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GALILEO AT JUPITER: FIRST RESULTS

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On the occasion of this historic meeting in **Padua,** it is interesting to speculate about how Galileo himself would have viewed the proceedings. I can easily image him coming into one of the sessions and conducting a little examination to bring himself up to date. What experiments are you doing? Why **are** you doing them? What have you learned? Despite the intervening centuries, I think it would have been very easy to describe what we are doing to Galileo. There would be a few things he would have to catch up on, for instance, quantum theory, high energy physics, and radio communications. He also would be very interested in the work our mission designers have done on the use of gravitational assists for our trajectories. However, many of the fundamentals are still the same as they were in Galileo's time. He **certainly** would understand **why** we want to understand. He would recognize that we are still asking many of the questions he was interested in – what are the planets, what **are** they made of, how did they form, what has happened to them since they formed. In this brief discussion of the preliminary results from the spacecraft named for the **great** astronomer/physicist I hope to convey some of the excitement and wonder of new discovery which motivated our illustrious predecessor. I hope and believe that Galileo would have been pleased with what we have done with his spacecraft.

On the 7th of December, 1995 the Galileo spacecraft arrived at Jupiter. It began its mission by collecting data radioed **from** the Probe as it descended into Jupiter's atmosphere. A short time later it fired its main engine for about 45 minutes, slowing the craft enough to be captured by Jupiter's gravity. The vessel named for the discoverer of Jupiter's natural satellites thus became the first known artificial satellite of the giant planet. As the data from the Probe were slowly relayed to the earth, the flight team at JPL prepared to send the necessary programs and commands to allow the Orbiter to begin its scientific exploration of the Jovian system. There are three broad scientific objectives of the Galileo mission: 1.) Studies of the planet itself, 2.) Studies of Jupiter's magnetospheric environment - the magnetic field, low and high energy particle radiation and wave phenomena, and 3.) Studies of the moons named after Galileo-The Galilean satellites Io, Europa, Ganymede, and Callisto. Galileo's experiments are interdisciplinary and designed to investigate each of these areas in depth as well as the many interactions among the different parts of the system.

I will first discuss some of the results connected with the planet itself. These came from Probe spacecraft, which provided the first ever *in situ* measurements of the atmosphere of an outer planet. It quickly became apparent that the probe had entered in an unusual part of the atmosphere – (that is, if any portion of the variegated mosaic of swirling storms and clouds that make up the "visible" surface of the planet can be termed more unusual than another)! Infrared images from NASA's Infrared Telescope Facility and pictures from the Hubble Space Telescope of the region near the equator of Jupiter where the Probe was targeted show that the Probe descended into a feature known as a "5-micron hot spot" – a relatively cloud-free region in the atmosphere where infrared radiation from deep, warm layers in the atmosphere can escape.

As the Probe descended on its parachute, the basic information about the atmosphere needed to interpret and compare all the data was provided by the Atmospheric Structure Instrument, which continuously recorded the temperature and pressure outside the Probe as the mission progressed. This experiment showed that temperature varies with pressure as expected if the gas is very dry and that the Probe survived to a depth of about 21 bars where the temperature was ??? K.

The Probe carried a very sophisticated instrument to measure the composition of the atmosphere called the Neutral Mass Spectrometer (NMS). The NMS team found that as the Probe descended through the atmosphere many chemical elements and species were present in more or less the abundances expected from earlier observations and theoretical models. Helium (also measured very precisely by the Helium Abundance Detector, or HAD) is present in approximately the same proportions relative to hydrogen as the early sun; Carbon and sulfur are enhanced relative to “solar abundances”, as expected. A major surprise were the low levels of oxygen during most of the descent, as inferred from the low content of water vapor in the atmosphere. Most of the science team feel it is unlikely that Jupiter as a whole is deficient in oxygen, but the puzzle is - why is the gas in the Probe entry site so dry?

