JPL PUBLICATION 77-51, VOLUME VII

Report of the Terrestrial Bodies Science Working Group

Volume VII. The Galilean Satellites

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91103

OVERLEAF: The Galilean Satellites—A Solar System in Miniature

The four largest satellites of Jupiter form a regular system very much like a system of planets about a sun. Their surface compositions and inferred interior structures suggest significant variations within the system, again much like that seen between planets. Indeed, two of the satellites are larger than Mercury.
(Drawing of the Galilean Satellite System, JPL photograph P-17054Ac)

JPL PUBLICATION 77-51, VOLUME VII

Report of the Terrestrial Bodies Science Working Group

Volume VII. The Galilean Satellites

September 15, 1977

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91103

PREFACE

This volume is one of a nine-volume series documenting the work of the NASA-sponsored Terrestrial Bodies Science Working Group in developing plans for the exploration of Mercury, Venus, the Moon, Mars, asteroids, Galilean satellites, and comets during the period 1980-1990. Principal recommendations and conclusions are contained in Volume I (Executive Summary); reports and working papers of the study subgroups are presented in Volumes II-IX.

This volume is the report of the Galilean satellites subgroup, whose members and contributors are F. P. Fanale (chairman), J. C. Beckman, C. R. Chapman, F. V. Coroniti, T. V. Johnson, and M. C. Malin.

CONTENTS

PRECEDING PAGE BLANK NOT FILMED

Figures

Tables

SECTION I

STATE OF OUR KNOWLEDGE OF THE SATELLITES AND MOTIVATION FOR FUTURE EXPLORATION

A. FORMATIONAL HISTORY

A major goal of the space program is the elucidation of the origin and evolution of the solar system. The Galilean satellites constitute a mini solar system, and therefore study of these four objects, as a set, can greatly aid by analogy our understanding of the origin of the solar system and the reasons why different planets have followed different evolutionary paths.

All multiple satellite systems resemble mini solar systems in appearance, but in the case of the Galilean satellites the resemblance is far from superficial: low mass star models, applied to Jupiter, predict an initial luminosity for that object of about 1/100 that of the present Sun. At the time that the satellites presumably formed, the luminosity was probably much lower, but still sufficient to prevent condensation of the "cosmic complement" of H_2O ice for Io (J1) and Europa (J2). The "cosmic complement" is the proportion of ice which would be added to any previously condensed silicate material during nebular condensation. The amount of H_2O and the temperature at which H_2O condenses can be deduced from the O:H ratio in the nebula, estimates of the H (or total) pressure, and the assumption that all the O is used to make water. Thus one calculates that ~200 K, H_2O ice would condense from the nebula, and its mass should be about twice that of the previously condensed silicates. In this scenerio, Ganymede (J3) and Callisto (J4) condensed at $\lesssim$200 K, whereas Io and Europa accreted at temperatures $\gtrsim$200 K because of the outflowing of heat from Jupiter. This resulted in Io ($\rho \sim 3.5$) and Europa ($\rho \sim 3.2$) accreting as rocky objects, while Ganymede ($\rho \sim 1.8$) and Callisto ($\rho \sim 1.7$) acquired their full "cosmic complement" of ice. Furthermore, consistent with the implied temperature and pressures in the circumjovian cloud based on the composition of Ganymede and Callisto, Europa and Io are thought to have accreted at temperatures below the temperature at which hydration of dispersed nebula material is thought to have been effective (between 200 and 400 K). Thus while Io has the same density and radius as the Earth's moon (both within 5%), Io-forming material is thought to have contained chemically bound water. Europa's density is 3.2 ± 0.2, suggesting the addition of ice or low-density hydrated phases to Io-like material. Thus, the range of bulk composition among the Galilean satellites results in a density range actually exceeding that exhibited by the terrestrial planets (see Table 1). Moreover, the cause of the density variation appears to be identical in the two instances; namely, the influence of a central heat source in producing differences in the condensation sequences at different radii in the protoplanetary disc. The analogy between the Galilean satellite system and the inner solar system seems strong indeed.

Table 1. Overview of Galilean Satellites, June 1976

	IO, J1	Europa, J2	Ganymede, J3	Callisto, J4
Size of Comparable Body	Moon	Moon	Mercury	Mercury
Bulk chemistry	Silicate $\rho = 3.5$ GM CM^{-3}	Silicate $\rho \cong 3.0$ GM CM^{-3}	Silicate and ice $\rho = 1.9$ GM CM^{-3}	Silicate and ice $\rho \cong 1.6$ GM CM^{-3}
Surface chemistry	~No H_2O ice sulfur, salts, silicates	Ice Crust $\leq$ ~75 km	"Dirty" ice surface	Very "dirty" ice surface
Albedo	~ 0.7	~ 0.7	~ 0.4	~ 0.2
Inferred interior zonal structure	Silicates	Silicates & thin H_2O ice crust	Lunar size silicate core/700 km liquid H_2O H_2O mantle. Ice-crust $\lesssim$ 75 km(?)	Lunar-sized silicate core, ~700 km liquid H_2O Mantle/ice-silicate crust ~120 km(?)
Surface markings	large albedo variation; large color variation, dark poles	Large albedo variation; moderate color variation, dark equator	Moderate albedo variation, small color variation, large "spots" with contrast (vis.) > 2	Small albedo variation, very small color variation, hemispheric difference in scattering, polarization & phase
Atmosphere	Na, K, H, S^+ & ? Ps $\lesssim 10^{-10}$ bar ionosphere with n_e(75 km) $\sim 10^4$ cm^{-3}	? H_2O evaporation H_2O evaporation	Stellar occulation suggests some atmosphere ?(~10^{-6} bar)?	? H_2O evaporation
Interaction with magnetosphere	Sputtering, extended atomic clouds, control of deca-metric radio bursts, ionization of "atmospheric" neutrals/sweeping	Possible He-channel glow in Pioneer 10 UV experiment (Bremstrahlung?)	?	?

