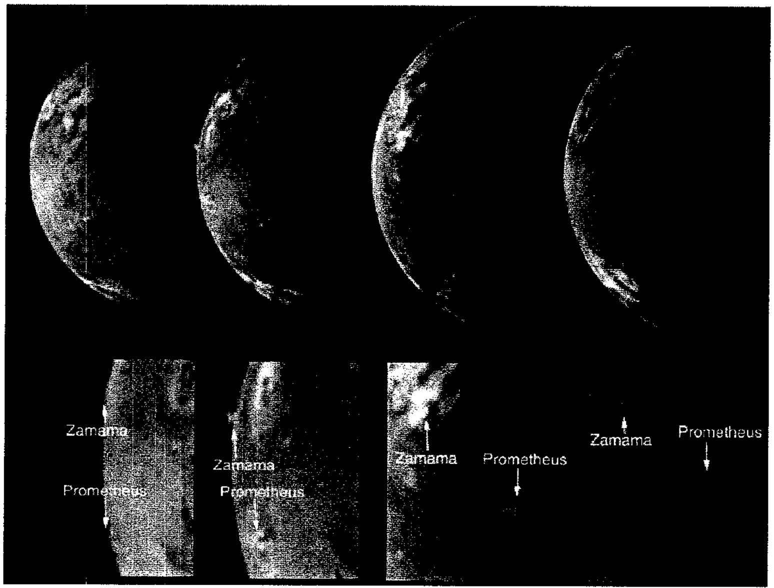

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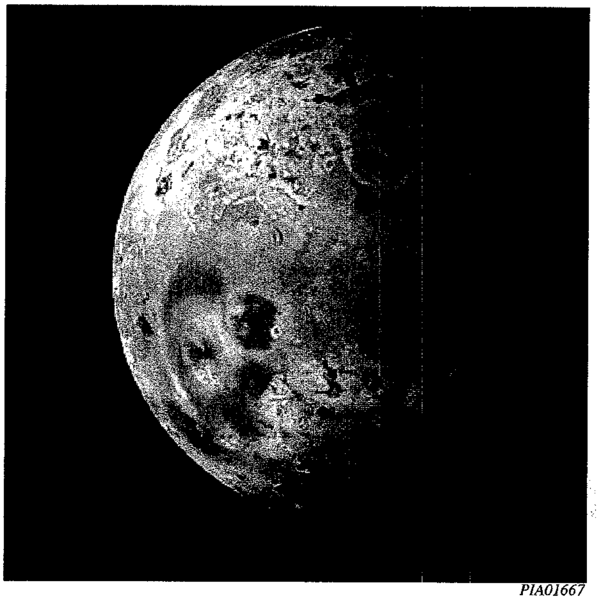

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