A clever experiment called the Doppler Wind Experiment allowed us to measure the strength of the winds as the Probe descended. This experiment uses the change in frequency of the radio signal from the Probe to derive how fast the little capsule was being carried along by the wind as it fell into Jupiter’s depths. Jupiter’s winds blow in jetstream-like bands at high velocities from west to east at the top of the atmosphere. The wind experiment found that as the Probe descended the winds did not diminish as they do on Earth, but actually got somewhat stronger and continued to remain strong throughout the descent, to pressure levels of more than 20 bars. This suggests strongly that the *driving* force for much of Jupiter’s weather is the deep-seated heat flowing from the interior rather than absorbed sunlight at the top.

The two instruments which were most sensitive to the presence of clouds were the Nephelometer (which shines a laser into the atmosphere from the Probe and measures how much light is scattered back from cloud particles) and the Net Flux Radiometer (which measures the amount of sunlight coming from above and the amount of thermal heat radiation from the atmosphere in the vicinity of the Probe). Both experiments saw evidence for only very tenuous cloud layers, consistent with the conclusion that the entry site was in a relatively cloud-free region generally. Another experiment, the LRD, searched for evidence of lightning both by looking for flashes of light and by scanning for the radio “static” that is produced by distant lightning. No optical flashes from lightning were detected near the Probe, but the radio picked up signals from distant lightning, which indicated that Jupiter has less frequent lightning (on a per square kilometer basis) than the Earth, but that the lightning strokes when they do occur are much stronger (carry more current) than their terrestrial counterparts.

Once in orbit, Galileo began to use its remote sensing instruments to study the atmosphere and the satellites. Four experiments are mounted on a platform which can be pointed with high precision, much like a telescope mount. The Ultraviolet Spectrometer (UVS) can be used to study composition and energetic in the atmosphere by looking for auroral emissions and other spectral “markers” in the atmosphere. The PhotoPolarimeter Radiometer (PPR) measures cloud properties and can make thermal maps of the atmosphere and satellite surfaces, sensing infrared radiation coming from various levels in the atmosphere. The camera system is called the Solid State Imager (SS1) and uses a very sensitive CCD chip and optical filters to take images at wavelengths ranging from the ultraviolet to the near infrared (~ 1.0 microns). The Near Infrared Mapping Spectrometer (NIMS) scans images in up to 408 spectral channels from 0.7 microns to 5.0 microns in the infrared.

Among the atmospheric results already obtained from the Orbiter are a composite study of Jupiter's huge storm system, the Great Red Spot (GRS), and "maps" of derived water vapor abundance at various places to compare with the Probe results. To study the region around the GRS, the camera team put together "false color" images from individual images taken in three infrared filters. Two of the filters are in spectral regions where methane gas absorbs light, the other covers wavelengths where there is little such absorption. These images can be used to infer the height of clouds around the GRS. The composite image shows regions in the atmosphere of Jupiter that are similar to huge convective cells in the Earth's atmosphere, in effect, huge scale thunderstorms. This suggests that, as with the Earth's atmosphere, one of the sources of energy driving Jupiter's weather may be the release of latent heat in these storms.

Spectra from the NIMS experiment in the 5 micron region can be modeled to derive estimates of the water vapor abundance down to pressure levels of about 5-6 bars. There are uncertainties in the modeling techniques, of course, but the preliminary results are very interesting. In regions where there is a reasonably strong signal, the NIMS investigators find that the derived water abundances can vary by up to a factor of 100-1000! This suggests that a meteorological explanation will have to be found for the extremely "dry" conditions found at the Probe entry site.

Each of the four Galilean (or Medician) satellites is an interesting world in its own right. We knew from Voyager data taken in 1979 that each has unique characteristics, and detailed study of these moons is a high priority objective for Galileo. Even before the spacecraft got into orbit it had begun its exploration of the satellites with a close (~ 900 km altitude) flyby of Io. This flyby helped slow the spacecraft so that it could get into orbit easier and therefore save propellant. It also gave us fascinating insights into this unique and highly volcanic world. By analyzing Io's gravity field through the use of the Doppler effect in the radio signal from Galileo, the Celestial Mechanics team were able to determine a key dynamical parameter, its moment of inertia. The low value of the moment of inertia shows that Io is not a homogeneous sphere, but rather must have denser material concentrated toward its center. A mathematical model based on these data and estimates of Io's composition indicates that the moon very likely has a metallic core of iron and iron sulfide approximately half its radius in size. We also found that Io profoundly affects the magnetic field and flow of high and low energy particles in its vicinity. The magnetic field decreased sharply near closest approach to Io with a complex signature. At the same time there were observations of both strong field aligned "beams" of high energy particles and a region of cold high density plasma 900 kilometers above Io's surface. There is still debate over whether the observed magnetic signature is due entirely to the interaction of Io with the plasma flow in the magnetosphere or whether there is some contribution from an intrinsic field from Io itself. Further close flybys of this intriguing moon may be necessary to resolve the question.

