The Interior Structure of Jupiter (Consequences of Pioneer 10 Data)[1]

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Models of the Jovian interiors are based on theoretical equations of state of hydrogen and helium supported by a few experimental points and on observed parameters such as oblateness, gravitational coefficients, heat emission, magnetic fields, etc. The models fall into three categories: (1) those that assume a uniform and rather low H_2/He ratio throughout the planet; (2) those in which this ratio is solar and thus higher; and (3) those that take into account the lack of complete miscibility of the two elements in the condensed state. Recent values of the observed parameters obtained by Pioneer 10 permit improvements of the first two models but also pose new questions. In the first category of models the new data indicate that the amount of hydrogen has to be increased, while in the "solar" models, which have a heavy core (made of SiO_2, MgO, Fe, and Ni), the abundance of hydrogen has to be decreased. Both changes point in the direction of incomplete miscibility present in the third category of models. It appears now also that within the limits of error the planet is in a hydrostatic equilibrium. The large heat emission and the need for an efficient source of internal heat is confirmed, but the results do not indicate which one of the various possible mechanisms is favored, although new evolutionary models suggest that the primordial heat may be insufficient. A new red spot has been discovered. Finally, the presence of a highly eccentric and inclined magnetic field poses new problems related to the pattern of internal convection and to the possibility of a north-south asymmetry of the interior. Further analysis of the available data may throw additional light on these questions.

The chemistry and physics of our whole planetary system can be approximated by those of Jupiter and Saturn with an error of only 8 percent. While the knowledge of the interior of Saturn is still rather uncertain, there are good reasons to suspect that it is similar to Jupiter which is much better known. The purpose of this paper is to summarize briefly the recent developments in our knowledge of the Jovian interior and to show how it is affected by the results obtained by Pioneer 10 (ref. 1). In this sense, this paper is a sequel to the Hubbard and Smoluchowski paper (ref. 2) containing theoretical background and various numerical data.

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The Hydrogen-Helium System

The low density of Jupiter requires that it is composed primarily of hydrogen and helium. Thus, the knowledge of the equations of state of the two elements and of their mixtures at high temperatures and pressures is essential. Equations for the pure elements have been proposed (ref. 2) by De Marcus, Peebles, Hubbard, Neece et al., Salpeter et al., Trubitsyn, and, more recently, by Caron (ref. 3), Graboske et al. (ref. 4), Slattery and Hubbard (ref. 5), Zharkov and Trubitsyn (ref. 6), and Podolak and Cameron (ref. 7). It is interesting to note that in the pressure region where hydrogen is metallic the calculations obtained by the Wigner-Seitz, Thomas-Fermi-Dirac, and dielectric function methods do not differ from each other by more than about 10 percent. The theoretical situation is less satisfactory in the H_2 region, although new experimental results of Swenson (ref. 8) have confirmed the older data of Stewart (ref. 2), and shock-wave compression results up to nearly 1 Mb of van Thiel et al. (ref. 9) permit further refinements. Grigoriev et al. (ref. 2) observed that the molecular to metallic transition occurs near 2.8 Mb, which falls in the range of theoretical predictions. An intriguing question is the nature of the molecular to metallic phase transition in the liquid: if it is a first-order transition, it may require the existence of a second critical point (ref. 2). The problem of the nature of the hydrogen-helium system is in a much less satisfactory condition than that of the pure elements. The additive volume approximation is reasonable in the range of solid solubility, but there are theoretical indications suggested by Smoluchowski's (ref. 2) physico-chemical arguments and by Hubbard and Slattery's (ref. 2) Monte Carlo results that the solubility is limited in the metallic hydrogen range. Streett's (ref. 10) experimental data extrapolated on the basis of Rigby et al.'s (ref. 11) theory show that this is true also of the H_2 range (ref. 2). Unfortunately, the solubility limits and their dependence on temperature and pressure are difficult to estimate; figure 1 summarizes in a qualitative manner the situation (ref. 12). (Recent unpublished theoretical results obtained by D. Stevenson confirm the existence of the solubility gap in the He-H system up to 10^4K.)

