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Giant Planets and their Satellites: What are the Relationships Between Their Properties and How They Formed?

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ABSTRACT

The giant planet region in our solar system appears to be bounded inside by the limit of water condensation, suggesting that the most abundant astrophysical condensate plays an important role in giant planet formation. Indeed, Jupiter and Saturn exhibit evidence for rock and/or ice cores or central concentrations that probably accumulated first, acting as nuclei for subsequent gas accumulation. This is a "planetary" accumulation process, distinct from the stellar formation process, even though most of Jupiter has a similar composition to the primordial Sun. Uranus and Neptune are more complicated and imperfectly understood, but appear to exhibit evidence of an important role for giant impacts in their structure and evolution. Despite some interesting systematics among the four major planets and their satellites, no simple picture emerges for the temperature structure of the solar nebula from observations alone. However, it seems likely that Jupiter is the key to our planetary system and a similar planet could be expected for other systems. It is further argued that we should expect a gradual transition from solar nebula dominance to interstellar dominance in the gas phase chemistry of the source material in the outer solar system because of the inefficiency of diffusion in the solar nebula. There may be evidence for this in comets. Similar effects to this may have occurred in the disks that formed around Jupiter and Saturn during their accretions; this may show up in satellite systematics. However, each satellite system is distinctive, preventing general conclusions.

THE MASS DISTRIBUTION

In our solar system, over 99.5% of the known planetary mass resides in the planets beyond the asteroid belt, primarily in Jupiter, Saturn, Uranus, and Neptune. However, from the point of view of an earthbound cosmochemist, these bodies are not a "well known" (i.e. sampled) part of the solar system, but from the point of view of the astronomer seeking a general understanding of planetary system detectability and taxonomy, the giant planets should be the most important source of information.

It is convenient to divide the constituents of planets into three components: 1) "gas" (primarily hydrogen and helium; not condensable as liquid or solid under solar system conditions); 2) "ices" (volatile but condensable to varying degrees; H_2O is the most common, CO, CH_4, NH_3, and N_2 are the other main ones); and 3) "rock" (essentially everything else; primarily silicates and metallic or oxidized iron).

Jupiter defines a remarkable transition in our planetary system. Inside of Jupiter's orbit at 5 AU, the planets are small and rocky, largely devoid of both "ices" (especially water, the most abundant condensate in the universe) and "gas." By contrast, Jupiter has about 300 Earth masses of gas, and the more distant giant planets, though less well endowed, also have large reservoirs of gas. It is perhaps even more significant that Jupiter is the first place outward from the Sun at which water ice appears to become a common condensate. Although we do not know the abundance of water in Jupiter (because it forms clouds deep in the atmosphere), we see satellites such as Ganymede and Callisto which contain about as much ice as rock by mass, and we observe enhancements of other "ices" (CH_4 and NH_3) in the Jovian atmosphere.

The outer edge of the solar system is ill defined. It is possible that the cometary cloud contains a greater amount of ice and rock than do all the giant planets combined, especially if the most massive comets are substantially larger than the comets we have seen. A more conservative estimate of total cometary mass is approximately 10 Earth masses, but some increase in this estimate is justified given the recent realization that Halley is more massive than previously suspected (Sagdeev *et al.* 1988; Marochnik *et al.* 1988). The inner part of the cometary distribution, sometimes called the Kuiper belt, has now been tentatively identified as a disk rather than a spherical cloud (Duncan *et al.* 1988) and is therefore clearly associated with the planetary formation process. Planet X (a body beyond Pluto) has been frequently mentioned as a possibility, but no firm corroborative evidence currently exists.

One game that can be played is called *reconstituting the nebula.* One surveys the estimated amounts of rock and ice in each of the giant planets, then attempts to determine how much material of cosmic composition would be required to provide that much rock and ice. Roughly speaking, this implies that each of the four major planets required $\sim 0.01\ M_{\odot}$ of cosmic composition material. The cometary reservoir may have required an amount comparable to each of the planets. The similarity for each giant planet arises because they have roughly similar amounts of ice and rock (10-20 Earth masses) but diminishing amounts of gas as one proceeds outwards. The planets are also spaced in orbits that define a roughly geometric progression. In other words,

$$0.01 M_{\odot} \simeq \int_{R}^{2R} \sigma(R') 2\pi R' dR', \tag{1}$$

independent of R, where $\sigma(R)$ is the "surface density" (mass per unit area) of the discoid nebula from which the planets form, and R is the (cylindrical) radius. This implies $\sigma(R) \sim (2 \times 10^4\ \mathrm{g\ cm^{-2}})/R^2$ where R is in astronomical units. Theoretical models for $\sigma(R)$ from accretion disk theory tend to give somewhat weaker dependences on R, implying a stronger tendency for most of the mass to be near the outer limits of the nebula. Naturally, most of the angular momentum is also concentrated in the outer extremities. The outer radius of the solar nebula is not known, but was presumably determined by the angular momentum budget of the cloud from which the Sun and planets formed.

