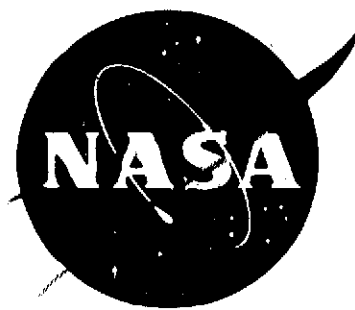


THE INTERIOR STRUCTURE OF JUPITER  
R. SMOLUCHOWSKI  
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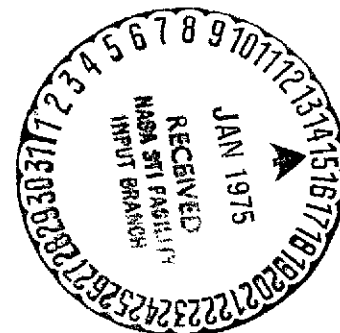
THE PROCEEDINGS OF THE SOVIET-AMERICAN CONFERENCE  
ON THE COSMOCHEMISTRY OF THE MOON AND PLANETS

HELD IN MOSCOW, USSR, ON JUNE 4-8, 1974



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THE INTERIOR STRUCTURE OF JUPITER  
(CONSEQUENCES OF PIONEER 10 DATA)

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USA-USSR Conference on Cosmochemistry of the Moon and Planets - Moscow  
June 3-8, 1974

## ABSTRACT

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 which 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 which 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 pointing 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, which are 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.

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The chemistry and physics of our whole planetary system can be approximated by that 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 (Pioneer 10 1974). In this sense this paper is a sequel to the review paper by Hubbard and Smoluchowski (1973) which contains theoretical background and various numerical data.

### 1. 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 (H&S, 1973) by De Marcus, Peebles, Hubbard, Neece et al., Salpeter et al., Trubitsyn and, more recently, by Caron (1974), Graboske et al. (1974a), Slattery and Hubbard (1973), Zharkov and Trubitsyn (1974), and by Podolak and Cameron (1974). It is interesting to note that in the pressure region where hydrogen is metallic the calculations obtained by the Wigner-Seitz, by the Thomas-Fermi-Dirac and by the 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 (1974) have confirmed the older data of Stewart (H&S, 1973) and shock wave compression results up to nearly one Mb of van Thiel et al. (1973) permit further refinements. Grigoriev et al. (H&S, 1973) 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 (H&S, 1973). 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 (H&S, 1973) physico-chemical arguments and by Hubbard and Slattery's (H&S, 1973) Monte Carlo results that the solubility is limited in the metallic hydrogen range. Streett's (1973) experimental data extrapolated on the basis of Rigby and al's (1970) theory show that this is true also of the H<sub>2</sub> range (H&S, 1973). Unfortunately, the solubility limits and their dependence on temperature and pressure are difficult to estimate; Figure 1 summarizes in a qualitative manner the situation (Smoluchowski 1973). (Recent unpublished theoretical results obtained by D. Stevenson confirm the existence of the solubility gap in the He-H system up to 10<sup>4</sup>K).

## 2. 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 (H&S, 1973) in metallic hydrogen, may reach 1500-2000K. 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 which is difficult to ascertain (Smoluchowski 1973). Similar uncertainty concerns the interactions between H<sub>2</sub> molecules (Slattery and Hubbard 1973). The recent trend towards 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 (H&S, 1973).