During the Orbiter's mission, the spacecraft does not perform further close flybys of Io because of possible darnage to the electronics from many passes through the intense radiation belts (which increase in intensity rapidly toward Jupiter). However, the orbits of the Galileo "tour" of the satellite system are well suited to conducting a long-term "volcano watch" program from a greater distance. Hence on most orbits, a series of observations of Io are planned to monitor the volcanic activity, comparing it to what was seen in 1979 by Voyager and cataloging the changes in the dynamic moon during the two year primary mission. During the planned Galileo Europa Mission, the Galileo flight team hopes to be able conduct one or two more final flybys of this satellite (accepting some risk from the radiation) to closeout the extended operations in late 1999.

So far Galileo has already recorded some remarkable changes on Io. In searching for the geyser-like volcanic “plumes” seen by Voyager, the SS1 team has found fewer of them than expected from the Voyager data. Several large plumes such as those at Pele and Loki Patera were not detected on the initial orbits. Given other evidence for continued volcanic activity in these regions and evidence for gas activity from Hubble Space Telescope data this lack of visibility maybe due to a lack of the tiny condensed particles which make the plumes visible in scattered sunlight. At least one new prominent plume was seen over Ra Patera in Galileo images along with evidence from HST and Galileo that large scale changes had occurred in surface deposits in the region. In addition, one of the plumes which was prominent in all the Voyager data, Prometheus, appears to be very similar to its appearance in 1979. Closer examination of the Prometheus images however shows that while the plume is very similar to the 1979 plume, the center of the activity (or vent) has shifted about 75 km to the west of where it was previously. Other changes in the surface and shifts in volcanic sites can be detected by detailed comparisons of Voyager and Galileo images.

The NIMS experiment also contributes significantly to Galileo’s “IO Volcano Observatory”. Although its images are not as detailed as thosefrom the camera, its broad spectral range allows it to detect many more volcanic hotspots and to infer their size and temperature from analysis of the emission spectrum at the longer wavelengths. The NIMS data show that small, high temperature hotspots are abundant on the surface, most of them probably due to silicate lava (molten rock) in small areas on the surface.

Much of Io’s tenuous atmosphere is apparently derived from volcanic gases and Galileo was able to take a picture of this patchy atmosphere while Io was in Jupiter’s shadow. With no light from the sun or from “Jupitershine”, all of the light seen in this clear filter image comes from either glowing volcanic lavas or auroral emissions from atmospheric gases excited by electron impact. The brightest spots in this image are less than a single resolution element (pixel) and are located at known volcanic sites on Io's surface. The intensity of these signals indicates that the hot lava on the surface must have temperatures of at least 700-800 K A thin faint glow outlines the entire circumference of the moon, probably originating in a low altitude layer of extremely thin gas spread everywhere over the surface. In addition there are patches of brighter glows. One of these is coincident with the plume seen over Ra Patera and probably comes from gases in this large volcanic geyser. The brightest of the other patches is a large area not located exactly over any particular known vent but in the general vicinity of several known or suspected eruption sites and is therefore probably mostly due to volcanically derived gases.

The first two orbits had as their target the huge icy moon Ganymede. Ganymede is a little bit larger than the planet Mercury and made of -50% ice and 50% rock. Its icy surface shows evidence for extensive geological modification. Older areas have *many* impact craters while other areas exhibit complex tectonic landforms known as "grooved terrain". The first Galileo encounter, appropriately enough, was a flyby over the region named by the International Astronomical Union after Galileo, Galileo Regio. On the second orbit the spacecraft approached the satellite from the same direction but flew over the north polar region. This combination of geometry was planned for several reasons. It provided a sampling of both the gravity field and the interaction of the moon with the magnetosphere at different latitudes. It also provided the opportunity to look at some of the same places on the surface from different viewing and lighting conditions.

