PRESENT KNOWLEDGE OF URANUS

THE ORIGIN OF URANUS: COMPOSITIONAL CONSIDERATIONS

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ABSTRACT

Several cosmogonic theories are examined for their ability to explain the details of Uranus' composition as inferred from observations and interior models. Suggestions are made as to how future work may enable us to decide among competing scenarios.

INTRODUCTION

Ever since its discovery, by Herschel, in 1781, the planet Uranus has provided a useful testing ground for astronomical theories. In addition to providing evidence for the correctness of Newton's law of gravitation at distances greater than previously accessible from planetary observations, it also provided an excellent confirmation of the Titius-Bode "law". Even when the observations did not quite agree with theory, as when Uranus' orbit was found to deviate from the path predicted by Newtonian mechanics, the result was still a happy one, as Neptune was thereby discovered. While the respective status of Newton's and the Titius-Bode law are no longer considered pressing issues, there are other areas where Uranus may provide a useful test case.

In studies of the origin of the solar system, the processes encountered are generally complex and non-linear. Their full solution requires details of radiative transfer in a complex geometry, hydrodynamics, plasma processes and chemical kinetics. Clearly we are not yet in a position to model, in detail, the early history of the solar system. For this reason, theorists have had to rely

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partly on their intuition to guide them through the nebulous regions where detailed computations are not practical. While intuition is a powerful aid, it is desirable to limit its use by relying on observations whenever possible, and constantly comparing the theory with the object theorized about. For an object as complex as the solar system, this is not easy, and so I will concentrate here on just the planet Uranus, more particularly, its composition. In this paper I would like to examine two broad categories of cosmogonic theory to determine which of them provide a consistent picture for Uranus' composition. The theories I will discuss are by no means the only ones found in the literature, but they do have the following merits:

1. they cover a wide range of physical processes,
2. they are presently popular,
3. they are conveniently summarized in review articles.

ACCRETIONAL THEORIES

Let us first consider the so-called accretional theories. These theories assume that the sun was once surrounded by a not too massive ($M \sim 0.1\ M_{sun}$) nebular disk. This disk may have been left behind by a contracting protosun (Prentice, 1978) or acquired in some other, unspecified way (Safronov, 1972). At any given position in the disk, the temperature and pressure in the gas determine which materials will be solid (Lewis, 1972; Grossman, 1972). These solids accumulate into protoplanetary embryos. Near the sun only rocky material will be solid, and terrestrial planets are formed. Further away, the temperatures are lower, and ices begin to condense, most notably H_2O, NH_3, and CH_4. With extra mass available, the embryo grows to a larger size, and finally induces a dynamical instability in the surrounding nebular gas. The gas falls onto the core (embryo), and a gas giant planet results (Perri and Cameron, 1974; Mizuno, 1980). There is, of course, the obvious difficulty of explaining why Jupiter and Saturn accumulated so much more gas than

Uranus and Neptune, but that may, in fact, depend on details of the background pressure in the nebula (Mizuno, 1980). These details have not yet been adequately studied.

Based on this picture we would conclude that Uranus consists of a core of rock surrounded by ices, hydrogen, and helium. A number of models have been built based on this picture (Reynolds and Summers, 1965; Podolak and Cameron, 1974; Podolak, 1976; Hubbard and MacFarlane, 1980a; Podolak and Reynolds, 1981). In general these models assume that the nebular temperature was sufficiently low so that all of the available H_2O, NH_3 and CH_4 was frozen, and that these ices were accreted with the same efficiency as rock. One would then expect a solar ice to rock ratio, i.e. between 2.6 and 3.2 (Cameron, 1980; Zharkov and Trubitsyn, 1978). There are, however, two points regarding the details of the composition that require clarification.