## 3. Models of the Interior.

One can classify the models of the Jovian interior into three categories: a). those of Peebles, Hubbard and others (H&S, 1973) which assume a uniform hydrogen-helium ratio throughout the planet except perhaps for a small core; b). those of Podolak and Cameron (1974) which require that this ratio is close to the solar value of 3.4-3.6 by mass (or 13.6-14.4 by number) and c). those which take into account the limited solubility of helium in hydrogen (Smoluchowski 1973) 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  $4 \text{ gr/cm}^3$ , the higher has to be the abundance of helium to give the correct planetary radius (Table I). 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 (1974), 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 further 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 (H&S, 1973). In particular, it is assumed that the core consists of "rock" that is  $\text{SiO}_2$ ,  $\text{MgO}$ ,  $\text{Fe}$  and  $\text{Ni}$  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 which 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  $\text{H}_2\text{O}$  in the atmosphere above the solar value. The best fit to the gravitational coefficients and to a temperature of about 190K at 1 b pressure, as required by the usual model of the atmosphere (Newburn and Gulkis 1973), was obtained for an enrichment of water by a factor of 7.5 and a core which constitutes 12.5 percent of the total mass of the planet as shown in Table II. 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 (Pioneer 10 1974), however, that the value of the gravitational coefficient  $J_2$  (obtained from the occultation of  $\beta$ -SCO (H&S, 1973)), 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" which 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 (Hubbard et al. 1974), 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 to satisfy both the correct  $J_2$  value and the permissible ratio of water to "rock".

The third category of models have not yet been evaluated quantitatively because of the 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 (Smoluchowski 1973). If the central temperature were below 10,000K there would be a solid mantle as indicated. In accord with Streett's (1973) 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 higher than average amount of helium. This can be true even if the planet is so hot that there is no solid mantle because 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 which may be resolved by taking into account the limited solubilities as suggested by the third category of models.

#### 4. Atmospheric Structure and Composition.

While the structure of the atmosphere of Jupiter is a huge topic by itself it cannot be here ignored because as it is well known (Gautier 1974) it does have an important impact on the models of the interior. In particular,

Anderson's interpretation of Pioneer 10 data (Pioneer 10 1974) suggests that the gravitational coefficient  $J_4$  is  $-0.00057$  rather than the older value of  $-0.00067$  (H&S, 1973). 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 (1973) equation of 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 (Pioneer 10 1974). This is, however, in striking contrast with the spectroscopic data which seem to favor lower temperatures of the usual model mentioned earlier. It is important to note in this connection that a number of measurements (Pioneer 10 1974) of the composition of the atmosphere made either by observing details of  $\beta$ -SCO occultation (Ververka et al.) or by ultraviolet photometry (Judge and Carlson) or 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 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 which 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, Pioneer 10 1974) in contrast to the earlier uncertainties (H&S, 1973).

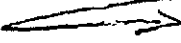


## 5. Internal Heat Source.

The fact that Jupiter (and probably also Saturn) emit much more heat than they receive from the sun has been known for some time (H&S, 1973). Of the many proposed sources of this energy three appear to lead to reasonable amounts: a). gradual loss of primordial heat; b). gradual increase of the radius of the metallic hydrogen layer at the expense of molecular hydrogen layer (about 1mm per year controlled by outward diffusion of helium) which would lead to the release of gravitational energy and c). self-controlled gravitational separation of the immiscible hydrogen-rich and helium-rich phases as proposed first by Salpeter (1973) for the metallic layer and extended to the  $H_2$  layer by Smoluchowski (1973). The self-regulation occurs because as the planet slowly cools and the precipitation of the less buoyant helium-rich phase and of 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 yield 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 (H&S, 1973), Hubbard (1973), Podolak and Cameron (1974) 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 (Pioneer 10 1974) 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 (H&S, 1973). Lowering of this ratio makes the accounting for the excess energy easier than before and thus does not permit to discriminate on this basis between the various mechanisms or models of the interior.

## 6. The Great Red Spot.

An interpretation of the Great Red Spot 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 (H&S, 1973). Kuiper looked at it as a purely atmospheric perturbation or storm analogous to those on Earth (H&S, 1973) but this model has not been evaluated in sufficient detail to account for the motions of the GRS. As pointed out by Golitsyn (1970) a local perturbation in the Jovian atmosphere could exist for a very long time. Hide (H&S, 1973) suggested that the spot is the top of a Taylor column whose base is connected with the surface of a solid mantle and this has been further elaborated by Runcorn (H&S, 1973). Streett (1973) 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 as discussed above (Figure 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 (H&S, 1973).

Pioneer 10 optical measurements as interpreted by Coffeen and by Doose (Pioneer 10 1974) 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. In how far 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 another smaller red spot 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 and 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 (H&S, 1973).