Melting Temperatures

A particularly difficult problem is the question of the Debye temperature of the solid hydrogen-helium system and of the thermal and quantum stability. The errors in the melting and Debye temperatures, related to the problem of screening of protons by electrons (ref. 2) in metallic hydrogen, may reach 1500 to 2000K. Furthermore, the effect of helium, which at sufficiently high pressures is supposed to be at least partially soluble in metallic hydrogen, will lower the latter's melting point to a degree difficult to ascertain (ref. 12). Similar uncertainty concerns the interactions between H_2 molecules (ref. 5). The recent trend toward Jovian models with very high central temperatures suggests that there may be no solid mantle at all. Nevertheless, the problem cannot be considered as being definitely settled at the present time. The central pressures of Jupiter are probably too low to imply the presence of a quantum liquid (ref. 2).

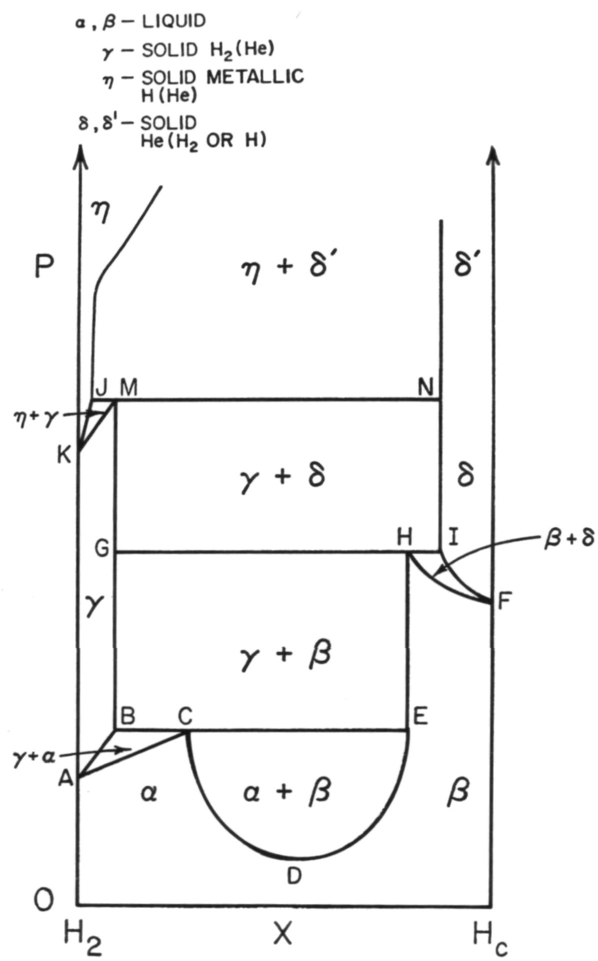

Figure 1.—*Isothermal hydrogen-helium equilibrium diagram (ref. 12).*

Table 1.—*Model of Jupiter*

Radius (10^4 km)	Fractional Mass	Pressure (M bars)	Density (g/cm³)
6.9	.99	0.004	0.03
6.5	.97	0.24	0.4
6.0	.90	1.1	0.7
5.5 (1)	.80	2.5	1.1
5.0	.70	4.5	1.6
4.5	.60	7.6	1.9
4.0	.40	11	2.3
3.5	.30	15	2.6
3.0	.20	20	3.0
2.5	.10	24	3.4
2.0	.06	28	3.7
1.5	.03	32	3.9
1.0	.01	35	4.1
0.5	.001	36	4.2
0.0	0.0	37	4.2

NOTE: (1) H_2 metal phase change.

