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ORIGIN AND EVOLUTION OF THE SATURN SYSTEM: OBSERVATIONAL CONSEQUENCES

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ABSTRACT

A number of important cosmogonic questions concerning the Saturn system can be addressed with a Saturn-orbiter-dual-probe spacecraft mission. These questions include: the origin of the Saturn system; the source of Saturn's excess luminosity; the mechanism by which the irregular satellites were captured; the influence of Saturn's early luminosity on the composition of its regular satellites; and the origin of the rings. The first two topics can be studied by measurements made from an entry probe into Saturn's atmosphere, while the remaining issues can be investigated by measurements conducted from an orbiter. In this paper, we present background information on these five questions describing the critical experiments needed to help resolve them.

INTRODUCTION

The planets of our solar system can be divided into three compositional classes: the terrestrial planets, which are made entirely of heavy elements; Jupiter and Saturn, which are composed chiefly of hydrogen and helium, although they have heavy element cores; and finally Uranus and Neptune, which are constructed in large measure of heavy element cores, but also contain significant gaseous envelopes. We are in a particularly fortunate situation in our attempts to understand the origin and subsequent evolution of Jupiter and Saturn. In the first place, their current characteristics as well as those of their attendant satellite systems are rife with clues about their history.

For example, the observed excess amount of thermal energy they radiate to space above the amount of absorbed solar energy may represent the embers of internal energy built up during an early rapid contraction phase (Graboske *et al.* , 1975; Pollack *et al.* 1977). In the second place, techniques used to study stellar evolution can be employed to model much of the evolution of these giant planets.

In this paper, we review current cosmogonic theories of the history of the Saturn system and describe how such models can be tested by comparisons with the present properties of Saturn, its rings, and its satellites. Emphasis will be placed on enumerating those cosmogonic clues that might be studied most profitably by a Saturn-Orbiter-Dual Probe (SOP^2) spacecraft mission.

RIVAL COSMOGONIC HYPOTHESES

Present-day Saturn has a mass equal to about 95 Earth masses, of which about 15 Earth masses is sequestered in a heavy element core composed presumably of a mixture of rocky and icy material (Slattery, 1977). The remaining material in the surrounding gaseous-liquid envelope is thought to consist of an approximately solar mixture of elements; i.e. hydrogen and helium are the dominant components. The composition of this envelope closely resembles that of the primordial solar nebula, which served as the source material for planetary construction. There are two logical possibilities for the way in which Saturn could have been assembled within the solar nebula. Either its core was formed first and served to focus a massive gaseous envelope about itself or a gaseous condensation developed initially within the solar nebula and subsequently collected a central core. Both these possibilities have been explored in recent years. Below we describe these alternative models for the formation of Saturn and indicate the stage at which its regular satellites may have formed.

Perri and Cameron (1974) investigated models in which massive planetary cores formed first and subsequently collected a portion of the nearby solar nebula about itself. As might be expected, the gas of the nebula becomes concentrated about the core, with the boundary of this gaseous envelope being the point at which the gravitational attraction of the core and envelope equals the gradient of the gravitational potential of the solar nebula, i.e., it equals the "tidal" radius. Below a certain critical mass, the envelope about the core is hydrodynamically stable, so that only a minor gaseous envelope could be expected at present. But, for cores more massive than a "critical mass", the envelope becomes hydrodynamically unstable and in a very short period of time assumes a much smaller radius than the tidal value. In this case, the product will be a planet with both a massive core and a massive gaseous envelope.

The value of the critical core mass needed to trigger a hydrodynamic instability in the surrounding gas depends on the temperature structure assumed for the envelope and its boundary conditions. Perri and Cameron (1974) assume that the envelope is convectively unstable, motivated in part by the large opacity expected from dust grains, and that the envelope is on the same adiabat as the solar nebula. Using nominal values for the solar nebula's adiabat, they obtained a critical mass of 115 Earth masses. Since this value was significantly higher than values of several tens of Earth masses found by Podolak and Cameron (1974) from models of the interior structure of the outer planets, they suggested that the instability occurred at a later epoch in the history of the solar nebula, when it was much cooler. Much smaller critical masses can also be realized by postulating an isothermal temperature structure for the envelope. According to Harris (1978), critical masses on the order of 1 Earth mass hold in this case. As mentioned in the introduction, the best current estimate of the mass of Saturn's core places it at 15 Earth masses. Thus, the actual core mass of Saturn may be large enough for it to have been able to initiate a hydrodynamical collapse in the surrounding gas.

An alternative scenario for the origin of Jupiter, and by implication Saturn, was first investigated in detail by Bodenheimer (1974). He suggested that the initial formation stage involved the condensation of the gaseous envelope. As in the case of star formation, a local density enhancement is assumed to be present in the solar nebula. When this density exceeds a critical value, the localized region begins to contract. If the sun has not yet formed and there is little mass in the solar nebula interior to the localized region of interest, the critical density is determined by the condition that the region's gravitational binding energy be comparable to its internal energy, as determined by its temperature. If the sun has formed or at least there is much mass in the solar nebula interior to the local region, the critical density is determined from a tidal criterion. In the case of Jupiter, Bodenheimer estimates the critical density to equal approximately 1.5×10^{-11} gm/cm^3 in the former case and about 1×10^{-8} gm/cm^3 in the latter case (Bodenheimer, 1978). For an object of Saturn's mass and distance, a simple scaling of Bodenheimer's prescriptions for the critical density leads to values of about 1×10^{-10} and 2×10^{-9} gm/cm^3. The corresponding initial radius for Saturn in both cases is approximately 2000 R_S, where R_S is its current radius.