## 7. Magnetic Field.

The most likely source of the Jovian magnetic field is an internal convection-driven dynamo (H&S, 1973) although other mechanisms such as processional motion or thermoelectric effects (Elsasser 1939) cannot be ruled out. Either the high central temperature or the low melting point of hydrogen-helium alloys assure the presence of a liquid, highly conductive core (Hide 1974). The most striking result deduced by E.J. Smith et al (Pioneer 10, 1974) is the fact that the field is about  $4 R_j^{-3}$  gauss 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  $15^\circ$  to the rotational axis but that the magnetic dipole is displaced by about  $.2R_j$  away from the rotational axis and by about  $.1R_j$  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 gauss. For comparison the corresponding values for Earth are  $12^\circ$ ,  $0.07 R_e$  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 (Pioneer 10 1974) 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 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. (Pioneer 10 1974) and E.J. Smith (JGR in press) at larger distances it is elongated

and concentrated along the equatorial plane. This effect appears to be due to centrifugal effects of co-rotation 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 towards the equatorial plane by about  $5^\circ$  (Figure 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.

#### 8. 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. (1974 b) made a study of the evolution of a star having an appropriate mass, i.e.  $9.5 \times 10^{-4}$  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  $4 \times 10^4$  K 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 which gives best agreement with the present radius and luminosity of the planet has an age of  $1.87 \times 10^9$  years which is much less than the expected age of  $4.5 \times 10^9$  years. At  $4.5 \times 10^9$  years 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 (1973) and Salpeter (1973). These sources of energy could account for the present high luminosity of Jupiter and its present radius.

Recently Bodenheimer (Pioneer 10 1974) has studied the very early stage of the gravitational collapse of a section of the primitive solar nebula having a density  $1.5 \times 10^{-11} \text{ g cm}^{-3}$ , temperature 40K, radius  $4.6 \times 10^3 R_j$  and assuming 65 percent of hydrogen by mass. After a decrease in size by about 10 percent the object reaches hydrostatic equilibrium and contracts slowly for  $7 \times 10^4$  years. When the radius has decreased to 5 percent of its initial value the central temperature reaches 2500K and the dissociation of  $\text{H}_2$  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. (Figure 7).

#### 9. Conclusions.

Within the last year important theoretical and observational progress has been made towards understanding of the chemical and physical internal structure of Jupiter and of its evolution. The results obtained by Pioneer 10 provide new parameters which 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. 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.

The author wishes to express his appreciation to the quoted participants of the April meeting of the DPS-AAS and to Drs. Fountain, Grossman, Hubbard, Podolak and Swenson for informing him about their most recent results.

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TABLE I

MODEL OF JUPITER

<u>Radius (10<sup>4</sup> km)</u>	<u>Fractional mass</u>	<u>Pressure (M bars)</u>	<u>Density (g/cm<sup>3</sup>)</u>
6.9	.99	0.004	0.03
6.5	.97	0.24	0.4
6.0	.90	1.1	0.7
5.5*	.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

\* H<sub>2</sub>-metal phase change

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TABLE II

JUPITER MODEL WITH 7.5 ENRICHMENT OF H<sub>2</sub>O

Radius (10 <sup>9</sup> cm)	Temp. (K)	Press. (Mb)	Density (gm/cm <sup>3</sup> )	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 <sub>2</sub>
7.00	1061	3.94 × 10 <sup>-4</sup>	0.010	
7.02	678	8.38 × 10 <sup>-5</sup>	3.6 × 10 <sup>-3</sup>	
7.04	192	1.01 × 10 <sup>-6</sup>	1.4 × 10 <sup>-4</sup>	

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FIGURE CAPTIONS

- Fig.1 Isothermal hydrogen-helium equilibrium diagram (Smoluchowski 1973).
- Fig.2 Mass of the Jovian rock core and of water as a function of  $J=(3/2)J_2$  (Podolak and Cameron 1974).
- Fig.3 Immiscible liquid layers on Jupiter (Smoluchowski 1973).
- Fig.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  $He(H_2)$  (H&S, 1973).
- Fig.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. (Pioneer 10 1974).
- Fig.6 Structure of the Jovian magnetic field according to Wolfe and to Dressler et al. (Pioneer 10 1974).
- Fig.7 Early evolution of Jupiter according to Bodenheimer (Pioneer 10 1974). GPGO indicates the results of Graboske et al. (1974 b), PC is the model of Podolak and Cameron (1974) and H is that of Hubbard (H&S, 1973).