Models of the Interior

One can classify the models of the Jovian interior into three categories: (1) those of Peebles, Hubbard, and others (ref. 2) that assume a uniform hydrogen-helium ratio throughout the planet except perhaps for a small core; (2) those of Podolak and Cameron (ref. 7) that require that this ratio is close to the solar value of 3.4 to 3.6 by mass (or 13.6 to 14.4 by number); and (3) those that take into account the limited solubility of helium in hydrogen (ref. 12) in both forms. The first category leads to an agreement with the observed average density, gravitational coefficients, etc., if the hydrogen-to-helium ratio is about 1.6 by mass (or 6.5 by number). In this model the higher the temperature at the center of the planet, typically 10 000K and density over 4 g/cm³, the higher the abundance of helium has to be to give the correct planetary radius (table 1). Clearly, a problem arises concerning the mechanism of depletion of hydrogen from its initial abundance, which is presumably given by the composition of the original solar nebula. The capture of the solar wind by Jupiter would increase rather than lower the abundance of hydrogen, while, according to Podolak and Cameron (ref. 7), the required gravitational escape time of hydrogen would be orders of magnitude longer than the age of the universe. One seems to be forced to assume that the planet is not homogenized convectively and that the hydrogen-to-helium ratio is a function of the radius. This will be discussed in greater detail below.

In the second category of models of the interior, the requirement of a solar hydrogen-to-helium ratio implies that there must be a dense central core to account for the total mass of the planet. This is reminiscent of the first Jovian model proposed by De Marcus (ref. 2). In particular, it is assumed that the core consists of "rock" that is SiO_2, MgO, Fe, and Ni, which had to condense first out of the gradually cooling solar nebula. When the core was big enough and sufficiently cold, it became covered with a layer of ice that subsequently evaporated when the remaining gaseous constituents of the solar nebula were captured by the gravitational field of the growing planet. This led to a net enrichment of H_2O in the atmosphere above the solar value. The best fit to the gravitational coefficients and to a temperature of about

Table 2.—*Jupiter Model With 7.5 Enrichment of H_2O*

Radius (10^9 cm)	Temperature (K)	Pressure (Mb)	Density (g/cm^3)	Comments
0.05	19750	309	41.15	
0.20	19750	300	40.63	
0.50	19750	254	37.75	Core
1.00	19750	129	28.04	
1.29	19750	60.4	20.27	
1.29	19750	60.4	4.72	
1.55	18810	48.4	4.24	
2.00	17485	36.3	3.66	
2.50	16256	27.1	3.17	Metallic H
3.00	15133	20.2	2.74	
4.00	12933	10.3	2.00	
4.95	10663	4.27	1.36	
4.95	10663	4.27	1.21	
5.51	8827	2.20	0.874	
6.01	7078	1.01	0.615	
6.50	5129	0.302	0.384	Molecular H_2
7.00	1061	3.94×10^{-4}	0.010	
7.02	678	8.38×10^{-5}	3.6×10^{-3}	
7.04	192	1.01×10^{-6}	1.4×10^{-4}	

190K at 1 b pressure, as required by the usual model of the atmosphere (ref. 13), was obtained for an enrichment of water by a factor of 7.5 and a core that constitutes 12.5 percent of the total mass of the planet as shown in table 2. It is important to note that this model has a much higher central temperature and pressure and a twice as high ratio of the volumes of the molecular to the metallic hydrogen layers as in the first category of models. Pioneer 10 data indicate (ref. 1), however, that the value of the gravitational coefficient J_2 (obtained from the occultation of β–SCO) (ref. 2) on which these calculations were based is too low, and that the older higher value of Brouwer and Clemence is more correct. This leads to a dilemma, illustrated in figure 2, because the higher $J_2 = \frac{2}{3}\ J$ leads to a ratio of water to "rock" that exceeds the value of about 2 permitted by the solar composition (it also lowers the central temperature to about 16 000K). The way out is to assume that at least in the upper layers of the planet, which alone influence J_2 and other higher moments (ref. 16), the helium and water abundance is somewhat higher than solar. In particular, taking into account the lack of complete miscibility of helium and hydrogen may permit satisfaction of both the correct J_2 value and the permissible ratio of water to "rock."