Once contraction is initiated as a result of the local density enhancement, the gaseous protoplanet will evolve through four stages (Bodenheimer, 1974). The first stage consists of a small contraction (~15%) on a hydrodynamic time scale (~10^2 years), during which the configuration settles into hydrostatic equilibrium. This stage is followed by one characterized by a slow contraction on a Kelvin-Helmholtz time scale (~10^5-10^7 years). As time progresses, the interior temperatures are gradually built up until they reach about 2500 K near the center. At this point significant dissociation of molecular hydrogen occurs, which alters the adiabatic lapse rate in such a way that a hydrostatic configuration is no longer possible and a hydrodynamical collapse phase is initiated. Within a very short time on the order of a few years, the radius of the protoplanet decreases from several hundred times the present value to several times the present value. However, near the end of the collapse, conservation of angular momentum probably leads to a spreading out of the outer regions of the protoplanet into an extended disk. Thus, while the central protoplanet is settling back into a hydrostatic configuration once more, the formation of its regular satellites begins within the extended disk. The fourth stage, which spans almost the entire lifetime of the planet, involves a slow hydrostatic contraction to its present size. From now on, we will refer to these four stages as the first hydrodynamic stage, the first hydrostatic stage, the second hydrodynamic stage, and the second hydrostatic stage, respectively.

Figures 1a and 1b illustrate the nature of the first hydrostatic phase for Saturn (DeCampli *et al.*, 1978). In these figures, radius and luminosity are plotted as a function of time. The time scale of this stage is determined principally by the opacity within the protoplanet, which is almost entirely due to grain opacity. In this calculation, the composition of the major grain species was determined from thermodynamic equilibrium considerations for a solar abundance mixture of elements, with the best available optical constants for each specie being used to determine the Rosseland mean opacity of the ensemble. A protoplanet with Saturn's mass takes about 10^7 years to progress through stage 2, whereas one with Jupiter's mass takes about 10^6 years. Thus, this time scale varies approximately as the square of the mass. Clearly a protoplanet's mass cannot be much less than an order of magnitude smaller than Saturn's mass or it would not complete stage 2 within the age of the solar system. Also, according to these calculations, the second hydrodynamic collapse begins when proto-Saturn has a radius of about 40 R_s.

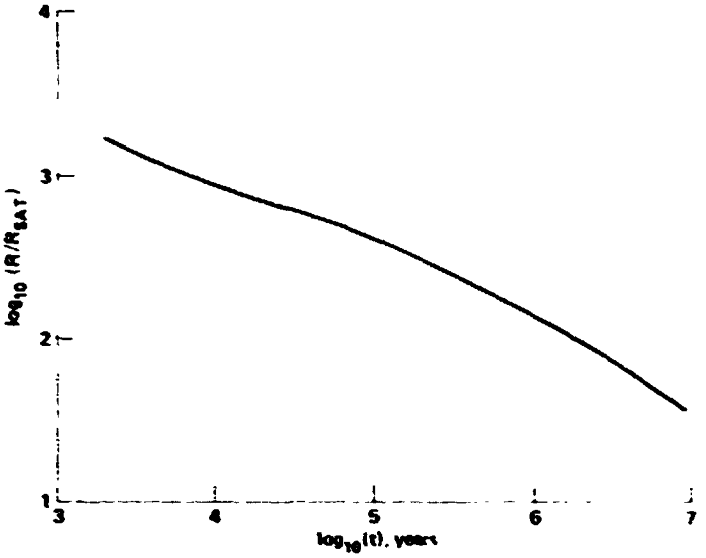

Figure 1a. Radius of Saturn, in units of its present value, as a function of time during the first hydrostatic stage

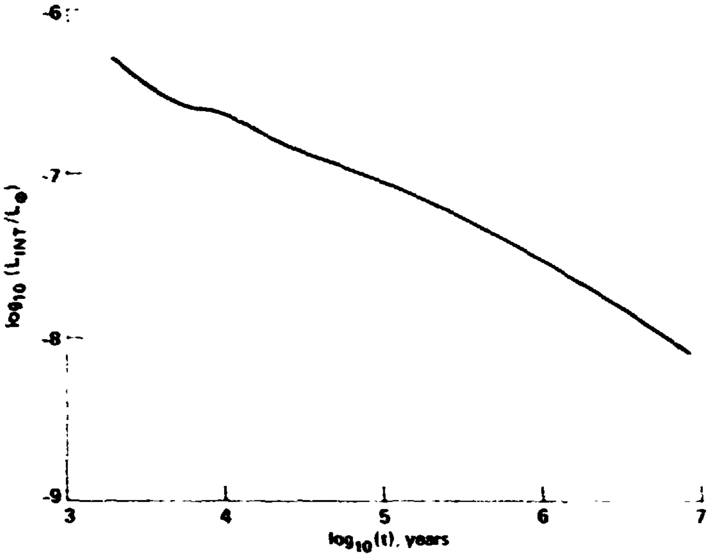

Figure 1b. Luminosity of Saturn, in units of the solar luminosity, as a function of time during the first hydrostatic stage.

Figures 2a and 2b present the temporal variations of Saturn's and Jupiter's radius and luminosity during the second hydrostatic stage (Pollack *et al.* , 1977). The initial radii for these calculations were arbitrarily chosen to be about ten times their current values. However, these curves are equally applicable to other initial conditions, by merely starting at the desired radius and measuring time relative to this initial epoch. Bodenheimer's (1974) calculations of the second hydrodynamic stage suggest that this stage concludes and the second hydrostatic stage begins at a radius of 4 to 5 times the current value. The present day values of radius and excess luminosity are shown by squares and circles in these figures for Jupiter and Saturn, respectively. These calculations refer to a solar mixture model, i.e., one lacking a heavy element core. Inclusion of a core, by design, leads to perfect agreement with the observed radius, but it does not substantially change the time scales nor the luminosity diagram (Grossman, 1978). Possible reasons for the underestimate of Saturn's current excess luminosity will be given below. In any case, we see that these calculations lead to reasonable first order estimates of the observed values. Finally, we note that gases are the only source of opacity for these models. This is reasonable since the interior temperatures are sufficiently high for grains to be evaporated.