Soon after the spacecraft completed its first pass by Ganymede, we got indications that this satellite was going to be very interesting geophysically. The Plasma Wave Spectrometer experiment (PWS) measures electrostatic and electromagnetic waves over a broad range of frequencies from just a few Hertz to over a mega-Hertz. For a period of about 45 minutes around closest approach on the first encounter, Ganymede was very noisy at these frequencies. Furthermore, the type of noise seen by the PWS team was the type typically associated with the interaction of high energy charged particles with a strong magnetic field in a planetary magnetosphere. In effect, they concluded that Ganymede might have its own magnetosphere! The magnetometer team soon Confined that the magnetic field, which had been registering as the normal background fieldfrom Jupiter as the spacecraft approached the satellite, suddenlyincreased by a factor of five in the region where the PWS saw the radio noise. In addition, the field direction near closest approach changed to point toward Ganymede. Magnetic field models to fit the data were tested on the second encounter, which was closer to Ganymede's north pole, and the data basically confined the predicted field structure and magnitude, with the field over the pole measured as a factor of ten larger than the ambient Jupiter field. As at Io, there are still questions about the degree to which the field is perturbed by the plasma interactions and currents near Ganymede. Here the field is so large that there seems little doubt that this icy moon must have its own magnetic field, which in turn creates a "magnetosphere within a magnetosphere" in the surrounding Jovian environment.

There are other fascinating things about Ganymede. The Plasma Experiment (PLS) and the Ultraviolet Spectrometer (UVS) both see evidence for an extended hydrogen atmosphere with the hydrogen is escaping at high rates. Some of the oxygen which remains behind may be in a tenuous atmosphere as suggested by HST reports of aurora on Ganymede. Even more oxygen maybe buried in the surface ices. Evidence for oxygen in the surface comes from ground-based telescopic spectra, and there are also ultraviolet spectra from IUE and HST that suggest ozone as well, possibly trapped as inclusions or "micro-bubbles" in the ice grains on the surface. Galileo's UVS has mapped this ozone signature and found that it is concentrated at higher latitudes. There is obviously still much to be learned about the interaction of Ganymede with the external Jupiter magnetosphere, its own magnetic field and its exotic surface chemistry.

Analysis of similar gravity and space physics data during the first encounters with Callisto and Europa emphasize the diversity among the satellites. Callisto's moment of inertia is essentially that of a uniform sphere, suggesting little or no separation of heavier rock and iron from ice in its interior. It also shows no evidence of any significant intrinsic magnetic field, its interaction with the Jovian magnetosphere resembling that of a simple non-conducting body. Europa is similar to Io and Ganymede in that its moment of inertia suggests a large dense core, but comparison of results from the first two encounters also suggests that its gravity field may be more "lumpy" than those of the other two satellites. There are complex interactions of magnetic fields and plasma around Europa but the data do not suggest a strong axially aligned internal dipole field as inferred for Ganymede. Six to eight further close passes by Europa during the GEM will help complete our picture of its geophysical state.

So, from our encounters with Io, Europa, Ganymede and Callisto, the number of solid planetary objects for which we have interior structure information has increased dramatically. The inner three moons join the list of objects with significant high density cores, with the Earth and possibly Mercury being the only terrestrial planets with as much central condensation. Callisto is essentially homogeneous. Ganymede becomes the only solid body other than the Earth and Mercury known to have an intrinsic magnetic field and it is the only satellite known to possess such a field (with Io's case still to be decided).

Understanding the geology and geochemistry of the icy satellites is one of Galileo's major goals. The two primary tools for this work are the SS1 camera and the NIMS, with PPR adding surface temperature information and the UVS providing insight into the modification of the surface chemistry by magnetospheric interactions, as discussed above. Based on the Voyager data, the initial foci of these investigations were to: 1) understand the cratering record on ancient Callisto, 2) unravel the sequence of tectonic disruptions and proposed icy volcanism on Ganymede, and 3.) search for clues to a possible frozen or still liquid ocean under Europa's icy crust.