B. EVOLUTIONARY HISTORY

Once formed, the Galilean satellites were not inert, but most likely proceeded to differentiate "endogenically", producing highly zoned interiors and four surfaces, the mineralogical compositions of which apparently resemble closely neither each other nor the corresponding inferred bulk compositions (see below and Table 1). Theoretical considerations suggesting extensive differentiation of Ganymede and Callisto are numerous. Although these objects are likely to contain only ~1/3 of the chondritic U, Th and K abundances, the observations that suggest they are mostly water ice indicate that their melting points are probably only a little over a hundred degrees over the space environmental temperature. Thermal models suggest extensive melting of Ganymede and Callisto's interiors, with most of the rocky material falling to the center to form a lunar-sized core. In all models this core is surmounted by a liquid H_2O mantle at a temperature ranging from over 1000°C at the "surface" of the core to slightly over 0°C at the ice-water interface.

The thickness of the ice crusts on Ganymede and Callisto are quite model-dependent. Our best theoretical estimates suggest a thickness of 50-100 km for Ganymede and 100-150 km for Callisto. The role of gravitational energy during accretion and that released by incipient separation of ice and silicate has not yet been incorporated into theoretical models, nor has convection or possible tidal heating by Jupiter. The ice crusts may be somewhat thinner than described above, owing to these effects, or possibly to mechanical disruption by either internal convection or large impacts. Expressions of the forces of convection, impact, tidal effects and either expansion or contraction caused by crystallization or melting during satellite history are largely matters of conjecture. We simply do not know enough about icy bodies to make reliable predictions of such features.

From the modeled differentiation history of Europa we expect a high proportion of rocky material relative to H_2O ice. However, details such as whether the planet accreted as 10% H_2O ice or 0.1% bound H_2O with no ice are impossible to determine at this time. Thermal models of Europa would suggest total melting and degassing of any initial ice and much of the bound water which may have been present. Is the ice crust on Europa thin enough that it can be pierced by large impacts which throw out nonicy material from below? Is it thick enough to allow the presence of a liquid H_2O layer between the ice and rocky material? Io's case was probably similar, although the thermal history is likely to have been somewhat more intense than Europa's. Io's thermal history would likely have been similar to that for a hypothetical chondritic Moon. Thermal modeling of Io suggests that basalt would have been molten at depths over 400 km for most of the object's history. Considerable internal degassing would be expected, but the nature of the surface morphological expression of such activity is largely conjectural.

It may be reasonably concluded that all four objects experienced intensive differentiation and degassing histories and that a variety of surface morphological expressions of these various scenarios of endogenic activity might be expected.

C. SURFACE MINERALOGICAL COMPOSITIONS

In keeping with the variety of bulk compositions and probable differentiation histories of these objects, we observe that all four surfaces have different surface reflectance properties. The surface reflectance of Europa is probably the easiest to interpret, as it greatly resembles that of slightly colored H_2O ice, including a very high albedo (~0.7) and very deep water absorption bands at 1.4 and 1.9 μm. This seems understandable in view of the Earth-like degassing history envisioned above in which a small proportion of H_2O is efficiently degassed to the surface of an essentially rocky object. Io's reflectance spectrum is harder to explain. It, like Europa, has a very high albedo (~0.7) but Io's spectrum is completely lacking in ice bands! One explanation of this might be that Io degassed water to its surface as did Europa, but that intense surface heating from Jupiter, combined with efficient atmospheric sweeping and a lower degassed water inventory, resulted in a dehydrated salt-rich "sedimentary" surface.

It should be noted that the Jovian luminosity history which is consistent with the production of the observed density variation among the satellites has the following surprising additional consequences: When the satellites formed, the luminosity had dropped from its maximum value of 10^{-2} that of the Sun to a much lower value ($\sim 10^{-4}$ to 10^{-5} that of the Sun). However, note that Callisto is only 1/50 the distance from Jupiter that Mercury is from the Sun and Io's distance from Jupiter only 1/200 the Mercurian distance from the Sun. Thus it turns out that the Jovian luminosity history referred to above predicts that, at the very beginning of its history, the surface of the newly formed Io was receiving as much energy from Jupiter as the Earth currently receives from the Sun!

We have considered thermal models in which H_2O is supplied to the surface by radioactive heating of the interior during Io's history. On the other hand, accretional heating or other initial heating seemingly has been important on the Earth's Moon which has the same radius and density as Io). Therefore, we must consider the possibility that the interesting part of Io's endogenic history (the period of major water supply) may have overlapped the interesting part of its exogenic history (the period during which it was receiving considerable energy from Jupiter). Such a circumstance could produce imaginative scenarios, however short-lived such unusual conditions might have been. We should bear in mind the possibly uniquely interesting very early history of surface conditions on Io even though our knowledge of that body's history is sparse.

In a sense, the surfaces of Europa, Ganymede and Callisto represent a series (see Table 1). The surface of Europa, a rocky object, has a very high albedo and exhibits deep infrared H_2O bands, but the surfaces of Ganymede and Callisto, which are, in bulk, mostly liquid H_2O and ice, have much lower albedos. Ganymede has an albedo of ~0.4;

Callisto has an albedo of only ~0.2 and water bands that are barely detectable. Since the nonicy material on Callisto's surface can be shown to have an albedo of ≲0.15, it might be carbonaceous. Such material dominates in the asteroid belt and is expected to dominate the nonicy portion of the satellites as well.

Other meteoritic materials have considerably higher albedos. A reasonable model for Callisto's surface would involve both hydrated carbonaceous material and a small amount of brighter materials. Such a mixture is of great interest from two points of view:

(1) This represents a possibly primordial conglomerate which is more "chemically complete" (or less fractionated relative to the Sun) then any other solid object that is easily accessible to exploration. Many asteroids such as Ceres are apparently carbonaceous but seem to lack their "cosmic complement" of ice. Other satellites of the outer planets may be slightly more chemically complete (containing their "cosmic complements" of $NH_3 \cdot H_2O$ and $CH_4 \cdot 7H_2O$ ice) but are much less accessible. Comets may turn out to be more "chemically complete" still, but the accessibility of their nuclei to detailed surface compositional mapping is less immediate than for Callisto, and the effects on the primitive character of their surfaces of repeated passes near the Sun is difficult to evaluate.