INTERIOR MODELS

One could say a lot about how giant planets formed if one knew their internal structures. However, there are as of yet no techniques that are similar to terrestrial or solar seismology and that enable inversion for the interior densities in a detailed way. Instead, one must rely on a very small set of data, the lower-order (hydrostatic) gravitational moments, and the correspondingly small number of confident statements regarding the interiors. Even if the *quantity* of information thus obtained is low, the *quality* is high and represents a quite large investment of theoretical and computational effort, together with some important experimental data from high-pressure physics. Although the theory is not always simple, its reliability is believed to be high. The great danger exists, however, in overinterpreting the very limited data.

Good reviews on the structure of giant planets include Zharkov and Trubitsyn (1978), Stevenson (1982), and Hubbard (1984), and it is unnecessary to repeat here the techniques, data, and procedures used. In the case of Jupiter, there is no doubt that $\sim$ 90-95% of the total mass can be approximated as "cosmic" composition (meaning primordial solar composition). However, the gravitational moment J_2 (which can be thought of as a measure of the moment of inertia) indicates that there must be some central concentration of more dense material (ice and rock). The uncertainties in hydrogen and helium equations of state are not sufficient to attribute this central density "excess" to an anomalously large compressibility of H-He mixtures or even to a helium core (since the latter can be limited in size by the observational constraints on depletion of helium in the outer regions of the planet). There is no way to tell what the "core" composition is; it could be all rock or all ice or any combination thereof. It does not even need to be a distinct core; it only needs to be a substantial enhancement of ice and/or rock in the innermost regions. The amount of such material might be as little as five Earth masses but is probably in the range of 10 – 30 Earth masses. The upper range of estimates is most reasonable if a substantial portion of this heavy material is mixed upward into the hydrogen and helium. One important point for the purposes of understanding origin is that Jupiter is enhanced in rock and ice by roughly a factor of 10 relative to cosmic composition. In other words, Jupiter formed from a cosmic reservoir containing 10^{-2} solar masses, even though its final mass is only 10^{-3} solar masses, a fact we had already noted in the previous section. The other important point about the dense material: it probably did not accumulate near the center by rainout of insoluble matter. This is in striking contrast to the Earth's core which formed because metallic iron was *both* more dense and insoluble in the mantle (silicates and oxides). The temperature in the center of Jupiter is very high (> 20,000 K) and the mole fraction of the ice or rock phases, were they mixed uniformly in hydrogen, would not exceed 10^{-2}. Although solubility calculations are difficult (Stevenson 1985), there does not seem to be any likelihood that some component would be insoluble at the level of 10^{-2} mole fraction at $T \sim 20{,}000$ K, since this requires an excess Gibbs energy of mixing of order kT ln 100 $\sim$ 8 eV, well in excess of any electronic estimate based on pseudopotential theory. It seems likely that Jupiter formed by first accumulating a dense core; the gas was added later. Subsequent convective "dredging" was insufficient to homogenize the planet (Stevenson 1985).

Saturn is further removed from a simple cosmic composition than Jupiter, a fact that can be deduced from the density alone since a body with the same composition as Jupiter but the same mass as Saturn would have about the same *radius* as Jupiter (Stevenson 1982). Saturn has only 83% of Jupiter's radius, implying a dense core that causes contraction of the overlying hydrogen-helium envelope. In fact, the ice and rock core of Saturn has a similar mass to that of Jupiter, but this is a larger fraction of the total mass in the case of Saturn. An additional complication in Saturn's evolution arises because of the limited solubility of helium in metallic hydrogen, predicted long ago but now verified by atmospheric abundance measurements. The presence of a helium-rich deep region is compatible with the gravity field (Gudkova *et al.* 1988) as well as being required by mass balance considerations. As with Jupiter, the ice and rock central concentration must be primordial and form the nucleus for subsequent accretion of gas.