An important aspect of Figure 2b is the occurrence of a very high luminosity during the early phases of stage four. Thus, during the time period over which the regular satellites were forming, its planet's luminosity was several orders of magnitude higher than its current value and furthermore was rapidly declining. Consequently, the formation of low temperature condensates, such as ices, may have been inhibited close to the planet at such times and a zonation of composition with distance from the primary may be created (Pollack and Reynolds, 1974; Pollack *et al.* , 1976). We also note from Figure 2b that, during early times of this stage, Jupiter's luminosity was about a factor of ten higher than Saturn's and consequently it was harder to form low temperature condensates close to Jupiter.

So far, we have discussed only the evolution of the gaseous portions of Saturn. There are several ways in which its heavy element core may have been created. First, if proto-Saturn was much more massive than Saturn's current mass, the core could have been formed entirely from grains initially present in the envelope, which were segregated into the central regions. For example, the interior temperatures around the time of the second hydrodynamic stage may have reached the *melting* point of the grains, leading to liquid particles, which rapidly coagulated into much bigger particles; the latter rapidly sank to the center (Cameron, 1977). Subsequently, much of the gaseous envelope was lost so that the end result was a planet enriched in heavy elements. To be consistent with Saturn's inferred core mass, we would have to postulate that *at least* 80% of the initial protoplanet's mass was later lost!

Alternatively, small rocky and icy bodies may have been produced outside of Saturn's sphere of influence, but at a similar distance in the solar nebula. These objects could have been collected efficiently when proto-Saturn was much larger than its current size, i.e., during the first hydrostatic stage. Planetoids smaller than 10 to 100 km in radius would have become captured by gas drag effects. Continued gas drag would have caused them to spiral very rapidly into the center of the proto-planet (Pollack *et al.*, 1978).

Finally, let us compare the two scenarios of planetary formation. The first hydrostatic stage of the gas instability model bears some resemblance to the stage during which the core is growing to the critical mass in the core instability model. During the core growth period, there will be a gaseous concentration about the core, which will be in hydrostatic equilibrium. The chief differences at this point between the two models is that the core and envelope mass are both growing with time in the core instability model, but not in the gas instability model (except perhaps for the core alone) and that the radius of the envelope in the former model is always determined by the tidal radius, and so will increase with time, not decrease as occurs for the latter model. Both models are characterized by a subsequent rapid hydrodynamical phase. At the end of this stage both models relax into a hydrostatic configuration and follow essentially the same evolutionary path.

PLANETARY OBSERVATIONS

In this section and in the following one, we enumerate critical observations that can be made from a SOP^2 mission that will test and illuminate key cosmogonic issues. In preparing this list of measurements, we have attempted to exclude ones that can be made from the Pioneer 11 and Voyager Flyby missions, which will reconnoiter the Saturn system first.

Assessment of the amount by which Saturn's interior is enriched in heavy elements in excess of their solar abundance values may aid in discriminating between the two theories for the formation of the Saturn system and in obtaining clues about core construction. In principle, the core mass can be determined from a knowledge of the planet's mass, radius, and rotational period, quantities that are presently well-known. However, such calculations rest on the implicit assumption that the composition of the envelope is known; e.g., that the envelope has a solar elemental abundance composition. But, the envelope may be enriched in such volatiles as water, ammonia, and methane: within the context of the core instability model, a shock wave is set up at the core-envelope interface during hydrodynamical collapse, which may cause the evaporation of some of the icy condensates (Perri and Cameron, 1974). Within the context of the gas instability model, the same result may accrue from the gas drag capture mechanism, as captured bodies are partially volatilized. Indeed some recent models of Saturn's interior have invoked heavy element enrichment of the envelope to fit the measured values of its gravitational moments (Podolak and Cameron, 1974).

While crude estimates of the abundance of methane and ammonia in Saturn's atmosphere can be made from Earth-based observations, truly good determinations can only come from in-situ compositional analyses below the levels at which these gases begin to condense and therefore require an atmospheric entry probe. Such measurements will also yield the water vapor abundance, provided the probe can survive until depths of several tens of bar pressure. Finally, a determination of the helium to hydrogen ratio in the observable atmosphere is also important, since, as discussed below, helium may partially be segregated towards the bottom of the envelope.

Conceivable, not only is the envelope of Saturn enriched in icy species, but also in rocky species (Podolak *et al.*,1977). Since the latter condense way below any altitude to which a probe can reasonably be expected to function, a more indirect assessment of the latter excess is needed. The needed constraint can be provided by the J_2 gravitational moment of Saturn. While this moment is currently known quite well from studies of satellite orbits (~0.1%), there is one important potential source of systematic error in its value. The current estimate of J_2 is based upon the assumption that the rings of Saturn have a negligible mass. Studies of the motion of a Saturn orbiter may provide a check on this assumption. If it turns out that the rings do have a non-trivial mass ($>10^{-6}$ Saturn's mass), corrections can readily be made to the current value of J_2 to convert it into the actual J_2 for Saturn. Similar corrections and refinements to J_4 (currently known to about 7%) will yield a value that will provide a valuable check on the validity of the interior models. Moments higher than J_4 will not be very useful since they are determined principally by the outermost layers of the envelope (Hubbard and Slattery, 1976).

Let us now suppose that the SOP^2 mission provides the needed compositional and gravitational information. Two theoretical steps are needed in order to realize the scientific objectives. First, interior models need to be constructed to define the amount of excess heavy elements and their spatial distribution, i.e., partition between core and envelope. Currently, the chief theoretical factor limiting the accuracy of interior models of the giant planets is the uncertainty in the thermodynamic properties of materials at high temperatures and pressures. In the case of the envelope, the equation of state of a solar elemental mixture is least well known for densities in the range of 0.1 to 1 gm/cm^3. Typically, the needed thermodynamic properties are interpolated from their more well defined values at lower and higher densities. It is reasonable to expect that the uncertainties in this critical density region will be substantially reduced by the time a SOP^2 Mission occurs. This is important since much of Saturn's interior lies within this density domain (~70% by mass!). Also, adequate equations of state for core materials should be available at the time of the SOP^2 mission.