(2) From the point of view of those concerned with abiotic organic synthesis in space, Callisto represents one of the most interesting objects. It quite possibly offers the complex assemblage of high-molecular-weight organic material associated with carbonaceous chondritic meteorites, but mixed with H_2O ice on its surface crust and mixed with liquid water beneath its surface crust!

One of the most interesting problems involving Ganymede involves the explanation of why Ganymede is so much brighter than Callisto. One possibility is that Ganymede had a somewhat more active history than Callisto and was more able to "purify" its surface of dense rocky materials by melting, extrusion and subduction. There is tenuous support for this idea based on differences in the thermal models for Ganymede and Callisto, but this is only one of several possible explanations.

D. OTHER SATELLITE PHENOMENA OF EXTREME INTEREST

Io represents the prime example in the solar system of the interaction of radiation with a planetary object, although the other satellites also interact strongly with the Jovian magnetosphere. One interesting aspect is that the uniquely high fluxes of high-energy magnetospheric particles hitting Io's surface ($\gtrsim 10^9$ proton/cm^2/sec, 10% in the MeV range) are apparently responsible for sputtering material from that surface into a cloud around Io. Emission lines for several elements have been detected in the cloud (K, Na and S^+), and searches are underway for lines of other elements. The emission (caused by resonant scattering of sunlight by neutrals) is so bright that it would be easily visible from Io's surface. Insights into planet-magnetosphere interaction could be gained by studies of lines of Io-originating elements in the cloud around Io (and the torus around Jupiter). Spacecraft-based studies of specific spectral lines could (1) confirm a surface origin, and (2) delineate the fates of both neutrals and ions in the cloud. Intrinsic magnetic fields for the satellites have not yet been detected. There are preliminary indications of some perturbations of the Jovian magnetic field in the vicinity of some of the satellites which would obviously be appropriate for spacecraft study. Io's anomalous post-eclipse brightening has been observed repeatedly but not consistently. Again, this fascinating if ephemeral phenomenon is highly amenable to synoptic observations from space.

Another whole set of observations which appear to require repeated spacecraft observations are satellite atmospheric conditions. Flyby occultations gave totally different results for the dayside and nightside ionospheres of Io. To understand the reasons, many occultations are necessary. Furthermore, synoptic atmospheric observations are needed because electron density, the parameter observed in the radio occultations, is different from that of most planetary atmospheres where the electron density profiles can be related to the atmospheric density using a photoionization model. In the case of the Galilean satellites, ionization of atmospheric neutrals by magnetospheric particles dominates greatly over photoionization. Moreover, this process is highly variable owing to the inclination of the plane of the magnetosphere to Io's orbital plane.

Repeated solar occultations by an orbiter should provide an independent set of results from the radio occultations. At the present time, we do not know whether Io possesses a thermalizing atmosphere with a basal pressure of between 10^{-8} and 10^{-11} atmospheres or a "ballistic" atmosphere at much lower pressures which can be traversed by particles leaving Io's surface without their encountering other atoms. Ganymede could have an atmosphere of between 10^{-3} and 10^{-6} bars based on a tentative observation made during a stellar occultation. However, the pressure could be orders-of-magnitude lower. We know virtually nothing about the atmospheres of Europa and Callisto. In keeping with their other puzzling properties, the Galilean satellites have the highest radar cross sections of any objects in the solar system. A completely satisfactory interpretation is lacking.

SECTION II

THE GALILEAN SATELLITES: KEY SCIENTIFIC QUESTIONS

Based on the preceding discussion of the present state of our knowledge concerning the Galilean satellites, the following are deemed to be key scientific questions to be investigated during the 1980's:

A. PRE-ACCRETION ENVIRONMENT

(1) What was the composition and state of the preplanetary gas/dust solar nebula at Jupiters heliocentric distance?

(2) How did the forming Jupiter affect conditions in the local Joviocentric nebula?

(a) What was Jupiter's energy output as a function of time?

(b) What were the P, T conditions as a function of time and Joviocentric distance around Jupiter? How does this relate to satellite bulk compositions/densities?

(3) What was the nature of any possible physical interaction with other portions of the accreting solar nebula, and what were the compositional relationships?

B. FORMATION OF SATELLITES

(1) When did satellites form; over what interval did they form; and did they all form at the same time?

(2) Were satellites formed of local material or was there a major "captured" component?

(3) Was satellite-forming material in constant chemical equilibrium with surrounding gas and with prior condensed material?

(4) Did Jupiter's magnetic field exist at this time and, if so, what role did it play (if any) in modifying the formation/accretion processes?

(5) How was energy deposited in each object during formation?

(6) What was the dynamical interaction and evolution among the accreting and accreted bodies of the system?

C. SUBSEQUENT EVOLUTION OF INDIVIDUAL SATELLITES

(1) What were the initial physical and chemical states of the satellites?

(a) Were the satellites initially homogeneous or layered?

(b) What were the major energy sources available?

Initial short- or long-lived radionuclide concentrations.

Accretion-deposited energy.

Tidal forces.

Jupiter -- magnetic fields, charged particle radiation, early luminosity.

(c) What was the initial volatile content of each satellite?

(2) Were the satellites subjected to the "heavy bombardment" which apparently extensively modified the surfaces of Mercury, the Moon, Mars early in their histories?

(3) Did the satellites differentiate and, if so, when?

(a) Did cores form?

(b) Did the satellites develop magnetic fields?

(c) Did they develop a crust/mantle structure and, if so, what was the nature of the crust?

(d) Was differentiation accompanied by strong degassing of the interiors?

(4) What was the history of volatiles on the satellites?

(a) Did early atmospheres form?

(b) How much volatile material was lost early in their history; what were the catastrophic early or continuing (uniform) loss processes?

(5) What were the major processes modifying the satellites' surfaces?

(a) What was the cratering rate; and how did it change with time?

(b) Did volcanism occur on any satellite?

(c) Do any of the satellites have a liquid mantle (including a liquid H_2O mantle) and have processes analogous to plate tectonics taken place?

Has there been crustal rifting, subduction or overturn?

Are major structures isostatically compensated?

Have mountain building processes operated?

(d) What processes have degraded or destroyed surface features?