If one examines the microwave spectrum of Uranus, one finds that at centimeter wavelengths, one sees brightness temperatures higher than one would expect if significant amounts of ammonia were present (Gulkis *et al.*, 1978). The implication is that Uranus' atmosphere (and possibly the planet as a whole) is strongly depleted in NH_3. Prinn and Lewis (1973) proposed that the atmospheric depletion could be accounted for by the combination of NH_3 and H_2S to form NH_4SH. The NH_4SH would condense and form clouds, and since NH_4SH does not absorb at these wavelengths, the NH_3 would be effectively hidden. The problem with this proposal is that roughly equal amounts of sulfur and nitrogen are required, while the N/S ratio in solar composition is about 5 (Cameron, 1980). Recently Lewis and Prinn (1980) have suggested a mechanism for enhancing the abundance of sulfur relative to nitrogen above the solar value. They point out that at high temperature the equilibrium composition of solar mix gas will have N_2 as the most abundant nitrogen species, while most of the carbon will be in the form of CO, with about 1% in the form of CO_2. At lower temperatures the equilibrium species will be NH_3 and CH_4, but the kinetic pathways to these products are extremely slow. Thus, in the vicinity of Uranus, most of the nitrogen will still be in the form of N_2 if it once passed through a high temperature region. It is thus possible to accrete solids with a relatively low nitrogen abundance, and therefore a low N/S ratio. In addition, since the vapor pressure of CO is approximately equal to that of N_2, it too will not condense in the vicinity of Uranus. Since substantial amounts of CO_2 ice will be available, the C/N ratio will be higher than solar. In such a situation, the additional nitrogen brought into the planet as N_2 during the hydrodynamic collapse phase is still not sufficient to make the total N/S greater than one, and NH_4SH formation provides an excellent mechanism for hiding the ammonia. In this scenario oxygen will be accreted as H_2O, carbon mostly as CO_2, and nitrogen as NH_4COONH_2 or NH_4NCO_3 [see Lewis and Prinn (1980) for details]. Most of the carbon (in the form of CO) will not be accreted as ice. Indeed since much of the oxygen is tied up as CO, less is available to form H_2O, and the expected ratio of ices to rock is about 0.5 (assuming $CO_2/CO \approx 0.01$).

It is useful to ask at this point what interior models can say about the composition. In what follows I will base myself on the results of Podolak and Reynolds (1981). In this work models of the following type were considered. Uranus was assumed to consist of a core of rock surrounded by an envelope of H_2, He, H_2O, NH_3, and CH_4. The H_2 and He were taken to be in the solar ratio, and the ices (H_2O, NH_3, and CH_4) were in the solar ratio to each other. The ratio of H_2 to ices in the envelope could be varied, however. The resulting models are shown in Figure 1. Here I have plotted the relationship between the oblateness and the quadrupole moment of the gravitational field, J_2, for various Uranus models (solid lines). The dashed lines show how the oblateness varies with J_2 for various rotation periods according to the relation

$$\varepsilon = (1 + 1.5J_2)\,(1.5\,J_2 + m/2)$$

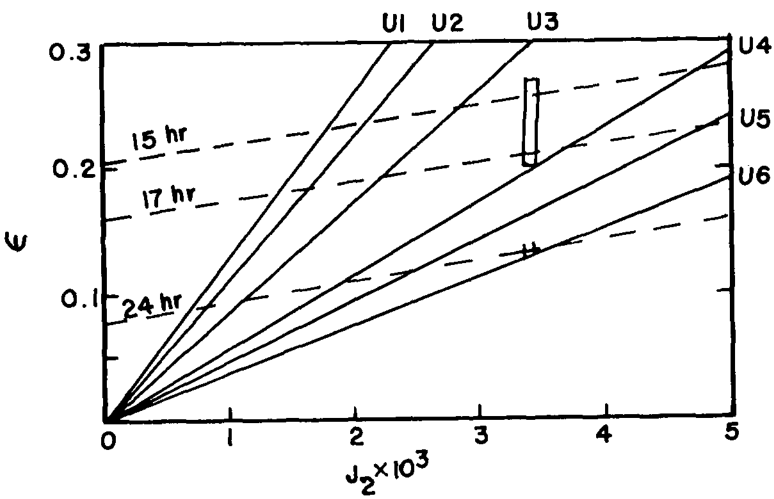
where m is the ratio between the centrifugal and gravitational accelerations:

$$m = \frac{\omega^2 R^3}{GM}$$

Here ω is the angular velocity of rotation, R is the equatorial radius of the Planet, M is its mass, and G is the Newtonian constant of gravitation. The rectangle in the figure encloses the range of measured values for ε and J_2 (Franklin *et al.*, 1980; Nicholson *et al.*, 1978). These data suggest a rotation period of 15-17 hrs., in agreement with a number of observers (Brown and Goody, 1980; Munch and Hippelein, 1980; see also Goody this volume). There is, however, another value found in the literature, and that is one of 24 hrs. (Smith and Slavsky, 1979; Belton *et al.*, 1980). This is indicated in the figure by the error bars on the 24 hr line.

As for the models themselves, U1 has a core of rock, and an envelope of solar composition. As one goes towards U6, the models

Figure 1. Oblateness and J_2 for various Uranus models. Observational limits on these quantities are also shown.



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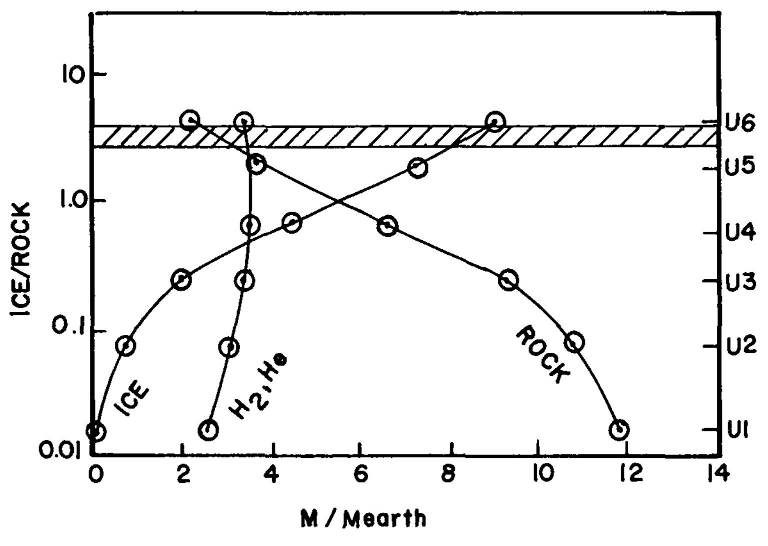
contain progressively more ices in the envelope, so that for U1 the ice to rock ratio is about 0.015, while for U6 the ratio is about 4.2. The relative amounts of $H_2 + H_e$, ice, and rock for the different models are shown in figure 2. The shaded area in the figure shows the range of estimates for the solar value of the ice to rock ratio. Comparison of figures 1 and 2 shows that if we accept the 24 hr period, this implies a model like U6, and hence a solar ice to rock ratio. This, in turn, implies that the material in the vicinity of Uranus had been in chemical equilibrium at the time of accretion. On the other hand, from consideration of the kinetics we would expect an ice to rock ratio of about 0.5, i.e. a model between U3 and U4. Such a model requires a rotation period of about 16 hrs. to fit the observations, and thus passes right through the rectangle in figure 1. It is worthwhile to note that while a 24 hr period requires a solar ice to rock ratio, a 16 hr. period does not

Figure 2. Amounts of rock, ice, and H_2 + He for various Uranus models.



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necessarily imply that the ratio is less. One can, for example, construct a planet with a solar ice to rock ratio, placing some of the ice in a shell around the core, and mixing the rest through the envelope (see the primed models in Podolak and Reynolds, 1981). In such a case the moment of inertia will be sufficiently low so that the observed J_2 can be fit with a 16 hr period. Thus a period in the vicinity of 16 hrs., while consistent with a non-equilibrium solar nebula, is not sufficient to rule out a solar ice to rock ratio. It is possible that a good value for J_4, the next term in the expansion of the gravitational field, will provide useful constraints once the rotation period has been unambiguously determined.