$\alpha, \beta$  - LIQUID

$\gamma$  - SOLID H<sub>2</sub>(He)

$\eta$  - SOLID METALLIC  
H(He)

$\delta, \delta'$  - SOLID  
He(H<sub>2</sub> OR H)

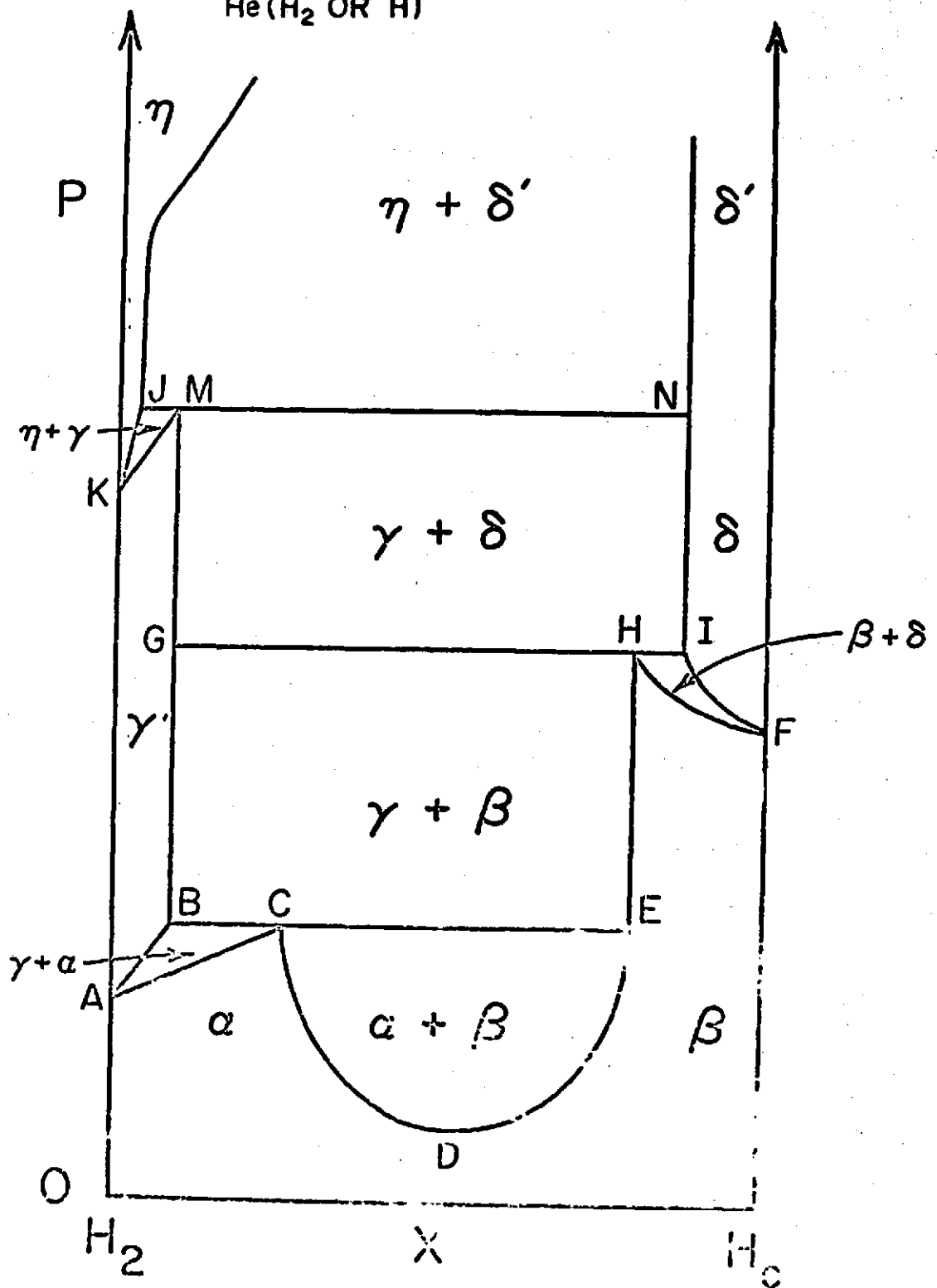


Fig. 1