Has deformation of ice crusts played a major role in modifying surfaces?

Has major resurfacing occurred? When?

(e) What role has charged particle bombardment played?

(f) Was interaction with atmospheres or the results of continuing atmospheric loss important?

D. CURRENT STATE OF SATELLITES -- OBSERVABLES

(1) What are their radii?

(2) What are the optical figures of the satellites and are they hydrostatic?

(3) Do any of the satellites have a magnetic field - fossil, induced or intrinsic?

(4) Are their surfaces cratered and, if so, what are the differences among the satellites and on different parts of each satellite?

(5) Do differences observable within large craters suggest planetary layering and/or a time relationship between internal geological evolution and external cratering?

(6) Are features other than craters prominent?

(a) Are there mountains?

(b) Are there volcanic landforms and/or mare?

(c) Are there scarps, faults, rifts, etc., indicative of major or global tectonic activity?

(7) What are the satellite surface compositions and how is material distributed on their surfaces?

(a) What is the distribution of chemical elements on the surfaces of each of the satellites?

(b) Do chemical or mineralogical differences among the satellites' surfaces reflect dominant differences in their accretional history or differences in their subsequent internal or geological evolution?

(c) In what way does the distribution of mineral phases on satellite surfaces reflect the precise history of physical and chemical conditions on the very surfaces of these objects?

What is the surface material of Io and what causes the variation in color on its surface?

How is ice distributed on the surfaces of Europa, Ganymede, and Callisto?

Are there latitudinal trends due to temperature effects?

Are ices other than water present?

What is the distribution of ice relative to surface features?

How deep is the solid ice or dirty ice layer or crust?

(d) What is the nonice material near the surfaces of Europa, Ganymede, and Callisto?

(8) What is the physical state of surface material?

(a) Are there impact regoliths?

(b) What disruptive/constructive processes result from impacts? Are surface materials fine-grained or coarse?

(c) What causes the longitudinal change in scattering properties on Callisto?

(d) What effect did/does charged particle bombardment have?

(9) What is the current state and history of each satellite atmosphere?

(a) What are the compositions and structures of these atmospheres?

(b) What loss processes operate or have operated and what is the current mean residence time for each species?

(c) What is the source of the atmospheres?

Are they resupplied by condensed surface volatiles?

Is deep interior degassing continuing?

Are they controlled by equilibrium with the surface (e.g., condensation at night or at the poles)?

(d) How has atmospheric evolution affected surface composition and state?

(10) What is the nature of the interaction between the satellites and the Jovian magnetosphere?

(a) What species are present in the Io/Jupiter-surrounding cloud or torus?

(b) How are they spatially distributed?

(c) Are they in steady-state?

(d) What are the loss mechanisms and the required supply rates?

(e) What is the source of cloud materials?

Do they come directly from Io's surface or from the atmosphere?

Are atoms and ions recycled via Io's surface or the Jovian upper atmosphere?

(f) How do atoms escape from Io? Is the cloud composition representative of Io's surface?

(g) How does the magnetospheric plasma interact with Io's atmosphere and ionosphere? What role do high-energy particles play?

(h) Do the other satellites have similar phenomena?

(i) How has magnetospheric interaction altered the state of surface materials?

(11) How does Io modulate Jovian decametric radio bursts?

SECTION III

KEY MEASUREMENTS, INSTRUMENTS, AND MISSION CONSIDERATIONS

A. INTRODUCTION

In this section we will discuss classes of measurements which are both within the realm of practicality for the 1980's and also promise major inputs to our understanding of the "key questions" listed above. The scientific significance of each class of measurements is also discussed. In each case our ambitions are viewed against the backdrop of information which we have obtained from Pioneer measurements and also the assemblage of information which we can reasonably hope to obtain from the Mariner Jupiter/Saturn 1977 mission. The specific advances in satellite science offered by a Jupiter orbiter mission over those offered by the MJS mission are given for each measurement. Of course, the degree of advancement for each type of measurement is a strong function of the mission profile or orbit option chosen, and there are numerous possibilities. The advantages for satellite science of each of the major types of orbit which have been suggested are given, and the corresponding orbits described. Our key recommendations are that (1) full advantage be taken of the opportunity for satellite studies offered by the JOP mission by increasing the number of satellite encounters as well as by inclusion of key instruments for remote sensing of solid surfaces, and (2) that a Galilean satellite lander mission be planned for the late 1980's. A description of the scientific potential of a possible lander on one of the Galilean satellites is given.

B. IMAGING

Visual and near-infrared imaging is still one of the most powerful remote tools for understanding planetary surfaces. MJS, with the current trajectory selection, should be able to perform a reasonable reconnaissance of the satellite system, with hemispheric coverage at 10-km resolution or better and significant portions ($\sim$10%) covered at 1-5 km (varying with satellite). For JOP it is proposed to link the MJS high-resolution optics with a charged-coupled device (CCD) imaging system. This results in much greater sensitivity (>10X) and extended spectral response (0.4 - 1.1 μm). This system is capable of achieving $\sim$50-m resolution, equivalent to the best Viking Orbiter photography of Mars. This may be particularly important for the icy Galilean satellites, which may have surfaces totally different from previously studied terrestrial bodies. The major limiting factor on data return from this imaging system is the number of satellite encounters achieved. The nominal orbit for the JOP standard mission (Mission A) has few satellite encounters with Ganymede and Callisto and none with Io or Europa. This trajectory is depicted in Figure 1 and Table 2. It would probably be possible to provide hemispheric coverage of Ganymede at 1-km resolution under this profile, with some small fraction covered at 100 m or better, and somewhat less on Callisto.