Despite recent accurate gravity field information (French *et al.* 1988) based on ring occultations, models for Uranus are not yet so well characterized. The problem lies not with the general features of the density structure, which are agreed upon by all modelers (Podolak *et al.* 1988), but with the interpretation of this structure, since no particular component (gas, ice, or rock) has predominance. A mixture of gas and rock can behave like ice, leading to a considerable ambiguity of interpretation. There is no doubt that the outermost $\sim 20\%$ in radius is mostly gas, and it is generally conceded that some rock is present within Uranus (though not much in a separate, central core). It is clear that the models require some mixing among the constituents: it is not possible to have a model consisting of a rock core with an ice shell and an overlying gas envelope as suggested around 1980. It is not even possible to have a model consisting of a rock core and a uniformly mixed envelope of ice and gas. The most likely model seems to involve a gradational mixing of constituents, with rock still primarily concentrated toward the center, and gas still primarily concentrated toward the outside.

Accurate models of Neptune must await the flyby in August, 1989. Based on the existing, approximate information it seems likely that the main difference between Uranus and Neptune is the extent of mixing of the constituents. Uranus has a substantial degree of central concentration (low moment of inertia), despite the inference of mixing described above. Neptune has a higher moment of inertia, suggesting far greater homogenization. At the high temperatures ($\sim 10^4$ K) and pressures (0.1 Mbar and above) of this mixing, phase separation is unlikely to occur, so the degree of homogenization may reflect the formation process (degree of impact stirring) rather than the phase diagram.

ATMOSPHERIC COMPOSITIONS AND THEIR IMPLICATIONS

Many of the minor constituents in giant planets undergo condensation (cloud formation) deep in the atmosphere and their abundances are accordingly not well known. The main exceptions are methane (which either does not condense or condenses in a region accessible to occultation and. IR studies) and deuterated hydrogen (HD). Some limited information on other species (especially NH_3) exists from radio observations, but we focus here on carbon and deuterium.

Carbon is enriched relative to cosmic by a factor of two (Jupiter), five (Saturn), and ~ 20 (Uranus). At least in the cases of Jupiter and Saturn, the enhancement cannot be due to local condensation of the expected carbon-bearing molecules present in the primordial solar nebula (CO or CH_4) even allowing for clathrate formation. This interpretation follows from the fact that water ice did not condense closer to the Sun than about Jupiter's orbit, yet any solid incorporating CO or CH_4 requires a much lower temperature than water to condense (Lewis 1972). The enhancement of carbon must arise either through ingestion of planetesimals containing involatile carbon or "comets" (planetesimals that formed further out and were scattered into Jupiter-crossing orbits). There is increasing awareness of involatile carbon as a major carbon reservoir in the interstellar medium and it has long been recognized as a significant component of primitive meteorites. Comets also possess a substantial involatile carbon reservoir (Kissel and Kreuger 1987), but much of the cometary carbon reservoir is in C-O bonded material (part but not all as carbon monoxide; Eberhardt *et al.* 1987). If we are to judge from known carbonaceous chondrites, then the amount of such material needed to create the observed Jovian or Saturnian carbon enrichment is very large, 20 to 30 Earth masses, especially when one considers that this must be *assimilated* material (not part of the unassimilated core). Comets would be a more "efficient" source of the needed carbon, but it is also possible that the currently known carbonaceous chondrites do not reflect the most carbon-rich (but ice-poor) material in the asteroid belt and beyond. Even with comets, one needs of order 10 Earth masses of material added to Jupiter after it has largely accumulated. The implication is that estimates of ice and rock in Jupiter or Saturn, based solely on the gravity field, are likely to be lower than the true value because much of the ice and rock is assimilated (and therefore has no clean gravitational signature).

In Jupiter and Saturn, the value of $D/H \sim 2 \times 10^{-5}$ is believed to be "cosmic." However, this interpretation is still imperfectly established because of uncertainties in the "cosmic" value, and its true meaning (i.e., is it a primordial, universal value?). A cosmic value seems like a reasonable expectation, but it must be recognized that there are very strong fractionation processes in the interstellar medium which deplete the gas phase and enrich the particulate material. This enrichment is well documented for meteorites and is also probably present in comets. It is likely that the gaseous component of protoJupiter was *depleted* in deuterium, but that the assimilation of the carbon-bearing solids described above also contributed deuterium-rich materials, probably more than compensating for the gas-phase depletion. Thus, D/H in Jupiter is probably in excess of cosmic, though perhaps not by a large enough factor to be detectable in the current data. In contrast, Uranus is clearly enriched ($D/H \sim 10^{-4}$), an expected result given the far higher ratio of ice or rock to gas in that planet and the evidence of at least partial mixing discussed earlier. Neptune might be expected to have an even larger D/H if it is more substantially mixed than Uranus.