The third category of models has not yet been evaluated quantitatively because of uncertainty about the actual limits of mutual solubility of hydrogen and helium as discussed above. An important feature of this model is the lack of a direct relation between the observable atmospheric hydrogen-helium ratio and the overall planetary composition. Figure 3 shows, in a qualitative manner, the expected sequence of layers in Jupiter in the absence of a "rock" core (ref. 12). If the central temperature were below

10 000K, there would be a solid mantle as indicated. In accord with Streett's (ref. 10) suggestion based on his experimental studies, the figure shows also that solid molecular hydrogen containing a small amount of dissolved helium can float at an appropriate level in liquid molecular hydrogen containing a higher than average amount of helium. This can be true even if the planet is so hot that there is no solid mantle, since the temperatures at that level will be sufficiently low. It appears, thus, that models based on a uniform composition and those based on solar composition encounter certain difficulties that may be resolved by taking into account the limited solubilities as suggested by the third category of models.

Atmospheric Structure and Composition

While the structure of the atmosphere of Jupiter is a huge topic by itself, it cannot be ignored here because, as is well known (ref. 17), it does have an important impact on the models of the interior. In particular, Anderson's interpretation of Pioneer 10 data (ref. 1) suggests that the gravitational coefficient J_4 is −0.00057 rather than the older value of −0.00067 (ref. 2). This throws new light on the nature of the outer envelope some 3000 km thick down to a pressure of about 800kb. According to Hubbard (private communication), the assumption of solar ratio and of the van Thiel (ref. 19) equation of the state of H_2 and its interaction potentials leads then to a very hot adiabatic atmosphere with a temperature of 250 to 300K at 1 b pressure. If helium is added, then the temperature is even higher, coming close to the values obtained by Kliore et al. from S-band occultation observation of Pioneer 10 (ref. 2). This is, however, in striking contrast with the spectroscopic data that seem to favor lower temperatures of the usual model mentioned earlier. It is important to note in this connection that a number of measurements (ref. 1) of the composition of the atmosphere made either by observing details of β–SCO occultation (Ververka et al.), by ultraviolet photometry (Judge and Carlson), from S-band absorption (Kliore et al.), or by airplane infrared data (Houck et al.) indicate that the hydrogen-to-helium ratio is 2.64 by mass (or 10.5 by number), with an

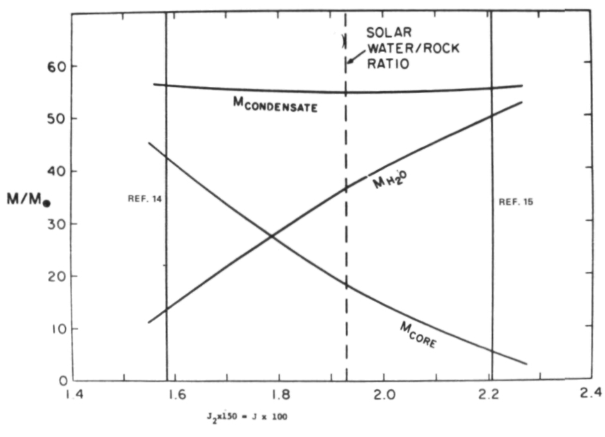

Figure 2.—*Mass of the Jovian rock core and of water as a function of* J = *(3/2)*J_2 *(ref. 7).*