Callisto appears to have the most ancient surface among the satellites. Its surface water ice is mixed with darker materials believed to include hydrated minerals and possibly carbon rich components similar to those found in primitive carbonaceous meteorites. At the resolutions of Voyager pictures, its surface is ubiquitously covered with impact structures, from the huge Valhalla basin to many small bright fresher appearing craters. Planetary geologists expected that the higher resolution Galileo images would continue to show more and more craters similar to what is observed in ancient cratered regions on the Moon, Mercury and Mars. Thus, the fiist high resolution Galileo data came as a surprise when they revealed areas within the Valhalla basin that were nearly devoid of craters at the scale of 50-100 meters. These surfaces appeared covered or "blanketed" by fine dark debris. In some cases this material has clearly slumped off steep icy slopes and covered lower lying areas, but in other areas the small craters appear to have essentially disintegrated, leaving a smooth degraded appearance to the surface. At present the processes responsible for this erosion are a mystery, with ideas ranging from the volatilization of non-ice surface materials to electrostatic movement of dust having been discussed. It is also not known whether this type of surface degradation is common everywhere on Callisto's surface or whether it localized.

Ganymede's surface has large areas superficially resembling Callisto's surface, darker regions with many craters seen in Voyager images. Much of this presumably older surface has been replaced with brighter units, probably containing cleaner ice and frost.

Some of this “new” terrain consists of the ridges and troughs of the “grooved terrain”, other bright, smooth areas were believed to be candidates for large scale flooding by icy volcanic processes. The first Galileo high resolution Voyager images were over twenty times closer than the best Voyager data and showed features as small as 70-100 meters. These pictures also showed a surface somewhat different from the geologists’ expectations based on the Voyager images. The overwhelming impressionleft by these pictures is that of a surface which has been massively disrupted by faulting and fracturing-tectonic forces driven presumably by motions in Ganymede’s icy mantle. There are many impact craters on most of these surfaces, even on the areas which appeared “smooth” at Voyager resolutions. In the area covered by the initial Galileo observations (Uruk Sulcus), the major process responsible for the appearance of the surface appears to be “tectonic resurfacing”, or disruption of pre-exisiting landforms by faulting, with little direct evidence for the expected icy volcanism. Observations on later orbits have found some areas where icy volcanism appears to occur but overall tectonic forces seem to dominate.

On closer inspection, the older darker areas do not appear as Callisto-like. Galileo’s images of the largest such region, Galileo Regio, show many craters at all scales. Unlike the blanketed appearance of the outer satellite these surfaces appear to be fractured and disrupted by tectonic forces, although less comprehensively than the brighter regions. In addition, in both Uruk Sulcus and Galileo Regio, the local dis-tribution of dark and light surface material is controlled by topography. Dark material is concentrated in low areas with bright fresher surfaces on the tops of ridges and steep slopes. In some areas the dark material gives the impression of having “sifted” down into every crack in the predominantly icy surface. This situation makes photo-interpretation very difficult since brightness variations due to lighting angles are confused by the natural “paint job” applied to the hills and valleys. Pictures taken from different directions on different orbits are providing the needed information to determine the true topographic relief in these areas. Digital stereo analyses performed by imaging team members at DLR Berlin have produced digital terrain maps for computer mapping and visualization of these distant landscapes.

Clues to the composition of the material on the surfaces of Europa, Callisto and Ganymede have come from analysis of NIMS spectral maps. In NIMS's 0.7 to 5.0 micron spectral range, the signal from all the icy satellites results from reflected sunlight and absorption due to the ices and minerals on their surfaces. The most prominent absorption in all their spectra is between 2 and 3 microns. It is due to the fundamental stretch frequency of O-H and is present in all water ice spectra and also virtually all heavily hydrated minerals. In the 1 to 2 micron region are numerous features due to various combinations and overtones of H-O-H due to water ice. Water ice is nearly "black" in the 3 to 5 micron range due to strong, overlapping absorption features, so signals in this range from the satellites result primarily from non-water-ice materials. Analyses of these data are ongoing, but preliminary results are extremely interesting.