Table 2. Reference Mission A: Satellite Encounter Conditions

Encounter	Satellite	Approach Speed km/sec	Periapse Altitude, km	Periapse Phase, deg	Targeting
1	Ganymede	5.7	1000	152	Occultation
2	Ganymede	5.6	1232	102	N. Pole
3	Ganymede	5.6	1185	151	Occultation

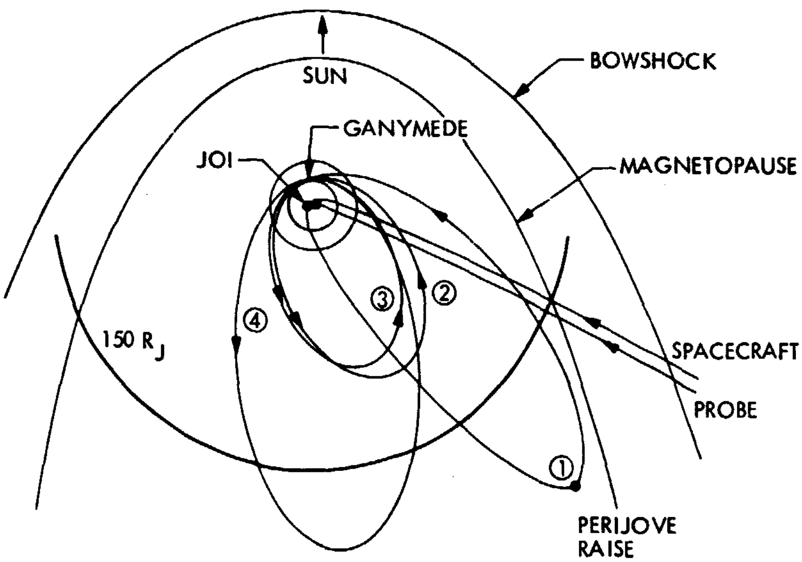

Figure 1. Jupiter Orbiter Probe, Reference Mission A

Mission A' provides substantially more encounters with Ganymede and Callisto (up to 12). This trajectory is depicted in Figure 2 and the encounter conditions are listed in Table 3. The A' trajectory not only increases total coverage at useful resolutions but provides for a variety of encounter geometric and lighting conditions for both topographic and multispectral objectives. An extended mission or a second spacecraft yield obvious advantages in extended coverage. In addition, they increase the possibility of achieving encounters with Io and Europa despite the higher radiation risk. Finally, the extended time base will be useful in studying time-variable phenomena such as atmospheric circulation, frost formation, and aurorae. In Table 4 we compare the likely imaging return from the A mission, the A prime mission and a two spacecraft JOP mission.

C. ULTRAVIOLET

Ultraviolet spectroscopy or photometry can provide unique information on atmospheric composition and extended atmospheric-magnetospheric phenomena such as the H atom torus around Io detected by Pioneer 10. MJS will carry a UV spectrometer which is expected to provide data on the H torus and perform airglow measurements on the satellites. For atmospheric composition information, however, UVS works best in the solar occultation mode. The current MJS trajectories do not allow any solar occultation experiments. A Jupiter orbiter has increased chances for achieving solar occultations for all satellites. These will be limited by the number of orbits and the ability to adjust timing and make small inclination variations in the orbit. Note that the method will yield useful results even if performed at large distances, although altitude resolution would be degraded. Thus, even if limited to periapsis at Ganymede, a JOP mission can probe the atmospheres of Io and Europa if proper instrumentation is carried. Mission A (Figure 1) allows only marginal attention to these studies in that it contains very few orbits, most of the time being spent at large jovicentric distances. A few occultation opportunities could be expected under this profile. Mission A' (Figure 2) has more orbits and therefore many more opportunities for setting up occultation experiments. Ganymede and Callisto occultations are virtually assured. Under an extended mission or a second spacecraft option the opportunities for occultations increase. Not only does this assure some data for each satellite, it allows study of time and space-dependent phenomena in these tenuous atmospheres. Io's ionosphere, for instance, appears to be grossly different in the two sets of Pioneer 10 radio data, implying either time-of-day variation in density or changes in interaction with the magnetosphere. The relative values of UV studies from MJS, the JOP A mission, the A prime mission, and a two spacecraft JOP are compared in Table 4.

D. INFRARED

Infrared instruments range from simple radiometers to very sophisticated spectrometers. Also, they include measurements both of reflected solar infrared radiation and thermal emission from the surface. In general, the reflected component (1-5 μm) is known to be

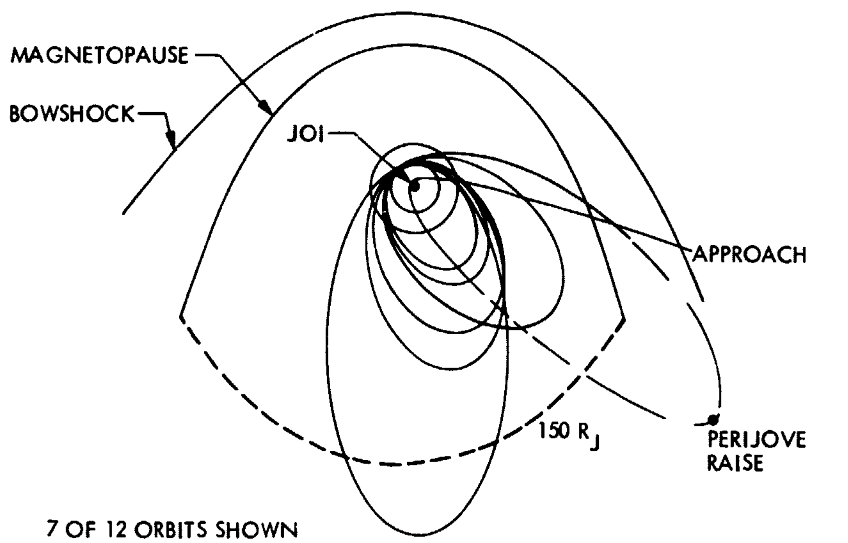

Figure 2. Jupiter Orbiter Probe, Reference Mission A Prime

Table 3. Reference Mission A': Satellite Encounter Conditions

Encounter	Satellite	Approach Speed km/sec	Periapse		Targeting		
			Altitude	Phase, deg	Polar	High Noon	Occultation
1	Ganymede	5.7	1000	152			X
2	Ganymede	5.7	1000	163			
3	Ganymede	5.5	2687	77	X (N)		
4	Callisto	6.3	1905	98	X (S)		
5	Callisto	6.3	1922	90	X (N)		
6	Callisto	6.2	7373	5		X	
7	Ganymede	5.7	5092	22		X	
8	Ganymede	5.8	3184	1		X	
9	Callisto	6.5	1492	175			X
10	Ganymede	4.7	1917	119	X (S)		
11	Ganymede	4.9	1000	156			X