Finally there is one other compositional issue that has been brought to light by the work of Hubbard and MacFarlane (1980b). This regards the deuterium to hydrogen ratio. For a gas of given (solar, say) composition, the relative amount of deuterium that will be confined in ices rather than in the hydrogen gas depends on temperature (Richet *et al.*, 1977). Thus at low temperatures (<200K) the ices will contain between 10 and 10^3 times more deuterium than at high temperatures. Thus Uranus (and Neptune), which accreted a large fraction of ices relative to H_2 should have a D/H ratio considerably enhanced over the solar value of ~ 20 ppm. (Cameron, 1980; Black, 1973). In fact, the observations indicate a D/H ratio some 1-3 times the solar value (Macy and Smith, 1978; Trafton and Ramsay, 1980). Hubbard and MacFarlane evaluate the D/H ratio expected for Uranus models with the full complement of ices relative to rock, and find that the ratio should be about six times the solar value if the original ices were enhanced in deuterium by only a factor of 10. If the solar nebula were in equilibrium, then at the temperatures prevailing in the vicinity of Uranus enhancements of several hundred should be found. That the observed value is much lower indicates that either equilibrium is not achieved, or that the lower and upper parts of the atmosphere are not mixed. It is hard to imagine that throughout its history Uranus never passed through a high temperature convective stage. In addition, the release of radioactive heat from the rock core (assuming chondritic composition) should be enough to drive mild convection even today (Danielson, 1974; private communication). A non-equilibrium process is thus implied.

Two processes suggest themselves. First, due to the slow kinetics at low temperatures, the material does not completely equilibrate, and the ices in Uranus' vicinity did not acquire their full complement of deuterium. A second non-equilibrium process is the one mentioned earlier, i.e. that nitrogen does not enter the planet as NH_3 ice, and carbon as CH_4, but rather as CO_2 ice. This has two effects: 1. a smaller fraction of the total planet mass is in the form of ice (the H_2/ice ratio is higher);2. the ice has a smaller mass fraction of hydrogen, and therefore of deuterium. These last two considerations alone are sufficient to reduce the expected D/H ratio to about three times the solar value (not inconsistent with the observed value). We see therefore that an accretional theory of Uranus' formation can account for:

1. The enhancement of rock and ices relative to solar composition.
2. The apparent absence of nitrogen.
3. The D/H ratio.

GIANT PROTOPLANET THEORIES

A second group of theories results in the formation of giant gaseous protoplanets. These come about in various ways. In the encounter theory of Woolfson (1978a,b) the sun passes close to an extended protostar, and draws off a filament of stellar material. Since the filament comes from the protostar, the angular momentum constraint of Russel (1935) doesn't arise, and since the material is at much lower temperatures than solar material, the objection of Spitzer (1939) doesn't apply. This theory is of special interest since, if it is correct, it implies that planetary systems are much less common than is generally assumed. According to the encounter picture, then, the filament, which is unstable, breaks up into several smaller masses. These protoplanets then evolve into the planetary system we see today. The important point for us is the fact that the planets originate as giant gaseous protoplanets whose overall composition is solar.

A second scenario which also results in the formation of giant protoplanets is the floccule theory of McCrea (1978). Here one treats a turbulent cloud of approximately one solar mass. The turbulence is supersonic, and the resulting eddies are approximated by so called "floccules" which act (and interact) like spheres orbiting about a common center of mass. Initially the inclinations of the orbit are random, as are the eccentricities and the sense of the orbit (prograde or retrograde). If two floccules collide with nearly zero total angular momentum, they fall towards the center of the cloud, and the sun gradually develops. If the net angular momentum is not zero, this new, larger floccule continues to orbit. When the mass of one of the floccules reaches the Jeans mass, it begins to contract, and from this point the evolution proceeds as it would for a giant gaseous protoplanet. The floccule theory is especially interesting since it combines aspects of giant planet theories with those of accretional theories.