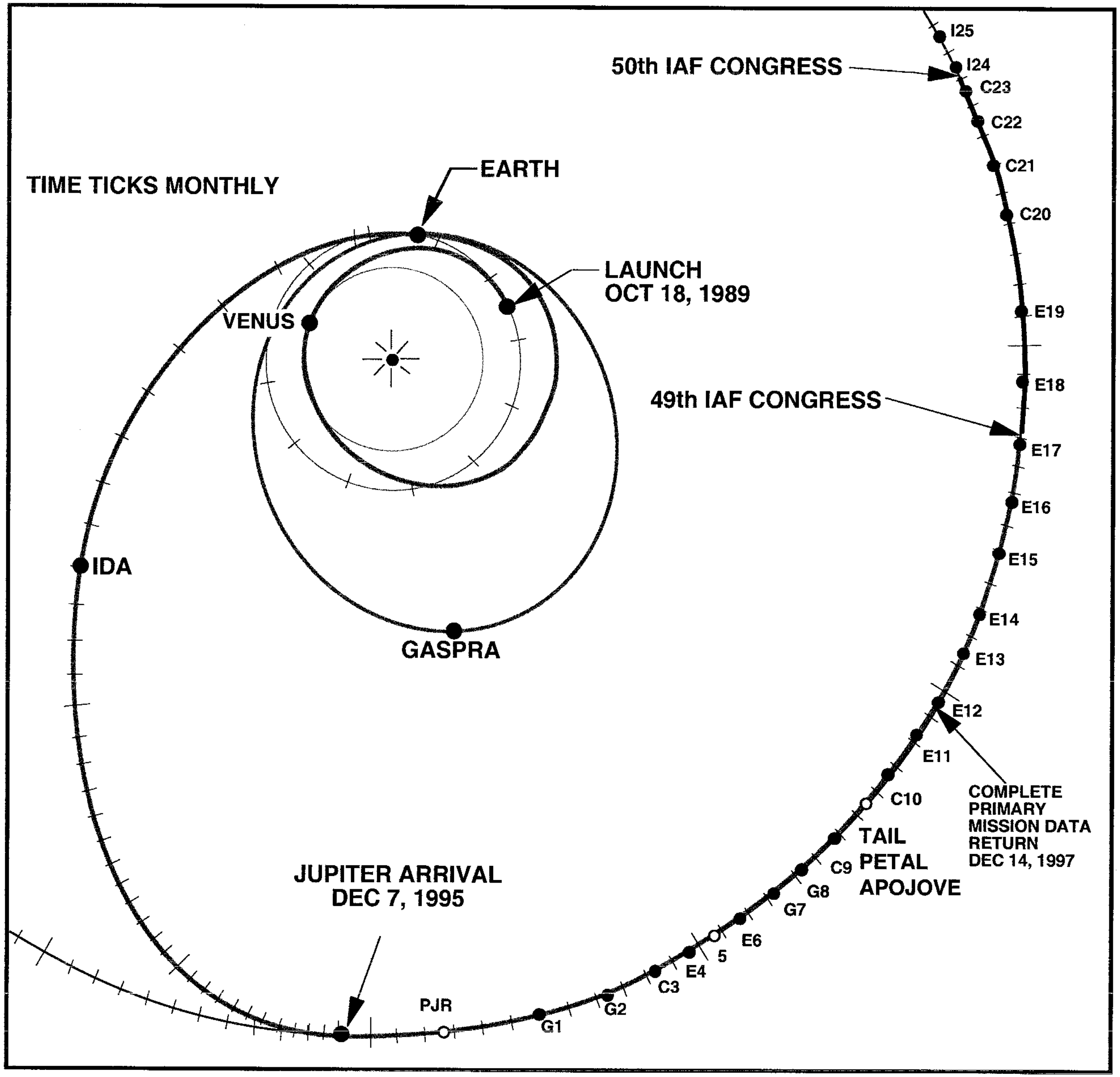
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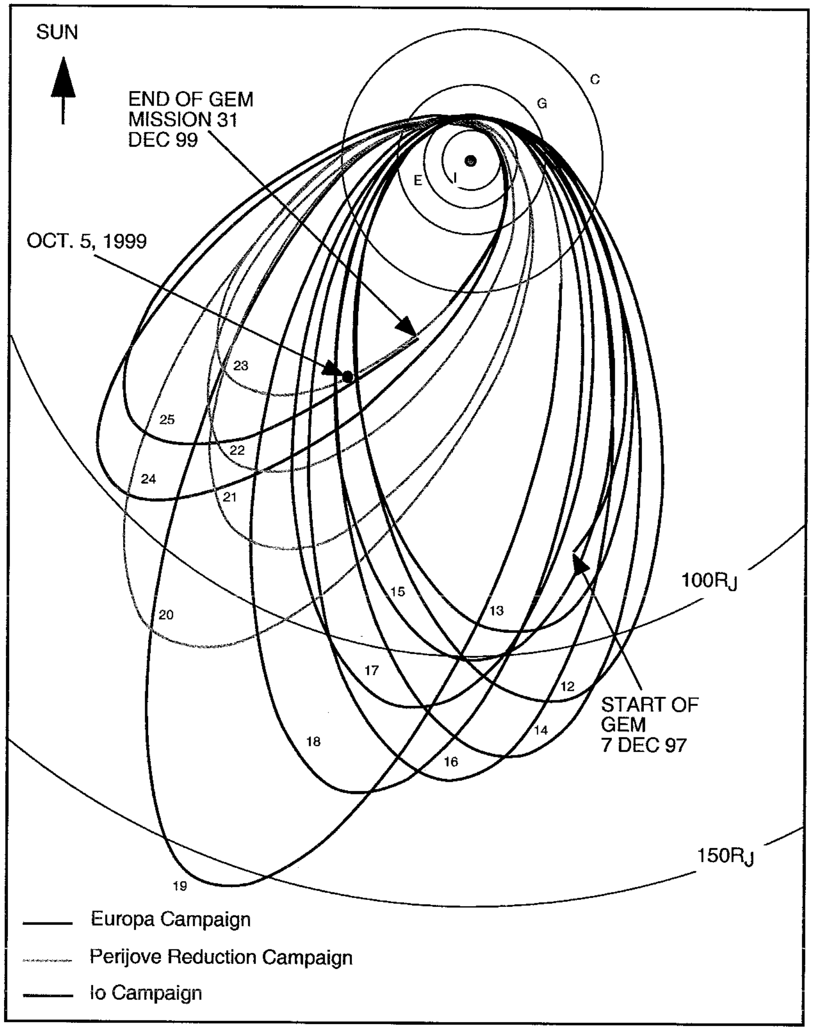
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