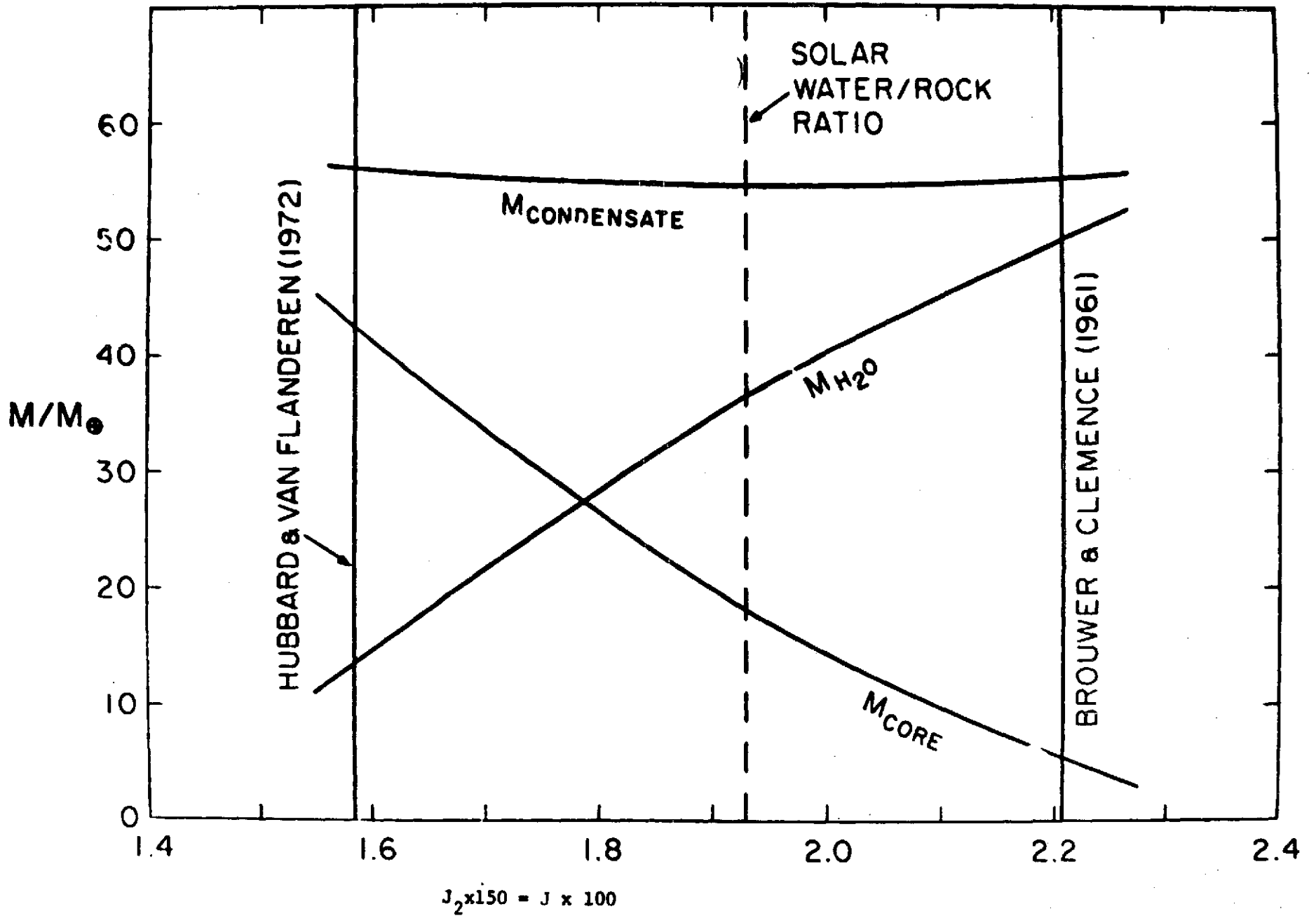


Fig. 2

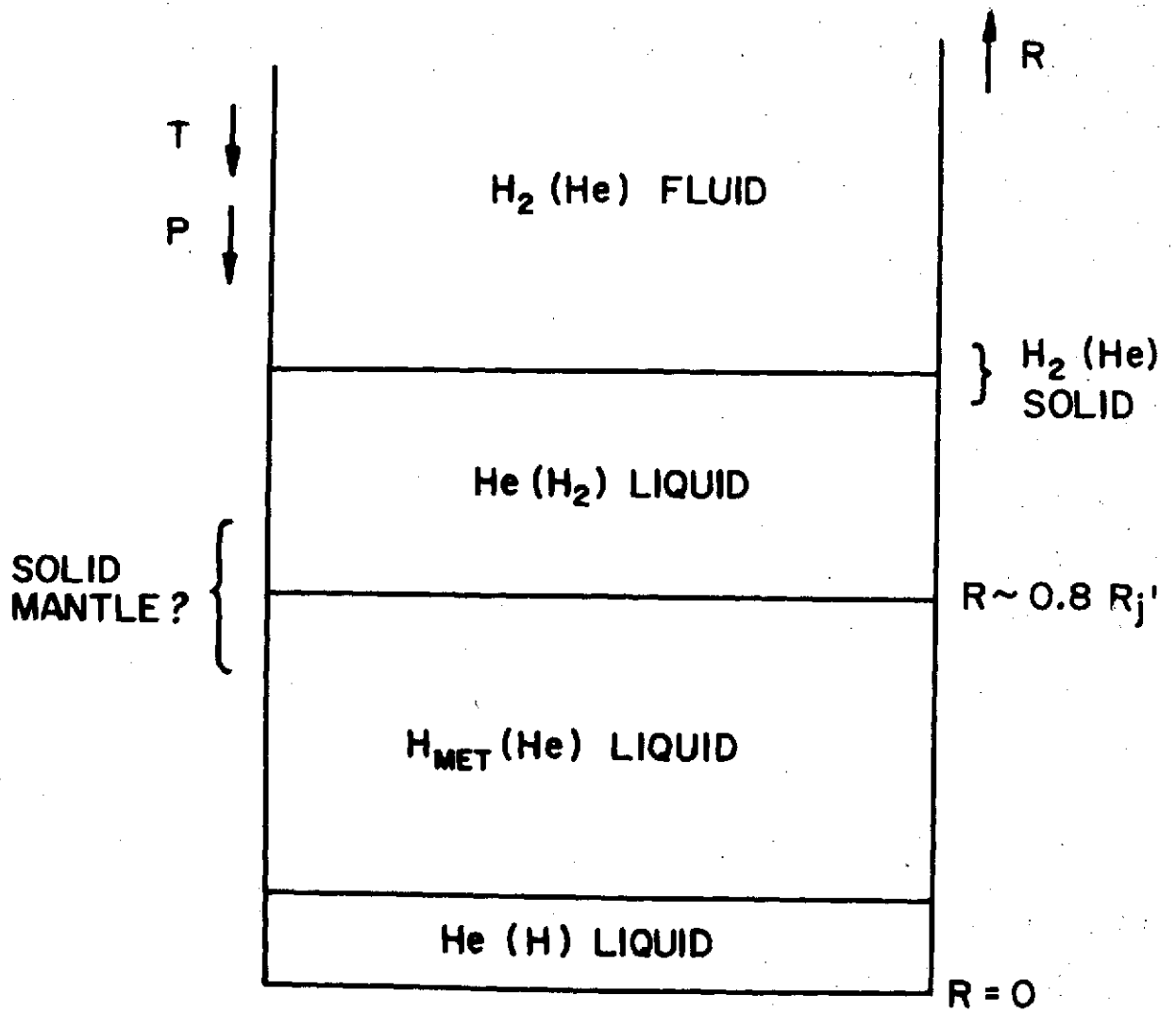


Fig. 3

L - LIQUID  