In summary, atmospheric observations provide additional evidence of noncosmic composition and partial assimilation of "heavy" material (ice and rock) into the envelopes of giant planets.

HEAT FLOWS AND THEIR IMPLICATIONS

Jupiter, Saturn, and Neptune emit more energy than they receive from the Sun, implying significant internal energy sources. The *ultimate* source of this energy is undoubtedly gravitational, but there are several ways in which this energy can become available. In Jupiter, the heat flow is consistent with a simple cooling model in which the planet was initially much hotter and has gradually cooled throughout the age of the solar system. In this case, the gravitational energy of accretion created the primordial heat reservoir responsible for the current heat leakage. In Saturn, the heat flow is marginally consistent with the same interpretation, but the observed depletion of helium in the atmosphere requires a large gravitational energy release from the downward migration of helium droplets. This process may also contribute part of the Jovian heat flow. Even with helium rainout, it is necessary to begin the evolution with a hot planet (at least twice as hot as the present interior thermal state), but this constraint is easily satisfied by accretion models.

Uranus and Neptune have strikingly different heat flows. The Uranus internal heat output is less than 6×10^{21} erg/s and might be zero; expressed as energy output per gram, this is an even lower luminosity than the *Earth*. The Neptune heat flow is about 2×10^{22} erg/s. Although clearly much larger, it is still *less* than one would expect if Neptune were fully adiabatic and began its evolution with an internal temperature of at least twice its present value (the assumption that works so well for Jupiter). The difference between Uranus and Neptune is striking and not easily explained solely by their different distances from the Sun. It is also unlikely that these planets began "cold," that is, only slightly hotter than their present states since the energy of accretion is enough to heat the interior by $\sim 2 \times 10^4$K. The low heat flow of Uranus may be due to stored heat of accretion; this heat is unable to escape because of compositional gradients, which inhibit thermal convection. In this way one can reconcile the low heat flow of Uranus with a high heat content and the inferred partial mixing of the interior discussed above (Podolak *et al.* 1990). By contrast, Neptune has a relatively high heat flow because it is more uniformly mixed. A speculative explanation for this difference in mixing efficiency is that the last giant impact on Uranus was oblique and created the large obliquity and disk from which the satellites formed. This impact was not efficient in mixing the deep interior. By contrast, the last giant impact on Neptune was nearly head on, which is a more efficient way of heating and mixing the interior and did not lead to the formation of a compact, regular satellite system. The high heat flow of Neptune is accordingly related to its higher moment of inertia. This speculation may be testable after the Voyager encounter at Neptune.

In summary, the heat flows of giant planets support the expectation that these planets began their life hot. In some cases (e.g., Jupiter) much of this heat has since leaked out. In at least one case (Uranus) the heat has been stored and prevented from escaping by compositional gradients which inhibit convection.

SATELLITE SYSTEMS

The four giant planets exhibit a startling diversity of satellite systems. Jupiter has four large, comparable mass satellites with a systematic variation of density with distance, suggesting a "miniature solar system." Saturn has an extensive satellite system, though only one of the satellites (Titan) is comparable to a Galilean satellite. Uranus has a compact family of icy satellites, regularly spaced and in the equatorial plane. Neptune has only two known satellites, in irregular orbits. One of these is Triton, a large body that has significant reservoirs of CH_4 and possibly N_2. Satellites are common, and they probably have diverse origins (Stevenson *et al.* 1986). Some of the diversity may arise as the stochastic outcome of a common physical process (this may explain the difference between Jovian and Saturnian systems) but the Neptunian system is clearly different. One suspects that the Uranian system has a different history also, since it formed around a planet that was tipped over and never had as much gas accretion as Jupiter or Saturn. The recent enthusiasm for an impact origin of the Earth's Moon suggests that the Uranian system deserves similar attention. Impact origin seems to make less sense for Jupiter and Saturn, where the target is mostly gas, even though these planets must also have had giant impacts. The issue for Neptune is unresolved, though one wonders how a distant, nonequatorial, and *inwardly* evolving satellite such as Triton could have an impact origin. Perhaps Triton was captured.

The formation of Jovian and Saturnian satellites is commonly attributed to a disk associated with the planet's formation, and therefore crudely analogous to solar system formation. Pollack and Bodenheimer (1988) discuss in some detail the implications of this picture. Even if a disk origin is accepted, there are two distinct circumstances from which this disk arises. One scenario involves the formation of satellites from the material shed by a shrinking protoplanet. In this picture, protoJupiter once filled its Roche lobe, then shed mass and angular momentum as it cooled.