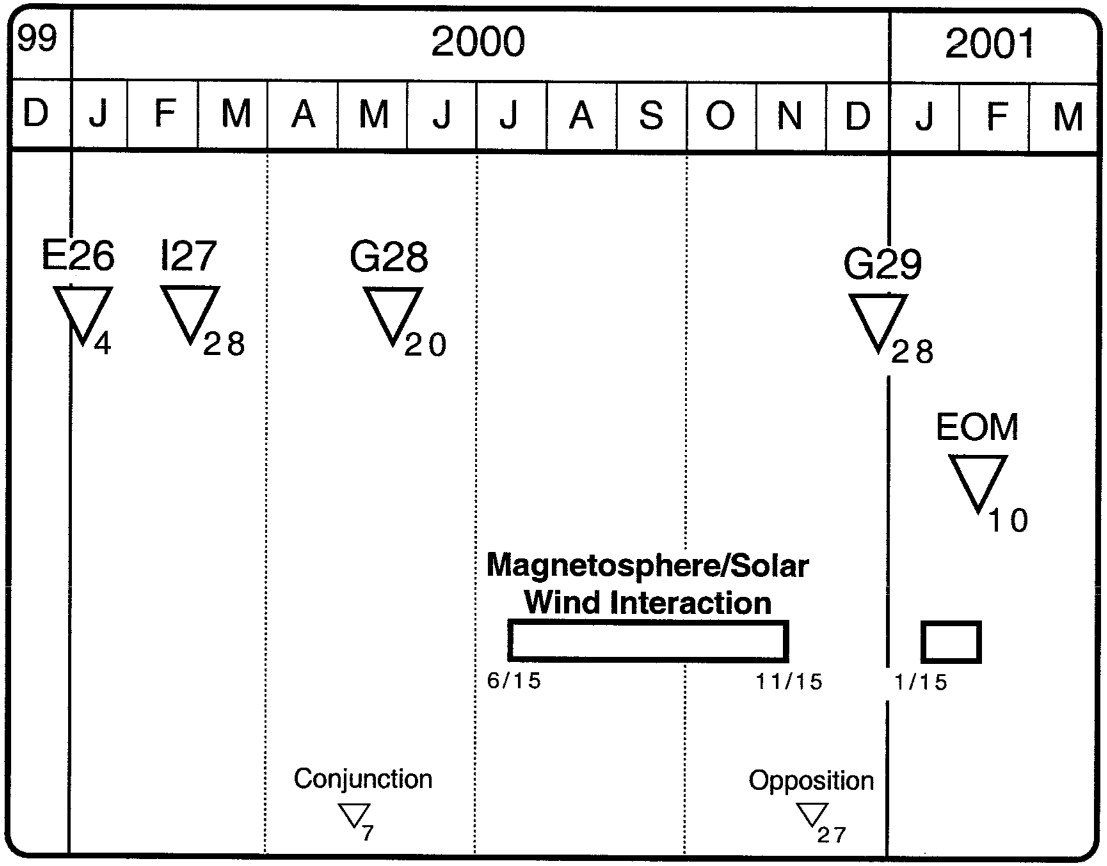

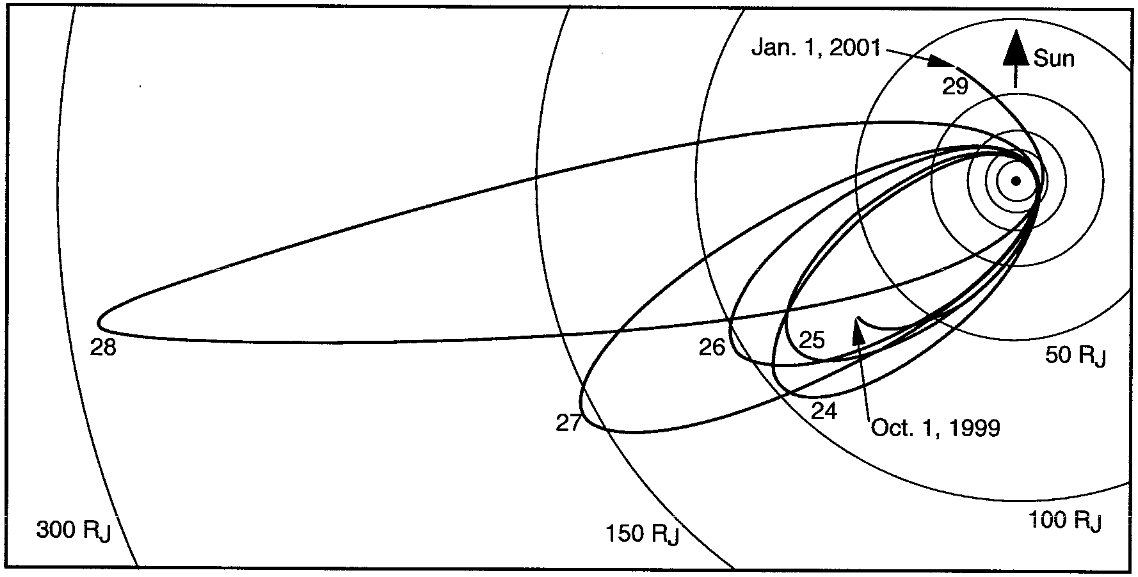

Orbit numbers denote position near apoapsis (except 29) following same numbered satellite encounter