S - SOLID  
A - ATMOSPHERE

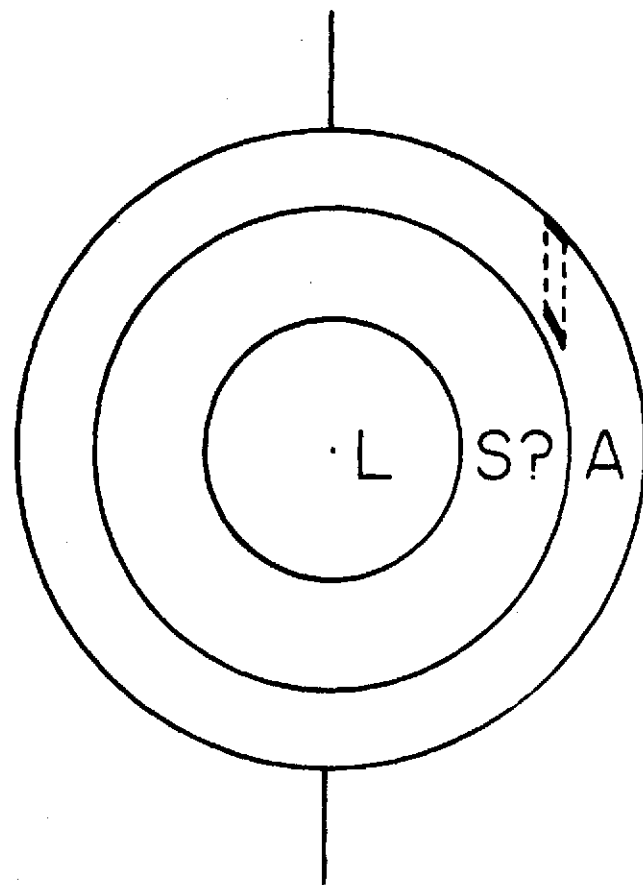
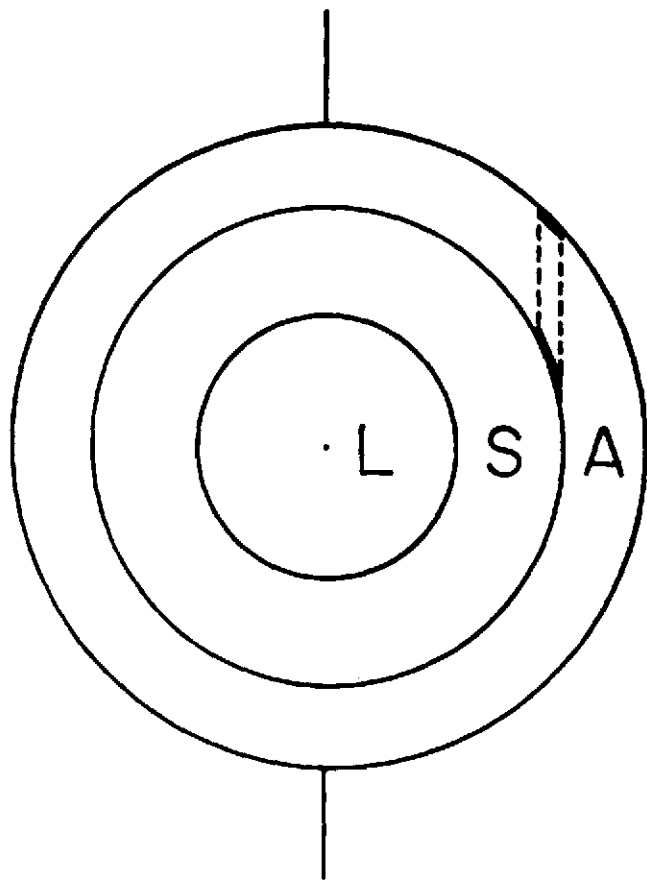