In addition to good interior models, careful determinations are needed of the critical core mass needed to cause hydrodynamic instability in the surrounding gas. Current estimates of this parameter are based on linear stability theory. More reliable values can be obtained from numerical hydrodynamical calculations and these should become available in the next few years. By comparing the inferred excess mass of heavy elements with the critical value, an assessment of the validity of the core instability model can be made.

We next consider the origin of the excess energy Saturn radiates to space. Gravitational energy represents the only plausible source for this excess that would allow Saturn to radiate at its present excess over the lifetime of the solar system (Graboske *et al.*, 1975; Cameron and Pollack, 1976; Pollack *et al.* , 1977). But there are three distinct ways in which Saturn's gravitational energy can be converted into luminosity (ibid). First, rapid contraction in Saturn's early history, when its interior was much more compressible than at present, could have led to a build-up of internal energy, i.e., high interior temperatures, which have subsequently been decreasing. Second, Saturn may be contracting sufficiently rapidly at present to generate the observed excess. Both the above modes of gravitational energy release refer to the behavior of a planet whose interior compositional structure does not change with time. But, according to calculations by Stevenson (1975), when temperatures decline to a certain threshold value in the envelopes of the giant planets, helium will start to become immiscible in metallic hydrogen and begin to sink towards the center of the planet. As this process proceeds, some helium in the molecular envelope will be mixed into the depleted region of the metallic zone, so that a helium depleted outer region encompassing both regions will be set up. Such a chemical differentiation could generate enough energy to account for much of the observed excess luminosity.

The evolutionary results shown in Figure 2b refer to the contraction history of homogeneous, solar elemental mixtures containing no cores. Thus, the predicted luminosity reflects only the first two gravitational processes. Figure 3 illustrates the relative effectiveness of these two processes for Saturn by displaying the time history of its gravitational and internal energies (Pollack *et al.*, 1977). During the first 10^7 years, contraction proceeds at a rapid enough rate for the internal energy to steadily increase. But, at subsequent times, it declines. Currently, the loss of internal energy is more important than present contraction in accounting for the excess luminosity, although the latter makes a non-negligible contribution. Qualitatively similar statements also hold for Jupiter.

As illustrated in Figure 2b, the calculated excess for Jupiter at a time equal to the age of the solar system is consistent with the observed excess. However, the corresponding theoretical value for Saturn falls noticeably below its observed excess. There are several points that need to be considered before we judge this discrepancy to be real. First determination of the observed value is complicated by the need to subtract out a contribution from the rings at the longer infrared wavelengths, where the two objects cannot be spatially resolved, as well as by uncertainties in calibration standards. Nevertheless, the most recent determinations of Saturn's excess luminosity are crudely consistent with the value displayed in Figure 2b (e.g., Ward, 1977). This situation should be substantially improved by having observations performed when the rings assume an edge-on orientation as viewed from Earth and by utilizing observations from the fly-by missions to obtain an accurate value for the phase integral in the visible. This latter is needed to compute the amount of solar energy absorbed by the planet. In addition to these observational issues, we also need to consider the influence of a core on Saturn's theoretical excess luminosity. Very recent calculations that incorporate a core-envelope structure lead to essentially the same curve as shown in Figure 2b (Grossman, 1978). Hence, the factor of 2 to 3 difference between the computed and observed excess energy may be real.

Is helium segregation an important source of the present excess luminosity? According to Figure 2b, this source is not needed to explain Jupiter's excess. Furthermore, temperatures within Jupiter's metallic zone are at least a factor of two above

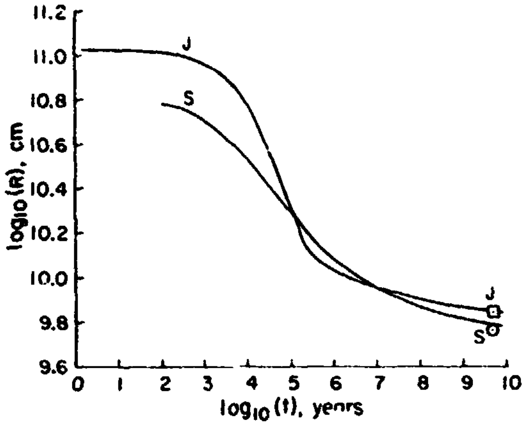

Figure 2a. Radius of Jupiter (J) and Saturn (S) as a function of time, t, during the second hydrostatic phase. The observed values at the 4.5×10^9 years time point are indicated by the square and circle for Jupiter and Saturn, respectively.

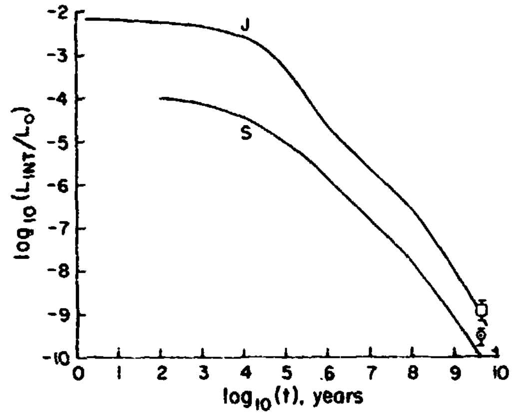

Figure 2b. Excess luminosity of Jupiter (J) and Saturn (S), in units of the solar luminosity, as a function of time, t, during the second hydrostatic stage. Observed values at the 4.5×10^9 years time point are indicated by the square and circle for Jupiter and Saturn, respectively.