Table 4. Satellite Experiment for Jupiter Orbiters

Experiment	Example Technical Base	MJS Return	Mission A [AO]	Mission A'	Extended Mission Niehoff Option
Imaging	MJS 1500 mm CCD camera	Some coverage of all 4 satellites at best resolution of 1 - 5 km	Hemispheric coverage at best MJS for J3, J4. Small arrears at 100 m. Extended spectral range.	Significant coverage at < 100 m resolution for J3, J4.	Extended coverage of J3, J4 at Viking resolution (< 100 m). Possible J1, J2 encounters.
Ultraviolet	MJS, UVS P10, P11 uv photometry	Some airglow experiments for all satellites. No occultations. No H torus observation.	Possible occultations depending on timing. H torus observation.	Many opportunities for solar occultations for all satellites. H torus mapping.	Extended coverage -- more events for spatial/temporal separation. Close J1, J2 possible.
Infrared-photometry spectroscopy	MJS IRIS MVM radiometer Viking IRTM LPO McCord	IRIS spectra of some regions on satellite	Limited observations of J3 and J4.	IR mapping of some portion of J3, J4	Extended coverage -- thermal mapping at many solar illuminations.
Gravity	P10, P11 | tracking MJS	Improved masses.	Some data on higher gravity moments for J3.	Siginficant data on moments of inertia J3, J4	Possibility of determining separate moments from multiple passes -- some information on J1, J2 possible.
Particles and fields	P10, P11 MJS	"Snapshot" of magnetosphere Io flux tube. Definition of plasma.	Look for intrinsic or induced fields on J3, J4(?). Study interaction with magnetosphere.	Many close passes for magnetics, interactions at J3, J4 - time variations.	Extended coverage opportunity for observing time variations J1, J2 passes.
Radio	P 10 MJS	No occultations.	Some occultations for ionosphere measurements.	Extended opportunities for occultations for all satellites.	Time base of ionosphere dynamics (expected)
X-Ray	Apollo 15, 16	---	Few close passes by satellites.	Many close passes by J3, J4. Extensive geochemical mapping.	More encounters possible J1, J2. More time for instrument development. 2nd a/c monitor of background.

more diagnostic of surface mineralogy, particularly frozen volatile phases. The emitted radiation, while containing compositional information, is more sensitive to the thermophysical character of the surface -- microstructure, albedo, and emissivity. Several infrared systems flown on previous spacecraft could be flown with profit on a JOP mission. They all have in common a need to achieve spatial resolution of at least ~0.1 of the satellite diameter to provide maps, since the global infrared properties of the satellites have been or can be studied from the ground and Earth orbit.

MJS will provide some limited satellite coverage with the IRIS experiment, and the major design driver for the instrument and mission has been Jupiter atmospheric objectives. Any Jupiter orbiter mission should be able to improve on MJS, for many satellites are encountered more than once. Mission A' does significantly better than Mission A and an extended/second spacecraft mission would be even better (Table 4). For mapping of thermal properties, coverage with different geometry and illumination is especially important. Increased encounters allow for high spatial resolution spectroscopy, which is exceedingly important. It should be noted that reflectance measurements indicate the phase distribution and therefore the history of physical conditions which led to surface evolution as well as the assemblage of elements that are present.

E. GRAVITY

One of the more exciting aspects of Jupiter orbiter missions is the opportunity of achieving low-altitude flybys ($\leqslant$1 satellite radius). This raises the possibility of probing their interior structures by the use of the higher moments of their gravity fields. Such measurements would be very useful for determining density structure and are feasible with the expected limits on detectable J_2 values. This information would be of profound importance in studying the evolution of icy terrestrial bodies by demonstrating whether the internal differentiation expected from thermal models has taken place. Again, the more encounters the better the information. Mission A might be limited to determining J_2 for only one satellite. Much more information would result from an increased number of encounters having different geometries.

F. FIELDS AND PARTICLES

The largest permanent object in the solar system is the Jovian magnetosphere. Assuming that MJS is successful, by 1980 four spacecraft will have traversed the Jovian magnetosphere and obtained snapshots of the plasma environment and the Galilean satellites. However, from Pioneers 10 and 11 we know that the outer magnetosphere can assume at least 3 or 4 different spatial configurations: (1) thin laminar magnetic disk (P-10 outbound), (2) thin turbulent disk (P-10 inbound), (3) thick turbulent structure (P-11), (4) a Chapman-Ferraro type magnetopause (P-10,11). Presumably changes in the solar wind or some internal dynamical instability triggered transitions between these different magnetospheric states. Another phenomenon which complicates magnetospheric dynamics is the interaction with the Galilean satellites, an effect which is absent at Earth. We know that Io is a source of mildly energetic electrons, produces decametric radiation by some as yet ill-defined coupling with the Jovian ionosphere, and creates a substantial heavy ion plasma. In fact Io, and possibly Europa, may be a substantial or dominant source of low-energy plasma whose presence, or absence, critically affects the dynamics of the energetic particle populations and may influence the structure of the outer magnetosphere. In addition, Pioneer 10 detected a possible field-aligned current at Ganymede's orbit indicating some interaction with the ionosphere. Note that J3 and J4 are both Mercury-sized rapid rotators, most probably with fluid interiors.

Mariner Jupiter/Saturn will provide a "snapshot" of the Jovian magnetosphere considerably improved over the initial reconnaissance of Pioneers 10 and 11. In particular, we should have much better measurements of the low-energy plasma thought to exist in the inner magnetosphere. Investigations directly related to the satellites will include a flythrough of Io's flux tube, but MJS will not achieve the low altitudes necessary to sample the near-satellite environments directly or search for satellite-related magnetic fields. A Jupiter orbiter provides a much improved base from which to investigate the time- and space-variable aspects of Jupiter's dynamic magnetosphere. Such information and improved energy and mass resolution in charged and energetic particle experiments will aid understanding of satellite interactions. Direct sampling of the interaction regions and searches for intrinsic or induced magnetic fields on the satellites require close approaches (~ 1 satellite radius), and Mission A provides few of these. Mission A' can yield a fairly thorough investigation of the electromagnetic environments of Ganymede and Callisto and will allow measurements to be made when the satellites are in various positions within the magnetosphere (the magnetic equator is inclined to the satellites' orbit plane and many phenomena are expected to display magnetic latitude dependence). An extended mission would, of course, enhance both the number of encounters and the variety of time and space relationships investigated as well as possibly allowing one or two close encounters with the inner two satellites.