A third scenario which results in the formation of giant gaseous protoplanets is that proposed by Cameron (1978a,b). He considers the evolution of a massive (twice the solar mass) solar nebula. As the collapse of the solar nebula proceeds, a central condensation, the protosun, is formed, surrounded by a gaseous disk. As material continues to fall onto the disk it becomes unstable, and a ring is formed. In some sense this ring is similar to the filament of the encounter theory. It too breaks up into a number of subcondensations which interact with each other, generally either colliding and coalescing, or escaping from the system. The

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remaining sub-condensation continues to evolve as a giant protoplanet. As the gas continues to fall onto the disk, additional rings and additional protoplanets are formed. Like the floccule theory this theory implies that stars and planets are formed in the same process and that planetary systems should be quite common. Unlike the floccule theory, it treats a number of different processes and, on the whole, presents a rather different picture.

In all three cases we start with protoplanets of solar composition. In order to form Uranus there must be some sort of loss mechanism for hydrogen and helium. One such mechanism has been proposed by Handbury and Williams (1975). They point out that for the temperatures and gravitational potentials found at the surface of giant protoplanets, cooling through Jeans escape is a much more efficient process than cooling through radiation into space. They suggest that if all of the gravitational energy released by settling of grains towards the planetary core were removed by Jeans escape of hydrogen and helium, one could explain the present densities of Uranus and Neptune. Indeed this mechanism is just the one suggested by Woolfson (1978b) as a possible way for the proto-Uranus and proto-Neptune of his theory to lose their excess hydrogen and helium. The difficulty with such a mechanism is the nitrogen abundance. If it is in the form of NH_3, it does not escape, and the N/H ratio should be much higher than solar. Similarly, if it was in the form of N_2, it would have too high a molecular weight to escape efficiently via the Jeans process. Again one would expect a N/H ratio much higher than solar in contradiction with the observations (Gulkis *et al.*, 1978). Here NH_4SH formation would not resolve the problem, because in solar composition the S/N ratio is too small. It is possible that some other mechanism exists for removing the NH_3 from the atmosphere, but no concrete proposal has yet been presented.

In the theory of McCrea a rotational instability results in the shedding of material as the protoplanet contracts. If the grains settle through the gas quickly, only gases are shed, and the resulting rocky core is the precursor of a terrestrial planet. If the grains settle slowly through the gas, both grains and gas are shed, and the resulting planet (with its nearly solar composition) is the precursor of one of the Jovian planets. McCrea suggests that something intermediate between these two extremes would describe the formation of Uranus and Neptune. This would account for the low (relative to rock and ice) hydrogen and helium abundance. The expected values of the N/H and S/N ratios will again be dependent on the form of nitrogen in the protoplanet. If it is in the form of NH_3 it will settle with the grains and the N/H ratio will be greater than solar while the S/N ratio will be solar, thus there will again not be enough sulfur for complete NH_4SH formation. If the nitrogen is in the form of N_2, the N/H ratio will be solar and the S/N ratio will be considerably higher than solar, so that enough sulfur will be available for complete conversion of NH_3 to NH_4SH. Clearly detailed modelling of giant protoplanet evolution for this theory is an important next step. In addition it would be important to show why the rate of settling of the grains should differ in different parts of the solar system.