Most spectra from Callisto show only weak water ice absorption but seem to be dominated by a hydrated mineral signature, confirming conclusions based on telescopic whole disk spectra. In addition, the NIMS team has discovered four (possibly five) new absorption in the 3 to 5 micron region. These were not seen in ground-based spectra due to a combination of the weakness of the absorption and masking of much of this spectral region by C02 in the Earth's atmosphere. The strength of these absorption varies across Callisto's surface in a different pattern for each feature suggesting that they are not all due to the same material. Work to identify the materials responsible for the absorption is just starting. The strongest feature is at a wavelength consistent with $C0_2$ in a condensed phase and this a strong candidate, although other hydrated mineral absorption have been suggested as possibilities. The other features may be due to materials containing carbon, sulfur and nitrogen. The same features have been identified in Ganymede spectra but at a lower signal-to-noise due to greater dominance of water ice over most of Ganymede's surface. Analysis of Europa spectra, which have the strongest water ice signatures of all the satellites, has concentrated on the 1 to 2 micron region, where some areas show spectra that appear to be strongly affected by hydrated materials.

Interest in Europa has been very high ever since Voyager returned images of its smooth icy surface, miss-crossed by a global network of linear features and thin, low ridges. These images, combined with the recognition of tidal energy as a major heat source for at least Io, led to theoretical studies into the possibility that there could be liquid water under the ice crust on Europa. Europa is a basically rocky moon (with a dense core!) covered with ice. We don't know how thick that ice is, perhaps 100-200 km thick, and there may be enough tidal heating plus radioactive heating within the body of Europa to keep that lower layer liquid. Investigating this possibility is one of major objectives of the Europa observations.

High resolution images of Europa have revealed an incredibly complex surface very different from those seen on any of the other icy Galilean satellites. Bands of ridges, no more than a few hundred meters high, are seen at essentially every scale on the surface. The surface in many places resembles brittle plates, cracked and "pulled apart" to form a jigsaw mosaic. There is evidence in several regions for viscous icy "flows" having cut and covered ridges. Perhaps the most spectacular results to date have been images of a region in what is know as "mottled terrain" from its visual and color appearance in Voyager images. At resolutions of 60-200 meters this area resembles a jumbled, broken up ice pack, with large ten kilometer ice rafts which are detached from the surrounding terrain and have apparently "floated" - translated and rotated - to new positions (in some case tilted up on end) and frozen in place. These images provide the strongest evidence to date that there was extensive melting and liquid water near the surface of Europa at time these features were formed.

A major remaining issue is - how ancient are the surfaces and the activity we see? There are very few impact craters on Europa's surface compared to any of the other satellites (except Io of course!). The problem is that we do not know the exact flux history of projectiles which have impacted the system over geologic time. There are at least two contending views at the present. One is that most of the craters seen everywhere in the system were made 3.5 to 4 billion years ago as fluxes from the last stages of planetary accretion declined exponentially. In this view, very little cratering has occurred since, meaning that even sparsely cratered areas such as those on Europa could be geologically ancient, dating back a billion years or more. The other view is that the Jupiter system has been heavily bombarded by so called Jupiter-family comets (such as Shoemaker-Levy 9) in recent geological times and that many surfaces on Europa are only a million years old or less. Resolution of this question is important for the question of whether liquid water may still be present below Europa's surface since more recent thermal activity would imply heat sources that might be sufficient to keep an "ocean" under the ice.

In conclusion I'd like to note that science is done by individuals but it is also a profoundly human collective activity. Galileo himself relied upon the results of those who went before him. Over the years and generations since then there have been many who have contributed to the things we are doing today, up through the present brilliant team of engineers and scientists who are performing the Galileo mission. Many of those who helped make Galileo an exciting reality are no longer with us today. Our late colleague Guiseppe Columbo, at Padua, worked on many of the concepts in celestial mechanics that are used in navigating the Galileo mission. All too many other members of our team have passed on in the course of the mission, including Clayne Yeates, Jim Dunne, Hal

Masursky, Fred Scarf and, most recently, our dear friend Carl Sagan. To all those past and present who have made this possible, I say thank you. To the next generation, I say look at what we have achieved - and don't be satisfied. Do more, do better, continue with what Galileo started.