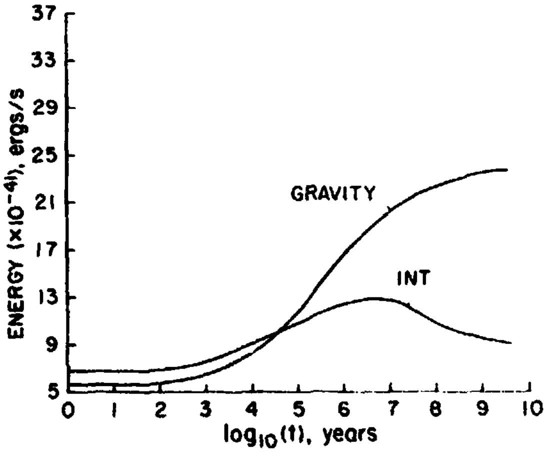

Figure 3. Variation with time during the second hydrostatic stage of ($-E_{GRAV}$), labelled GRAVITY, and E_{INT}, labelled INT, where E_{GRAV} and E_{INT} are the potential energy and internal thermal energy, respectively. These results pertain to a model of Saturn using solar elemental abundances

the temperature at which phase separation starts to occur (Pollack *et al.* , 1977). But the reverse may be true for Saturn. The computed excess appears to be too low. Also, as illustrated in Figure 4, the interior of a chemically *homogeneous* model crosses the phase separation curve after about 1 billion years of evolution. Allowance for a core-envelope structure leads to higher interior temperatures in the metallic hydrogen zone, with current Saturn lying close to the separation curve. Thus, helium segregation, while apparently not yet an important source for Jupiter, may represent a major source of Saturn's current excess (Pollack *et al.* , 1977).

If the phase separation of helium from hydrogen is in fact a significant source of Saturn's excess energy, planet-wide segregation is required (Pollack *et al.* , 1977). Therefore, an in-situ determination of the helium to hydrogen ratio by experiments carried aboard an entry probe can provide a critical test of this possibility. Not only will it be useful to compare this measurement with solar abundance figures, but, equally important, to compare it with the value found for the atmosphere of Jupiter by experiments aboard the JOP entry probe. This latter comparison is needed since the solar ratio is not as well established as one might like.

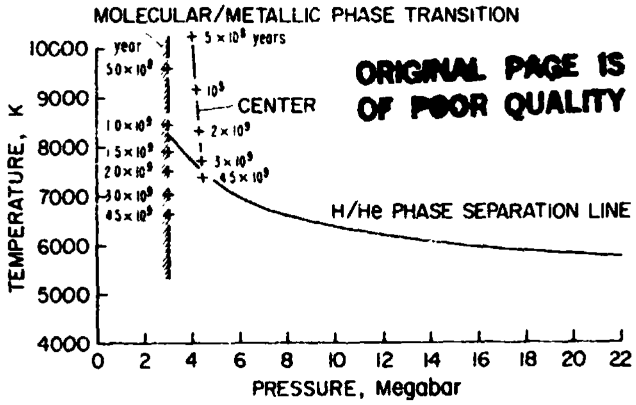

Figure 4. Phase boundaries for the molecular and metallic phases of hydrogen and for the separation of helium from hydrogen. For points lying below the separation line, helium becomes partially immiscible in metallic hydrogen. Also shown on this diagram is the evolutionary track of the center of a solar mix Saturn model. Numbers next to crosses on this track and on the molecular-metallic phase boundary indicate time from the start of the calculation for the second hydrostatic stage.

SATELLITE AND RING OBSERVATIONS

In this section, we discuss sequentially cosmogonically relevant observations of Saturn's irregular satellite(s), regular ones, and the rings. The outer satellites of Jupiter, Saturn, and Neptune differ markedly from the inner satellites of these planets in having highly inclined and eccentric orbits, with about half of them traveling in a retrograde direction. These orbital characteristics suggest that the outer satellites may be captured objects. Pollack *et al.*, (1978) have proposed that capture occurred as a result of the gas drag experienced by bodies passing through the extended gaseous envelopes of the primordial giant planets, just prior to the second hydrodynamical stage. We have earlier pointed out that gas drag capture offers one mechanism of generating core material. In such cases, continued gas drag causes the captured body to quickly spiral into the center of the protoplanet. However, if capture occurs in the outer portion of the protoplanet shortly before initiation of the second hydrodynamical collapse (within $\sim 10^1$ years) and if the captured body is sufficiently large ($\sim 10^2$ - 10^3 km), it will experience only limited orbital evolution prior to the removal of gaseous material from its neighborhood. In this case, the captured body would remain a captured satellite. Pollack *et al.*, (1978) showed that this mechanism could lead to the capture of objects comparable in size to that of the irregular satellites, when nebular densities similar to those exhibited by models of the latest phases of the first hydrostatic stage are utilized (Bodenheimer, 1978). In addition, this model is capable of accounting for many other observed properties of the irregular satellites.

Besides modifying a body's velocity, gas drag also subjects it to mechanical stresses and to significant surface heating. When the dynamical pressure due to gas drag exceeds the body's strength, it will fracture into several large pieces. However, the mutual gravitational attraction between the fragments is larger than the gas drag fo[illegible] so the fragments remain together until separated by collision with a sufficiently la[illegible]ray body. In this way, Pollack *et al.*, (1978) attempt to account for the existence of Jupiter's two families of irregular satellites with the members of each family being characterized by similar orbital semi-major axes and inclinations.