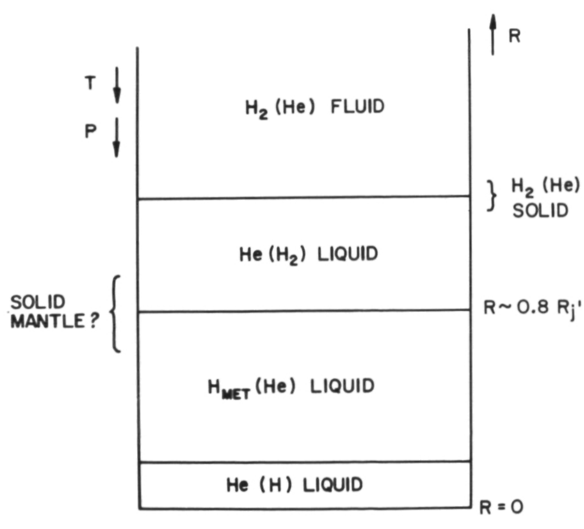

Figure 3.—*Immiscible liquid layers on Jupiter (ref. 12).*

error of about 10 percent. This is lower than the solar abundance. If in the solar composition model of Podolak and Cameron the temperature at 1 b pressure were, say, 350K rather than 190K, then the dense core would be much smaller, and the enrichment in water still higher. This would make the water-to-"rock" ratio higher than permitted by the solar composition. Taking into account limited solubility of the two elements and an atmosphere independent of solar composition could bring this model into agreement with observations. As mentioned in the next section, the phase-change model of the gravitational contraction as the source of internal heat could imply an enrichment of helium in the atmosphere as observed.

It should be pointed out that while the Pioneer 10 values of the gravitational coefficients pose certain difficulties for some of the models of the Jovian interior they lead to a value of the dynamic oblateness that is within the limits of error equal to the oblateness observed directly by Pioneer 10. Thus the planet appears to be in hydrostatic equilibrium (Woiceshyn, ref. 1) in contrast to the earlier uncertainties (ref. 2).

Internal Heat Source

The fact that Jupiter (and probably also Saturn) emits much more heat than it receives from the Sun has been known for some time (ref. 2). Of the many proposed sources of this energy, three appear to lead to reasonable amounts: (1) gradual loss of primordial heat; (2) gradual increase of the radius of the metallic hydrogen layer at the expense of the molecular hydrogen layer (about 1 mm per year controlled by outward diffusion of helium), which would lead to the release of gravitational energy; and (3) self-controlled gravitational separation of the immiscible hydrogen-rich and helium-rich phases, as proposed first by Salpeter (ref. 18) for the metallic layer and extended to the H_2 layer by Smoluchowski (ref. 12). The self-regulation occurs because, as the planet slowly cools and the precipitation of the less buoyant helium-rich phase and the more buoyant hydrogen-rich phase proceeds, the heating caused by the release of the gravitational energy slows down the rate of precipitation until a more or less steady state is reached. Nevertheless, the presence of an oscillatory variation of the heat flux is not excluded. Each of these sources easily yields enough heat during a period of several billions of years, provided that certain requirements are met: the first mechanism requires, naturally, a very high central temperature T_c as suggested by Trubitsyn (ref. 2), Hubbard (ref. 19), Podolak and Cameron (ref. 7) and others; the second and the third do not require a high T_c, but the limited solubilities in the hydrogen-helium system have to be taken into account. As discussed above, this assumption is not only theoretically plausible, but probably necessary in order to bring the models into agreement with the Pioneer 10 gravitational data. Preliminary conclusions obtained by G. Munch et al. from infrared measurements (ref. 1), and assuming an albedo of 0.45, suggest that the ratio of the emitted heat to that received from the Sun may be somewhat lower than 2.7 as proposed by Aumann et al. using their earlier observations (ref. 2). Lowering this ratio makes accounting for the excess energy easier than before and thus does not permit discrimination on this basis between the various mechanisms or models of the interior.

The Great Red Spot

An interpretation of the Great Red Spot (GRS) has to account not only for its existence, for its large azimuthal, negligible latitudinal, and small regular periodic motions, but also for variations in size and color (ref. 2). Kuiper looked at it as a purely atmospheric perturbation or storm analogous to those on Earth (ref. 2), but this model has not been evaluated in sufficient detail to account for the motions of the GRS. As pointed out by Golitsyn (ref. 20), a local perturbation in the Jovian atmosphere could exist for a very long time. Hide (ref. 2) suggested that the spot is the top of a Taylor column whose base is connected with the