An alternative view is an accretion disk which forms and evolves before Jupiter or Saturn approaches its final mass. In this picture, the disk serves a role more similar to that of the solar nebula, though with some important dynamical differences: it is more compact (because of tidal truncation), and it is evolving more rapidly relative to the accretion time (whereas the viscous evolution time and accretion time are roughly comparable in the solar nebula). The solar system analogy must be used with care when applied to satellite systems! The choice between a disk that is shed and a true accretion disk has important implications for the chemistry (Stevenson 1990) but must be resolved by future dynamical modeling.

TEMPERATURES IN THE SOLAR NEBULA

Is there evidence in the outer solar system for the expected temperature gradient of the solar nebula? Perhaps surprisingly, the answer is no. There is a trend of *decreasing* gas content in giant planets as one goes outward, but this surely reflects formation time scales and the ability of a proto-giant planet to accrete large amounts of gas before the onset of T Tauri. Satellite compositions seem to reflect more the immediate environment of the central planet than the background temperature of the nebula. The lack of CO in Titan, and presumably Triton, may reflect the processing of solar nebula CO into CH_4 in the disk or envelope surrounding the proto-giant planet, rather than any statement about solar nebula conditions. The only statement about temperature that seems reasonably firm is the placement of water condensation ($T \sim 160$ K) at around 5 AU at the time of condensate accumulation.

Of course, absence of evidence is not the same as evidence of absence. Nevertheless, we have to admit that we know remarkably little about the temperature variation in the solar nebula, either spatially or with time. One possible constraint could arise if there were a better knowledge and understanding of chemical trends in the outer solar system. For example, chemical processing such as catalyzed hydrogenation of CO to CH_4 and higher hydrocarbons is thermally mediated. The contamination by the products at greater radii in the nebula depends on where these reactions are quenched and how quickly or efficiently the species are dispersed by winds and turbulent diffusion. Stevenson (1990) has argued that the transport is inefficient so that the more distant regions of the nebula are dominated by interstellar speciation. Prinn (1990) has pointed out, however, that the uncertainties in momentum and species transport make it difficult to reach firm conclusions. In any event, chemical indicators are the best hope for obtaining information on outer solar system temperatures. If comets are found to have compositional trends as a function of formation position (as is suspected for asteroids) then these may provide the best clues.

GIANT PLANET FORMATION

The formation of the giant planets remains a major theoretical problem. Evidence presented above supports the idea that these planets may have formed by accumulating a core of ice and rock first, with gas accretion following—but truncated at some point, presumably because of the T Tauri mass loss or perhaps (in Jupiter's case) by tidal truncation of the accretion zone (Lin and Papaloizou 1979). The problem lies in the accumulation of the rock-ice core on a sufficiently short time scale, so that the gas is still present. Conventional accumulation models, based on Safronov's theory (1969) predict long time scales ($> 10^7$ years), even with allowances for gas-drag effects (Hayashi *et al.* 1985). Rock-ice cores may begin to accumulate gas when they are only approximately one Earth mass (Stevenson 1984) and this aids the accumulation somewhat, but does not solve the problem. Lissauer (1987) pointed out that if the surface density of solids is sufficiently high in the region of Jupiter formation then a runaway accretion may take place, forming the necessary Jupiter core in $\sim 10^5$ years. The onset of ice condensation helps increase the surface density by a factor of three, but this may not be sufficient by itself. Stevenson and Lunine (1988) suggest that a further enhancement may arise because of a diffusive transport of water molecules from the terrestrial zone into the Jupiter formation region. Several criteria must be satisfied to make this work well and they may not all be met. However, even a modest additional enhancement of the surface density in this region may make the mechanism work, at least to the extent of favoring the first (largest) giant planet at the water condensation front.

This suggests a speculative prediction for other planetary systems: giant planets should occupy the region outward from the point of water condensation. The largest of these (the extrasolar equivalent of Jupiter) may be near the condensation point. This position will vary with the mass of the central star (or with the mass of the nebula that the star once had) but is presumably a calculable quantity as a function of star mass and angular momentum budget. We await the exciting prospect of identifying Jupiters and superJupiters about nearby stars and characterizing their orbital distributions and properties.

The 1989 flyby of Neptune by Voyager reveals that Uranus and Neptune are more similar in structure than suggested above. This reduces the strength of arguments presented here for the role of giant impacts. Tremaine (preprint 1990) has suggested that the obliquity of Uranus is not related to impact.

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