However, a second spacecraft would provide the best return. A second spacecraft has all of the above advantages and offers a powerful additional tool for magnetospheric investigation by providing simultaneous measurements in widely separated parts of the magnetosphere. On Earth, our experience has shown that the most cost-effective way to investigate a huge, complex and temporally unsteady magnetospheric system is with two simultaneously operating, separated spacecraft. The scientific payoff from such studies has been so great that, despite the increased cost, future terrestrial magnetospheric missions (ISEE and Electrodynamic Explorer) will be in the multiple spacecraft mode.

The proposed JOP mission will carry a complete set of plasma and wave diagnostics and should provide a substantial increase in our knowledge of the outer magnetosphere. However, the 150 R_J orbit size means that the spacecraft will spend most of the time in the very distant magnetosphere or even in the solar wind. Since it will be a single observation point, ambiguities of space-time changes will plague the interpretation of the data; in addition we simply will not know what is simultaneously happening in the inner magnetosphere. Since the Galilean satellites probably have a significant interaction with the surrounding plasma environment, we assume the second spacecraft would carry at least a limited complement of particles and fields experiments. The dual-satellite mission would vastly improve our chances of resolving the spatial and temporal structure of the magnetosphere. One could study how changes in the outer (inner) magnetosphere propagate inward (outward), and if JOP were in the solar wind, one could investigate how changes in the solar wind dynamic pressure and magnetic field influenced the inner magnetosphere (See Table 4).

G. RADIO SCIENCE

Radio occultations of the satellites can provide measurements of their ionospheric densities. The Pioneer 10 Io occultation has shown that at least one satellite has an exceedingly interesting ionosphere, with the dayside and nightside ionospheres exhibiting striking differences. These data have shown us that interpretation of ionospheric electron densities from a single occultation is difficult because of the strong interactions of surface, atmosphere and ionosphere with the magnetosphere. Multiple occultations and correlation with solar occultation and particles and fields data would greatly improve the situation. MJS is not currently scheduled for any radio occultations. As with the UV solar occultation experiment, a Jupiter orbiter provides many opportunities for radio (i.e., Earth) occultations. A mission with many orbits or an extended mission improves the situation tremendously (see Table 4).

H. X-RAY FLUORESCENCE

In contrast to spectral investigations, which pertain to mineralogy, X-ray fluorescence measurements pertain directly to elemental composition. The satellite X-rays result from excitation and ionization by energetic electrons and protons in the magnetosphere, and from bremsstrahlung produced by the impacting electrons. Both the signal and the background noise are much higher for the Galilean satellites than the Moon because of these effects, and thus a philosophy of instrument design different from that utilized during Apollo is required. Even if only crude chemical analyses are possible, it will represent an enormous advance because satellite surface chemical composition is hardly known at all. For example, some investigators believe that the surface of J1 is coated with NH_3 frost which has its bands suppressed by dissolved cations, while others believe the surface to be frost-free and largely covered with a mixture of sulfates and elemental S. The point is that even imprecise compositional data could represent a significant increase in our knowledge of the surface. Similar comments can be made about J2, J3 and J4 where few suggestions have been made concerning the non-H_2O component (although carbonaceous material has been suggested to occur on J4).

Calculations of the production of characteristic X-rays from the satellites and of background produced at the satellites and from local interactions show that the signals expected are sufficient to detect surface concentrations of about 1% or less for all elements with atomic number greater than Na for a single pass at each satellite. In contrast, the radiation environment appears to pose insurmountable problems for γ-ray spectrometry.

Unlike the case for the spectral data, even whole-disc chemical results would represent the introduction of data of an entirely new type to serve as a very powerful constraint on models of surface evolution. The key issue is whether good geochemical maps of the satellites can be produced. Precision of any spatial element and the number of spatial elements can be traded off against each other, but only the A' mission or some other mission providing repeated encounters as well as extended coverage can yield high-coverage/moderate-resolution geochemical maps of these objects (see Table 4).

The combination of even modest spatial-resolution chemical data with moderate spatial-resolution spectroscopic data and very good spatial-resolution multispectral mapping would be highly synergistic and would allow detailed compositional and phase mapping of the surfaces of all the satellites.

I. MASS SPECTROMETRY

Neutral H, Na, and K are now known to exist in the cloud and partial torus extending around Io and Jupiter. S^+ ions have also been detected. Sputtering of Io's surface by magnetospheric protons is thought to be the source of the Na, K, and probably S. It is thought that many other Io-originating species may be present as well but are not yet detected because their spectral lines are not strong enough. Mass spectrometric measurements of both ions and neutrals in the torus and Io-surrounding cloud could reveal much concerning (1) the composition of Io's surface, (2) the interaction between Io and the Jovian magnetosphere, (3) the origin of the H and other species in the Jupiter-surrounding torus and any exchange of material between both Jupiter and the torus or magnetosphere, and (4) the processes of ionization of cloud/torus neutrals, the rate of occurrence, and the fate of the ions produced. As with other experiments, mass spectrometry would be greatly dependent on having numerous close approaches to the satellites, representing reasonable integration times and some sort of long time base so variables can be correlated with other magnetospheric variations.

J. A GALILEAN SATELLITE LANDER FOR THE LATE 1980'S

We have not considered the problem of the role of landers in Galilean satellite studies in detail. However, the following represents our preliminary conclusions. As the next logical step following JOP, it is possible and would be desirable for an orbiter mission in the very late 1980's to include a lander for one of the satellites. At present it appears that either J3 or J4 would be suitable, but that a lander on J1 or J2 would have an exceedingly short effective lifetime (perhaps only a few hours). A lander would represent our first long-lived scientific base in the outer solar system, and would provide, among other data:

(1) Our first close-up look at the surface of one of the most abundant types of planetary objects in the solar system: an icy body.