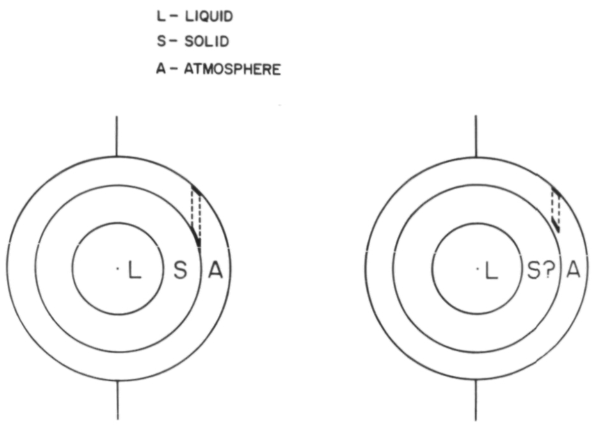

Figure 4.—*The Great Red Spot as a top of a Taylor column based on solid mantle or on solid H_2 (He) floating in liquid $He(H_2)$ (ref. 2).*

surface of a solid mantle; this has been further elaborated by Runcorn (ref. 2). Streett (ref. 10) pointed out that the column could be based on an island of solid H_2 floating in helium-rich liquid H_2 at the appropriate level of the supercritical atmosphere discussed above (fig. 4). This model is particularly attractive because in the absence of a solid mantle it accounts easily not only for the complicated large and small motions of the GRS but also for the periodic change of its size (ref. 2).

Pioneer 10 optical measurements as interpreted by Coffeen and by Doose (ref. 1) reveal a wealth of details within the GRS, anomalous polarization and contrast in scattering at large phase angles as compared with the surroundings. In particular, the presence of high clouds above the GRS is suggested. How closely these observations agree with the Taylor column or the tropical storm models remains to be shown. The most striking result is the confirmation of the existence of a Smaller Red Spot (SRS) between the north tropical zone and the north equatorial belt. This SRS is about one-third the size of the GRS, which is in the southern hemisphere, and it resembles it strongly in shape, color, and other features. Its azimuthal motion is slower than that of the GRS (Fountain, private communication), which further undermines the model of a Taylor column based on a solid mantle. Its very presence suggests also that the GRS is not the result of an anomaly of a magnetic field of the planet as it has been variously suggested. It also casts further doubt on the frequently expressed point of view that the azimuthal motion of the GRS is coupled to the rotation of the magnetic field of the planet, the so-called System III of the decametric radiation (ref. 2).

Magnetic Field

The most likely source of the Jovian magnetic field is an internal convection-driven dynamo (ref. 2), although other mechanisms such as processional motion or thermolectric effects (ref. 21) cannot be ruled out. Either the high central temperature or the low melting point of hydrogen-helium alloys assures the presence of a liquid, highly conductive core (ref. 22). The most striking result deduced by E. J. Smith et al. (ref. 1) is that the field is about 4 R_j^{-3}Gs, which is much weaker than the initially deduced value based on decimetric radiation studies, and that it is not only inclined by as much as 15° to the rotational axis, but that the magnetic dipole is displaced by about $.2R_j$ away from the rotational axis and by about $0.1R_j$ northward from the equatorial plane as shown in figure 5. Thus, depending on latitude and longitude, the surface magnetic field varies from a 2.3 to 11.7 Gs. For comparison, the corresponding values for Earth are 12°, 0.07 R_e, and 0.02 R_e. The quantitative aspects of the theory of a hydromagnetic dynamo are not sufficiently developed to conclude whether the huge asymmetry of the Jovian field implies also an essential asymmetry of the liquid interior or of the mantle, if it exists. In this connection it should be mentioned that Anderson's preliminary results (ref. 1) obtained from an analysis of Pioneer 10 data suggest that the gravitational moment J_3, which is a measure of north-south anomaly, is smaller than 10^{-4}. In any case, the magnetic poles of Jupiter do not seem to be associated with any particular surface