Cameron's theory considers two major stages for protoplanet evolution. The first occurs when the run of pressures and temperatures inside the protoplanet passes through the liquid part of the phase diagram of some rocky or metallic component (iron for example). When this occurs, droplets are formed which grow rapidly (Slattery, 1978) and fall towards the center to form a core. The second stage involves tidal stripping of the envelope by the sun. The protoplanetary core, a terrestrial planet, remains. If the protoplanet is too far from the sun for tidal stripping to occur, the envelope contracts until temperatures at the core boundary become high enough for hydrogen to dissociate. The envelope then becomes unstable and a hydrodynamic collapse ensues. A giant planet is thus formed. The difficulty is that even for Jupiter and Saturn, and all the more so for Uranus and Neptune, there is an enhancement of rock and ice above the solar value relative to hydrogen. It is important to recall that in this theory the protoplanet is imbedded in the solar nebula, and the protoplanetary envelope joins to the nebula itself. It may be that transport of material between the envelope and the nebula occurs right up to the time of envelope collapse (see, however, Cameron, 1979). If such mixing occurs, then the amount of gas participating in the final collapse may vary depending on the background conditions in the nebula. As Cameron (1978a,b) has pointed out, there may be a nebular "breeze" which will greatly reduce the mass of the nebula in the last stages of evolution. If the Uranus and Neptune protoplanets evolved more slowly than their Jovian and Kronian counterparts, they would have found themselves in a nebula with very different physical conditions at the time of collapse. This could easily affect the size of the collapsing envelope.

Finally, the idea of mixing between the protoplanet and the nebula bears on the problem of the N/H ratio. Here again we have to turn to protoplanet models to determine the form that nitrogen will be in. The most detailed models to date of the giant protoplanets are those by DeCampli and Cameron (1979). They find that interior temperatures of more than 10^3K are reached as the protoplanet evolves. For the relevant pressures the equilibrium form of nitrogen is N_2. In addition, the convection they find is sufficiently vigorous that in the lower temperature regions where the kinetics is still sufficiently slow (Norris, 1980), the major nitrogen species is still N_2. In this case the following scenario suggests itself. Suppose that gases move between the protoplanet and the nebula, but that near the top of the protoplanetary atmosphere there is a cold trap. H_2 and He will pass through, and if the temperature is sufficiently high N_2 will pass through as well.

H_2O (or H_2S for that matter) will not, however. When the final collapse of the atmosphere occurs, there may well be a high H_2O/H_2 ratio, and an S/N ratio larger than one. An ice rich envelope will therefore be formed where NH_4SH formation will hide any NH_3 produced when the planet reequilibrates after collapse.

The question that remains concerns the status of carbon. If most of the carbon is in the form of CO, it should pass through the cold trap if N_2 does, since their vapor pressures are similar. The resulting planetary composition (ice/rock $\approx$ 0.5) will be similar to that expected for the non-equilibrium accretion model. If the carbon is in the form of CH_4 (as happens for the ranges of temperature and pressure found in some of the models of DeCampli and Cameron), then it has a smaller chance of passing through the cold trap, since its vapor pressure is lower. If it does pass through, then the expected ice/rock ratio will be about 2, since more oxygen is now available to form H_2O. If the CH_4 does not pass through, the expected ice/rock ratio is about 3. As pointed out earlier, models of Uranus and Neptune do not as yet provide definitive values for this quantity. It should be possible, by more careful studies of the evolution of imbedded giant gaseous protoplanets, and more detailed modeling of the present day interiors of Uranus and Neptune, combined with an improved knowledge of their gravitational field to decide if a massive solar nebula is indeed a viable scenario for planet formation. Finally it is important to point out that all the giant planet scenarios start with a solar D/H ratio, which should be maintained throughout their evolution. Within the uncertainties in the measurements, this agrees with the observed value.

CONCLUSIONS

In this paper I have tried to show how the composition of Uranus can be used as a benchmark to test theories of the origin of the solar system. Since the details of Uranus' composition are still not unambiguously determined, it is impossible to draw firm conclusions, nontheless it does seem that accretional theories reproduce the low hydrogen abundance together with a low N/H and N/S ratio in a more straightforward way. Thus they can explain Uranus' high density (relative to Jupiter and Saturn) and the apparent absence of NH_3. Giant protoplanet theories are not obviously inconsistent with these data, but neither do they show clearly how such a situation developed. With regard to the D/H ratio, giant protoplanet theories predict a ratio near the solar value, while accretional theories have difficulty in keeping the ratio even as low as three times the solar value. Overall, it seems that accretional theories provide a somewhat more comfortable framework for understanding the composition of Uranus, but it is clear that it will require considerable work before we can claim we truly understand the planet's origin.

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