(2) Indications of the degree of internal seismic activity resulting from possibly highly dynamic processes (e.g., liquid H_2O convection and H_2O freezing/melting).

(3) Our first opportunity to examine the actual (as opposed to inferred) interaction of the Jovian magnetosphere with a satellite surface - including sheath effects and effects of any indigenous satellite field - via landed magnetometer and charged particle measurements.

(4) The first comprehensive compositional measurements of a satellite atmosphere, including highly time-variable phenomena.

(5) The first measurements of the chemical composition of a small domain on the surface of such a remote object.

(6) A good base from which to make synoptic observations of the other satellites, the torus and (possibly) Jupiter.

Even the rather limited landed scientific payload (~12 kg) afforded by present hard landers could be made generally compatible with the foregoing objectives owing to recent advances in miniaturization. For example, it might include a multispectral facsimile camera (~1.5 kg), a seismometer (~1 kg), a magnetometer (~0.6 kg) a neutral/ion mass spectrometer (~6 kg) and an α backscatter/X-ray fluorescence instrument.

SECTION IV

RECOMMENDATIONS

We believe that spacecraft investigations of the surfaces and interiors of these four different terrestrial planets and their interaction with the space environment should rank very high on NASA's list for terrestrial body studies. Considerable enhancement of our current knowledge of these objects will hopefully occur as the result of the MJS 1977 mission. We emphasize, however, that outstanding opportunities for investigation of these objects are represented by a Jupiter Orbiter mission in the mid-80's and a possible satellite lander mission in the late 80's. We recognize that many of the most exciting observational and theoretical developments in Galilean satellite science have occurred recently - after preliminary planning of the Jupiter Orbiter Probe 1984/85 mission was well under way. Fortunately, this mission is extremely flexible owing to the innumerable possible trajectories allowed by satellite gravitational assists. We urge that every effort be made to take full advantage of the outstanding opportunities for satellite studies offered by a possible JOP mission. It is our belief that this can be accomplished without compromising the probe delivery and magnetosphere study objectives of the orbiter portion of JOP and that in fact the return from at least the magnetosphere studies portion could be greatly augmented if our recommendations are followed. Implementation of major satellite objectives can be accomplished by careful selection of the mission profile or orbit trajectory together with inclusion of certain key instruments in the scientific payload which are particularly powerful tools for remote studies of planetary surfaces. Specifically, we conclude:

(1) That the satellite science return from the JOP mission could be greatly augmented if the trajectory were chosen to yield numerous close encounters with as many of the satellites as possible. The A' trajectory shown in Figure 2 is an excellent example of such a mission. It provides 11 satellite encounters of J3 and J4 (vs three of J3 provided by the nominal or A mission). Also, all possible modifications of the trajectory which may provide encounters with J1 and J2 without subjecting the spacecraft to an intolerable radiation dosage should be seriously considered. A still greater increment to satellite (and magnetospheric) science would occur if a second spacecraft were launched in 1983. This would provide still greater coverage of J3 and J4 and allow for possible encounters of J1 and J2. We therefore recommend this second spacecraft at least be considered as a cost-effective way for studying the system.

(2) Since proper satellite science will require an appropriate assemblage of instruments as well as an appropriate trajectory, we recommend that the following key instruments be carefully considered for inclusion in the payload: (a) a visible and infrared spectrometer for studies of the distribution of mineral phases on the satellite surfaces and

the thermophysical properties of these surfaces; (b) an ultraviolet spectrometer, primarily for satellite atmospheric occultation studies and studies of extended atmospheric phenomena and atmospheric-ionospheric phenomena, including the Io-Jupiter cloud or partial torus; (c) an X-ray fluorescence experiment designed to measure the abundance and distribution of chemical elements on the satellite surfaces; and (d) an ion mass spectrometer designed for detailed study of the distribution and mass and velocity spectra of ions near the satellites and elsewhere in the magnetosphere, especially those which may have originated from the satellite surfaces. Also of great value will be (e) the interior studies afforded by the tracking data which require no special instrumentation, but only the adoption of an appropriate trajectory. In essentially the same category are (f) atmospheric radio occultation data; (g) the magnetometer and particle-counting experiments which we assume will be included; and (g) multispectral imaging, which would benefit from as many broadband filters as it is practical to include.

(3) We consider that the next most ambiticus and most logical step in exploration of these objects in addition to orbital studies would be the landing of a spacecraft on one of their surfaces. At present it appears that J3 or J4 might have the advantage (over J1 or J2) of having a sufficiently low level of background radiation to allow survival of a long-lived ($\gtrsim$1 yr) scientific observatory on one of these surfaces. It does not appear absolutely essential that such a lander have the vast complement of sophisticated instrumentation characteristics of a Viking-class spacecraft. A major advance would be represented by the landing of even a 12- to 15-kg scientific payload on the surface - such as could be accomplished with a hard-lander package. Even a small payload such as this could provide exciting close-up multispectral imaging, seismic studies, atmospheric studies, near-surface fields and particles studies, surface chemical analysis observations, and synoptic observations of the satellites, the torus and Jupiter. A mission including orbital studies and such a hard lander is already essentially within our capability. We believe that what it offers as our first very-close-up look at an icy body and our first scientific base in the outer solar system is sufficient to recommend it for implementation prior to 1990.

(4) As indicated earlier, even thoroughly successful and accepted techniques such as X-ray fluorescence must often be largely recast for application near Jupiter because of the special radiation, lifetime, and other problems posed by Galilean satellite studies. Resources should be made available prior to mission starts so that the necessary design changes can be thoughtfully planned and their feasibility studied prior to the onset of fabrication deadlines associated with a new start. In addition to problems of redesign, studies of radiation hardening of fundamental spacecraft or instrument

parts should proceed apace. It is largely radiation sensitivity which may limit the number of possible encounters and our science return, especially for perhaps the most fascinating and least approachable of the four objects - Io.