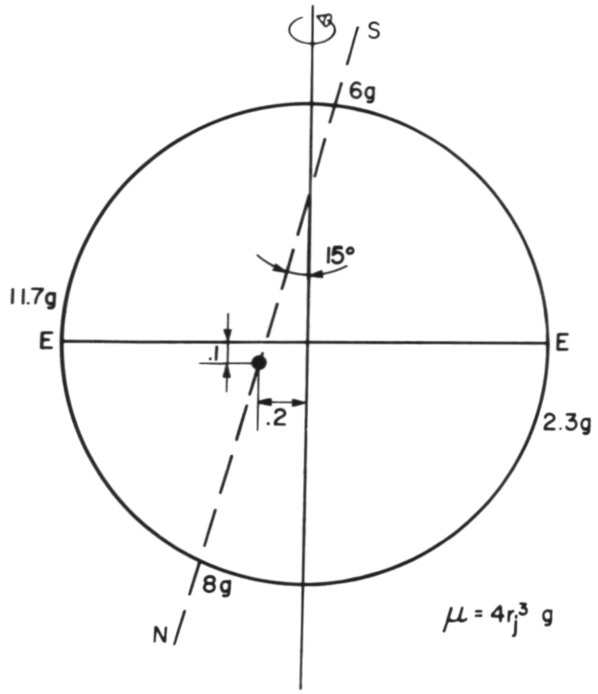

Figure 5.—*Displacement and inclination of the Jovian magnetic dipole (the magnetic and the rotational axes are not actually co-planar) according to E. J. Smith et al. (ref. 1).*

features, and the fact that the cloud zones and bands are perpendicular to the rotational axis and show essentially no strong azimuthal variation indicates that there is very little coupling between the magnetic field and the convective motions in the visible atmosphere.

It should be pointed out also that the Jovian magnetic field is reasonably dipolar up to about $10R_j$, but, as discussed by Wolfe and by Dessler et al. (ref. 1) and E. J. Smith, (in press), at larger distances it is elongated and concentrated along the equatorial plane. This effect appears to be due to centrifugal effects of corotation on the Jovian ionosphere which reaches, near the equatorial plane, temperatures corresponding to several keV. As a result of the inclination between the rotational and magnetic equatorial planes, the outer parts of the magnetic field are pulled toward the equatorial plane by about 5° (fig. 6). This situation complicates among others the quantitative interpretation of the intensity of the decimetric radiation and of the interaction of the planetary field with the solar wind and its magnetic field.

Evolution of Jupiter

From the point of view of the cosmochemistry of the solar system and understanding of the present structure of Jupiter, a study of the history of the early evolution of that planet is of crucial importance. For this reason, Graboske et al. (ref. 23) made a study of the evolution of a star having an appropriate mass, i.e., 9.5×10^{-4} solar mass, and composed of a convective, adiabatic, and homogeneous fluid. Taking into account the sources of opacity and the deposition rate of solar energy, they discerned two phases: the first phase in which the fluid contraction is associated with a high luminosity and with central temperature reaching 4×10^4K, and a second phase in which the cooling rate approaches that of a degenerate dwarf. The high luminosity phase has an important bearing upon the composition of the Jovian satellites. The model that gives best agreement with the present radius and luminosity of the planet has an age of 1.87×10^9 yr, which is much less than the expected age of 4.5×10^9 yr. At 4.5×10^9 yr the radius would be smaller by 2 percent and the luminosity 4.2 times smaller than the present value. It follows that if Jupiter is a homogeneous fluid it cannot be completely adiabatic as assumed in many models. The most likely explanation of the discrepancies is either that the fluid contraction stage is superadiabatic or that there is a slow post-fluid contraction stage. The latter would be related to the release of the latent heat of crystallization and of gravitational energy due to immiscibility and segregation as discussed by Smoluchowski (ref. 12) and Salpeter (ref. 18). These sources of energy could account for the present high luminosity of Jupiter and its present radius.