Figure 5 illustrates the heating rate experienced on the forward hemisphere of a captured body as a function of angular distance θ from the stagnation point. (M. Tauber, private communication). These calculations pertain to typical parameter choices of 5 km/s for the relative velocity between the body and the nebula and

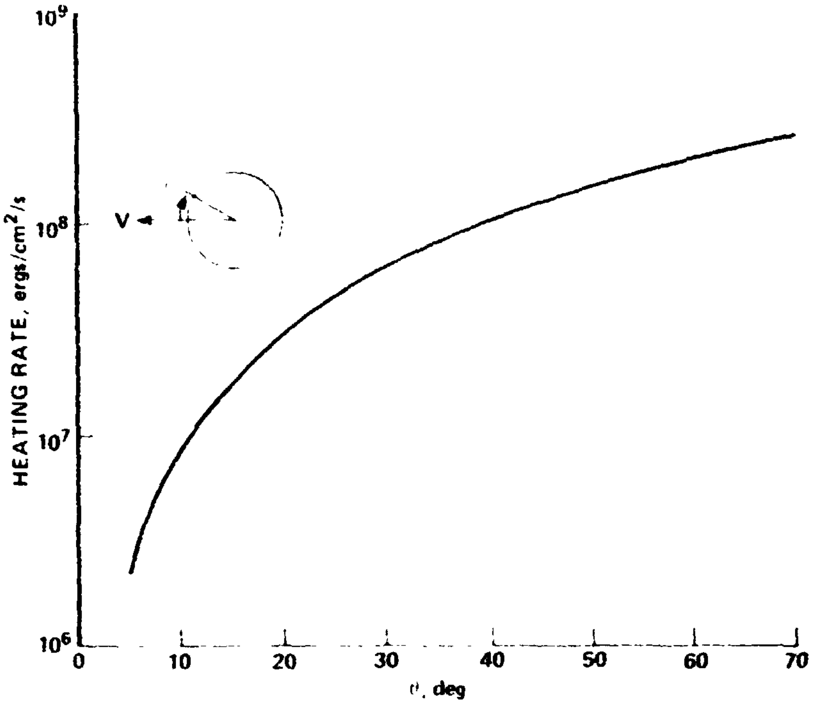

Figure 5 Heating rates on the forward hemisphere of a body experiencing gas drag as a function of angular distance θ from the stagnation point. These calculations were done for a relative velocity of 5 km/sec between the body and the gaseous medium and a gas density of 2×10^{-6} gm/cm^3.

2×10^{-6} gm/cm^3 for the gas density. Orders of magnitude smaller heating rates occur on the trailing hemisphere. If we use a representative value of 10^8 ergs/cm^2/s for the heating rate and assume it is used simply to enhance the surface temperature, we obtain a surface temperature of 1150 K! Alternatively, if some of the heat is used to melt or vaporize surface deposits of water ice, we find that meters of ice can experience a phase change during the time of the capture process.

Saturn's outermost satellite, Phoebe, is definitely an irregular satellite: it travels in a highly eccentric, highly inclined orbit in the retrograde direction. Conceivably, the second outermost satellite, Iapetus, might also be considered an irregular satellite since its orbital inclination is substantially larger than those of satellites located closer to Saturn. But, Iapetus travels in a prograde direction and has a very low orbital eccentricity.

Photography of Phoebe, its neighborhood, and Iapetus may provide valuable data for assessing the validity of the gas drag capture mechanism. Close-up pictures of Saturn's irregular satellite(s) may reveal morphological features created during the hypothetical capture event(s). The mechanical stresses experienced during capture may be manifested in extensive fractures, while the strong surface heating may have produced flow features as well as pit-like structures created by outgassing.

As mentioned above, capture led to clusters of irregular satellites in the case of the Jovian system, with cluster members representing fragments of the captured parent body. In the case of the Saturn system, no such families of irregular satellites are known to exist. The presence of single, irregular satellite(s) rather than clusters can be attributed to the following: there were differences in the mechanical properties of the captured bodies so that total fracture never occurred for the Saturn captured objects(s); or fracture did occur, but there was never a subsequent collision with a large enough stray body to separate the pieces; or separation did occur, but the smaller fragments are too faint to be readily observed from the Earth. The last possibility gives rise to the suggestion that a systematic photographic search be conducted from a Saturn orbiter for faint objects with orbital inclinations and semi-major axes similar to those of Phoebe.

We next consider studies of the regular satellites. The Galilean satellites of Jupiter exhibit a systematic increase in their mean density with decreasing distance from Jupiter. This trend has been attributed to the high luminosity of Jupiter during the early phases of its second hydrostatic stage (see Figure 2b) (Pollack and Reynolds, 1974). As discussed earlier, the high luminosity inhibited the condensation of ices in the region close to the planet during the satellite formation period. Saturn's lower luminosity during this epoch means that ices were stable closer to it than to Jupiter during the formation of its satellite system. Nevertheless, a compositional gradient may also be present for the Saturn system.

In Figure 6a, we illustrate the possible effects of Saturn's early high luminosity on the composition of the material forming its satellite system (Pollack *et al.*, 1976). Each curve in this figure shows the temperature of a condensing ice grain at the distance of a given satellite as a function of time from the start of the second hydrostatic stage. The curves are labelled by the first letter of a satellite's name, with A, B referring to the two brightest rings. Analogous curves for the Jovian system are shown in Figure 6b. In both cases, the region of satellite formation has been assumed to have a low opacity to the planet's thermal radiation. Qualitatively similar curves hold in the high opacity case (Pollack *et al.*, 1976).

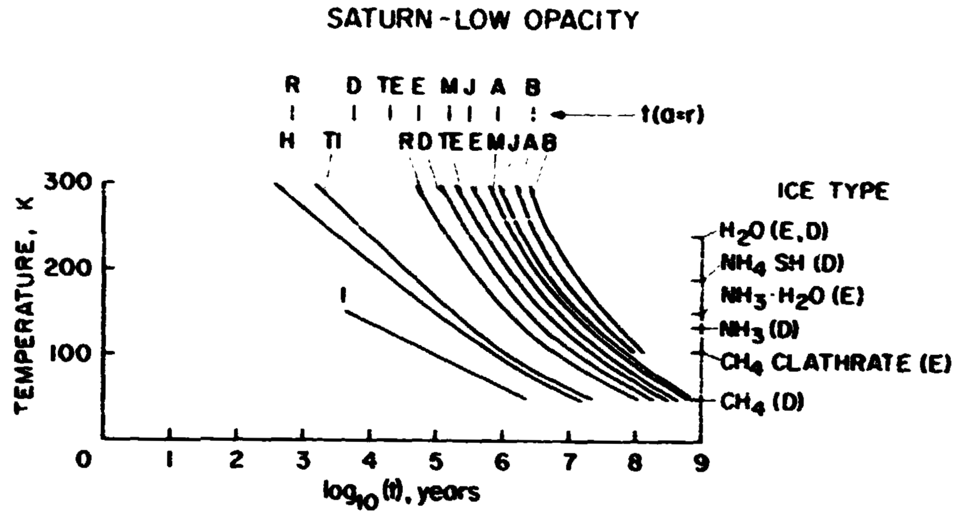
SATURN - LOW OPACITY

Figure 6a. Temperature of a condensing ice grain as a function of time from the start of the second hydrostatic stage. The calculations of this figure are for the Saturn system and the low-opacity case. Each curve refers to a fixed distance from the center of the planet and is labelled by the first letter of the name of the satellite or ring segment, which is currently at that distance. Further details about this figure are given in the text.

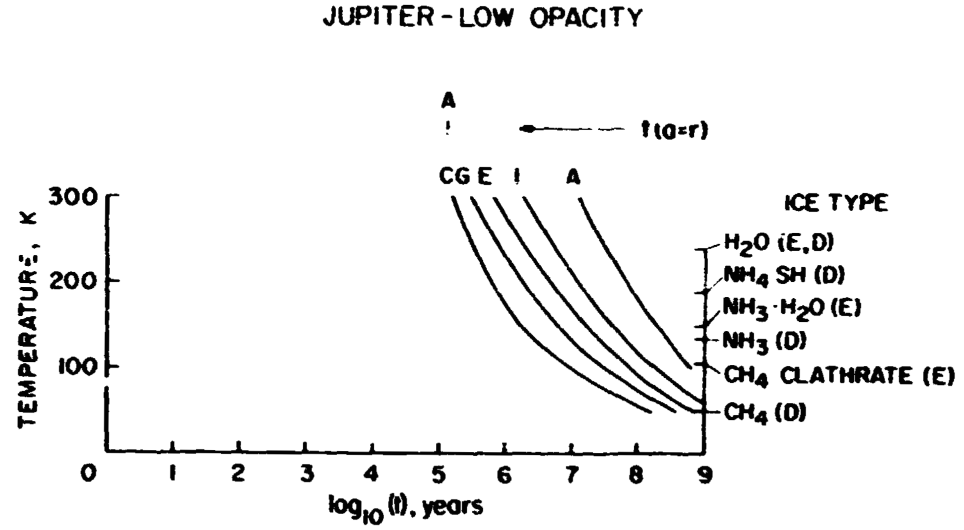
JUPITER - LOW OPACITY

Figure 6b. Same as figure 6a, but for the Jupiter system.

The vertical axis on the right hand side of Figure 6 displays the temperature at which various ice species condense. Thus, at times along a given satellite's curve when the temperature is higher than the condensation temperature of a particular ice specie, it will be entirely in the gas phase and so will not be incorporated into the forming satellite. After a certain time, satellite formation ceases because the disk of material from which they form has been eliminated. If the temperatures have remained too hot for certain ice species to condense up until the end of the satellite formation period, they will be absent from a satellite formed at the distance under consideration. Hence, satellites close to Saturn will lack the more volatile ice species incorporated into satellites formed further away.

The short vertical line segments near the top of Figure 6 indicate the time, t (a = r), at which the radius of the planet equalled the orbital distance of the satellite. Presumably, satellite formation at that distance did not occur at earlier times. Titan may be larger than satellites closer to Saturn because its formation could have started with the commencement of the second hydrostatic stage (Pollack *et al.* , 1977).

Accurate measurements of the mean density of Saturn's regular satellites represent the most important data for assessing the possible influence of Saturn's early excess luminosity on the composition of its satellite system. When graphs, such as Figure 6, are constrained by the currently known compositional properties of Saturn's satellites or the time of satellite formation for Saturn is assumed to be the same as for Jupiter, the following general picture emerges of the bulk compositional gradient within the Saturn system: water ice may represent the only ice species incorporated into the innermost satellites of Saturn; ammonia ices, principally NH_4SH, as well as water ice are present in all the remaining satellites; and methane clathrate is to be found in satellites starting at Titan's distance from Saturn. Also, there may be variations in the fractional amount of rocky material incorporated into the satellites because of the delay in the formation of the inner ones caused by Saturn's size exceeding their orbital distances at the beginning of this period. While the resultant variations in bulk density among the regular satellites of Saturn may not be nearly as spectacular as for the Galilean satellites (Lewis, 1972), they still may be discerned through precise measurements.

Currently, the mean density of five of Saturn's satellites is poorly known and it is not known at all for the remaining ones (Morrison *et al.* , 1977). Undoubtedly, the mean density of a few satellites, especially Titan, will be determined with high precision when Pioneer 11 and the Voyager spacecraft pass through the Saturn system. But accurate values for the remaining satellites will await a Saturn orbiter.

Finally, let us consider the origin of the rings of Saturn. There are two principal competing theories. Either the rings were formed as part of the same process that resulted in the regular satellites, but tidal forces prevented the aggregation of a single large object at the rings' distance from Saturn; or alternatively, they represent fragments from a stray body that passed close to Saturn and was tidally disrupted (Pollack, 1975). The composition of the ring particles offers a way of testing the first possibility. As illustrated in Figure 6a, temperatures may have become cool enough close to the end of the satellite formation period for the Saturn system so that water ice was able to condense in the region of the rings. Any silicate grains, which condensed at earlier times in this region or were present from the start, would have been incorporated into the planet since Saturn's size exceeded the orbital distance of the rings for most of the satellite formation period (see the top of Figure 6a). Thus, if the particles constituting the rings were derived from material generated during Saturn's satellite formation epoch, they should be composed almost entirely of water ice.