Recently Bodenheimer (ref. 1) has studied the very early stage of the gravitational collapse of a section of the primitive solar nebula having a density 1.5×10^{-11}g cm^{-3}, temperature 40K, radius $4.6 \times 10^3 R_j$, and assuming

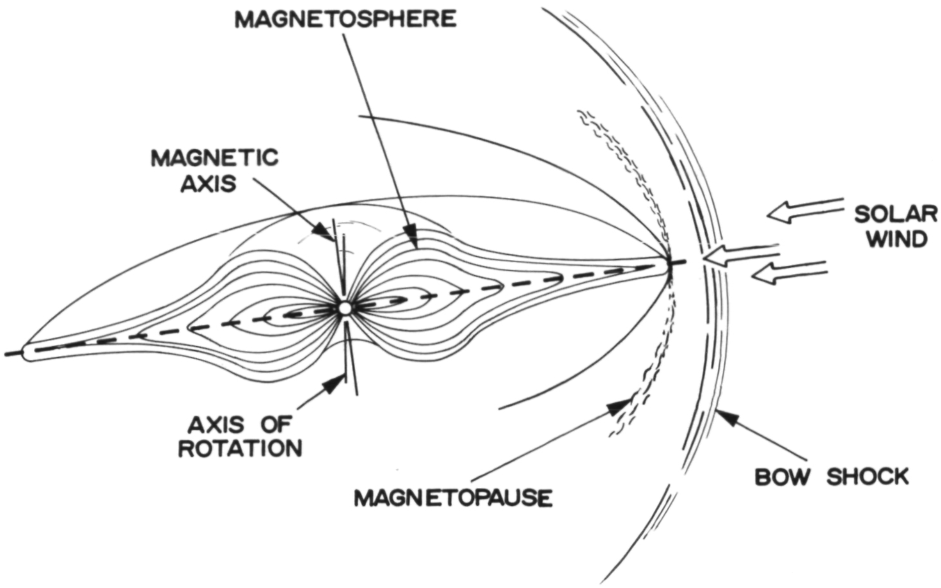

Figure 6.—*Structure of the Jovian magnetic field according to Wolfe and to Dressler et al. (ref. 1).*

65 percent of hydrogen by mass. After a decrease in size by about 10 percent, the object reaches hydrostatic equilibrium and contracts slowly for 7×10^4 yr. When the radius has decreased to 5 percent of its initial value, the central temperature reaches 2500K and the dissociation of H_2 begins with the resulting rapid hydrodynamic collapse. These results fit very nicely into the subsequent stage of evolution analyzed by Graboske et al., as described in the previous paragraph, and they are in reasonable agreement with the Hubbard and the Podolak and Cameron calculations (fig. 7).

Conclusions

Within the last year, important theoretical and observational progress has been made toward understanding the chemical and physical internal structure of Jupiter and its evolution. The results obtained by Pioneer 10 provide new parameters that require changes and improvements of the various models. For various reasons it seems that the assumption of a fully adiabatic and homogeneous interior is not tenable and that the limited solubility in the hydrogen-helium system has to be taken into account. The planet appears to be in hydrostatic equilibrium, and there is no problem with accounting for the excess energy emitted by Jupiter nor for the presence of a magnetic field. The high eccentricity of the magnetic field is a notable new feature, as is its unusual external shape.

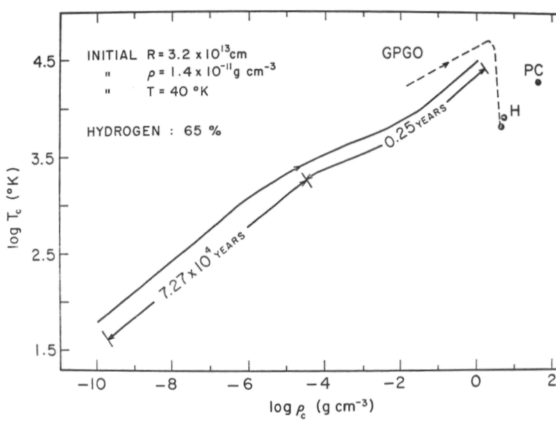

Figure 7.—*Early evolution of Jupiter according to Bodenheimer (ref. 1). GPGO indicates the results of Graboske et al. (ref. 23), PC is the model of Podolak and Cameron (ref. 7), and H is that of Hubbard (ref. 2)*

The nature of the Great Red Spot is perhaps now better understood, primarily because of the existence and behavior of the new Small Red Spot. There are still serious problems associated with the temperature profile and composition of the atmosphere.

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