There is, in fact, some evidence that the ring particles contain water ice. Near infrared spectra demonstrate that water ice is an important component of the particles' surface material (Pilcher *et al.* , 1970). Constraints on their bulk composition are provided by radar and radio observations. Analysis of these observations show that water ice could be the dominant component of the ring particles, whereas rocky material cannot (Pollack *et al.* , 1973; Pollack, 1975; Cuzzi and Pollack, 1978). However, with the present data, it is more difficult to exclude models in which metals, such as iron, represent the major bulk material (Cuzzi and Pollack, 1978).

We know that the rings have a high brightness temperature in the middle infrared (~10 to 20 μm) and a very low one in the microwave (>3 mm) (Pollack, 1975). Unfortunately, there is conflicting evidence as to where the transition from one brightness temperature regime to the next occurs. In part, this situation arises from the difficulty in spatially resolving the rings from the Earth at the wavelengths of interest. Therefore, it may be worthwhile to have a multi-channel infrared radiometer aboard a Saturn orbiter, which will observe the rings in the 20 μm to 1 mm wavelength region. Determination of the location and shape of the transition point would provide a good means of determining whether water ice is the major component of the ring particles.

SUMMARY

Table 1 provides a summary of the major recommendations given in this paper for an SOP^2 mission. The first column lists the cosmogonic problem, with the second and third columns defining the critical measurements that can be done to help resolve it. Clearly, much insight into the origin and evolution of the Saturn system can be realized from a combined orbiter-probe mission to this system.

Table 1. Cosmogonically Relevant Measurements for an SOP^2 Mission

Cosmogonic Issue	Key Measurements	Observational Technique
Origin of the Saturn system: core instability vs. gas instability.	Assess composition, amount, and distribution of excess heavy elements.	In situ compositional measurements of NH_3, CH_4, H_2O, He, and H_2 from an entry probe; track orbiter to determine the mass of the rings to establish values of J_2 and J_4 for Saturn.
Source of Saturn's current excess luminosity: Is He segregation an important source?	He/H_2 ratio in observable atmosphere.	In situ measurement made from an entry probe.
Capture mechanism for irregular satellites: Did capture occur due to gas drag within the primordial Saturnian nebula?	Morphological properties of the surfaces of the irregular satellites; existence of clusters.	Close-up photography of irregular satellites from an orbiter; photographic search for faint cluster members.
Influence of Saturn's early luminosity on the composition of its regular satellites.	Accurate values of the mean density of the regular satellites.	Good mass and size determinations from tracking an orbiter and from photography during close passages by the satellites.
Origin of the rings.	Composition of the ring particles; especially determining whether they are made primarily of H_2O ice.	Multi-channel infrared radiometer, operating in the 20 μm to 1 mm wavelength region.

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DISCUSSION

J. CALDWELL: If you invoke a gas drag mechanism for capturing Phoebe, does that not give you trouble with the very existence of the inner satellites? If the gas drag is enough to capture, how do the others survive?

J. POLLACK: Well, it's a question of the phase at which different things happen. The capture that we're speaking about is occurring at a very early time when Saturn may have been maybe a hundred times bigger than its present size, while in the case of the regular satellites themselves, one is speaking about much later when Saturn was perhaps five times its present size. You're quite right in the sense that one has to be very careful at the stage that the regular satellites are forming. There is a delicate balance between having enough material in the disk for condensation and the aggregation of the satellites, and yet not having so much gas around that the protosatellites spiral into Saturn.

J. CALDWELL: Jupiter doesn't have a major ring system while Uranus has a small one. Is there anything potentially to learn about the Saturn rings from this?

J. POLLACK: Remember that in the Saturn system just before the end of the satellite formation period, temperatures in the ring region could have gotten cold enough for water ice to condense. In the case of Jupiter, its luminosity at the same time was a factor of 10 higher, so that it never got cold enough within its Roche limit for water ice to condense.

In the case of an alternative material like silicates, there may well have been silicates around initially to condense, but at the time that silicates would have been available, Saturn would have been so large that it exceeded the outer boundary of the rings, so that any silicates there would have been incorporated into Saturn itself.

In the case of Uranus, I do not care to speculate very much at this time on why its rings are so different from Saturn's. The only thing I can say is that temperatures could have gotten cold enough to allow material to condense inside the Roche limit.

B. SMITH: But not ice, because the Uranus rings are too dark.

G. ORTON: If helium is capable of segregating from hydrogen at the present time in the interior of Saturn, what does that imply in terms of the heavy elements, methane, water, and silicates.

J. POLLACK: The physics is different, so I'm not sure whether one would expect a phase separation or not. The ultimate answer to the question may require measurements of gravitational moments.

G. ORTON: What precision is required in the measurements of excess thermal flux from Saturn?

J. POLLACK: Well, I'd really like to know whether it's significantly higher than my prediction or not. Thus a precision of ±30% would be quite significant, and I think ultimately one might like to go to ±10%.

G. ORTON: For the observations for the presence of water ice in the rings you recommended very long wavelength infrared observations.

J. POLLACK: Longer wavelength observation may distinguish between composition of the surface and the bulk composition. I don't think that there is any question that water ice is the major surface constituent of the particles. In the case of water ice, it's very absorbent up to about 150 μm and then its absorption coefficient starts decreasing very rapidly. And we know from current observation at a few millimeters that the opacity is quite low. The transition wavelength region will surely contain the information we need on the bulk composition.

R. MURPHY: Couldn't radar techniques from orbit or even radio occultation measurements be diagnostic of bulk composition?

J. POLLACK: An occultation basically measures the total cross section, so it is sensitive to the sum of scattering plus absorption. It doesn't separate the two components. Radar is a very nice complementary measurement to the passive brightness temperatures. But we still need to know the brightness temperatures in the long-wave IR region.