Fig. 4

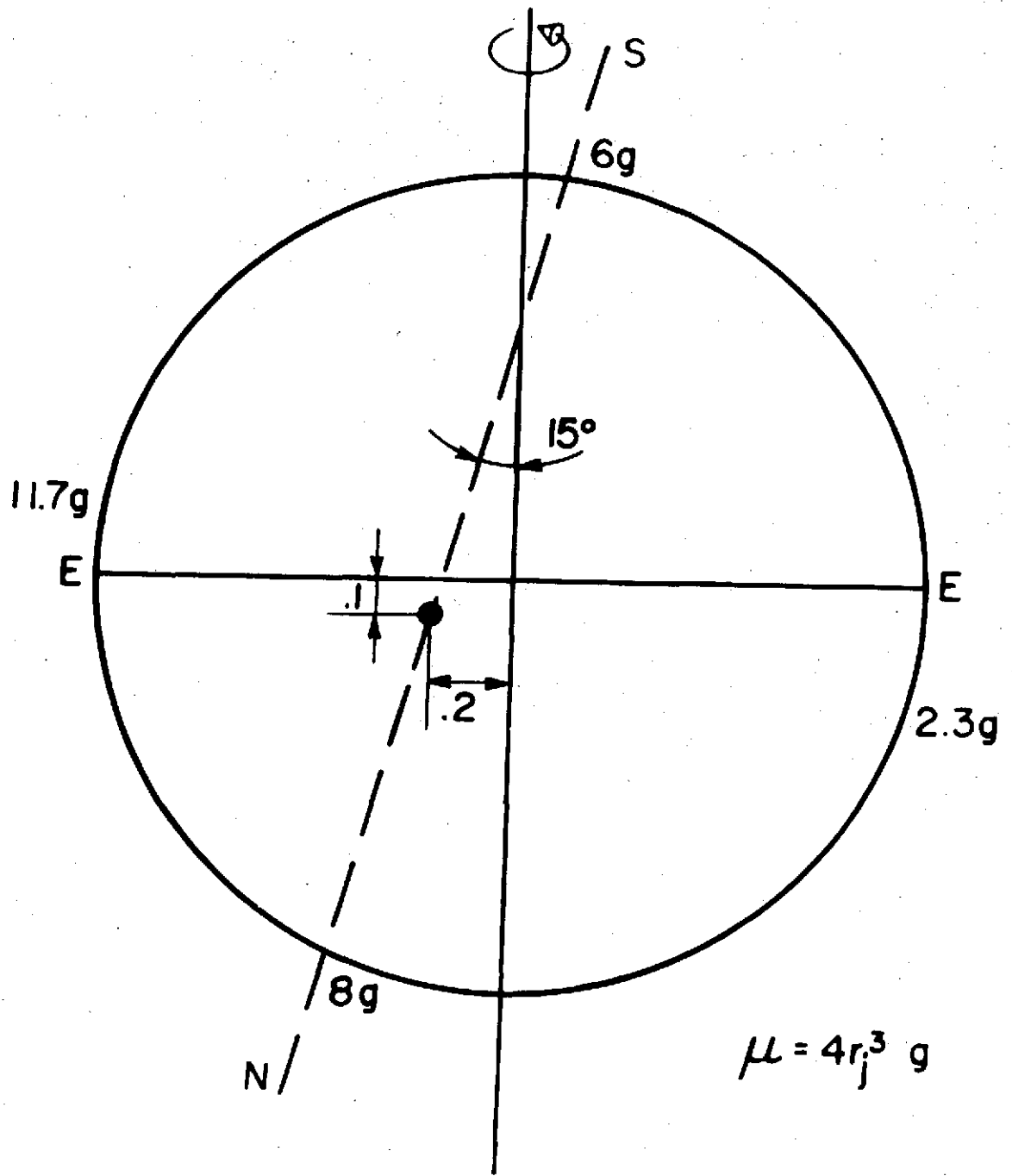


Fig. 5

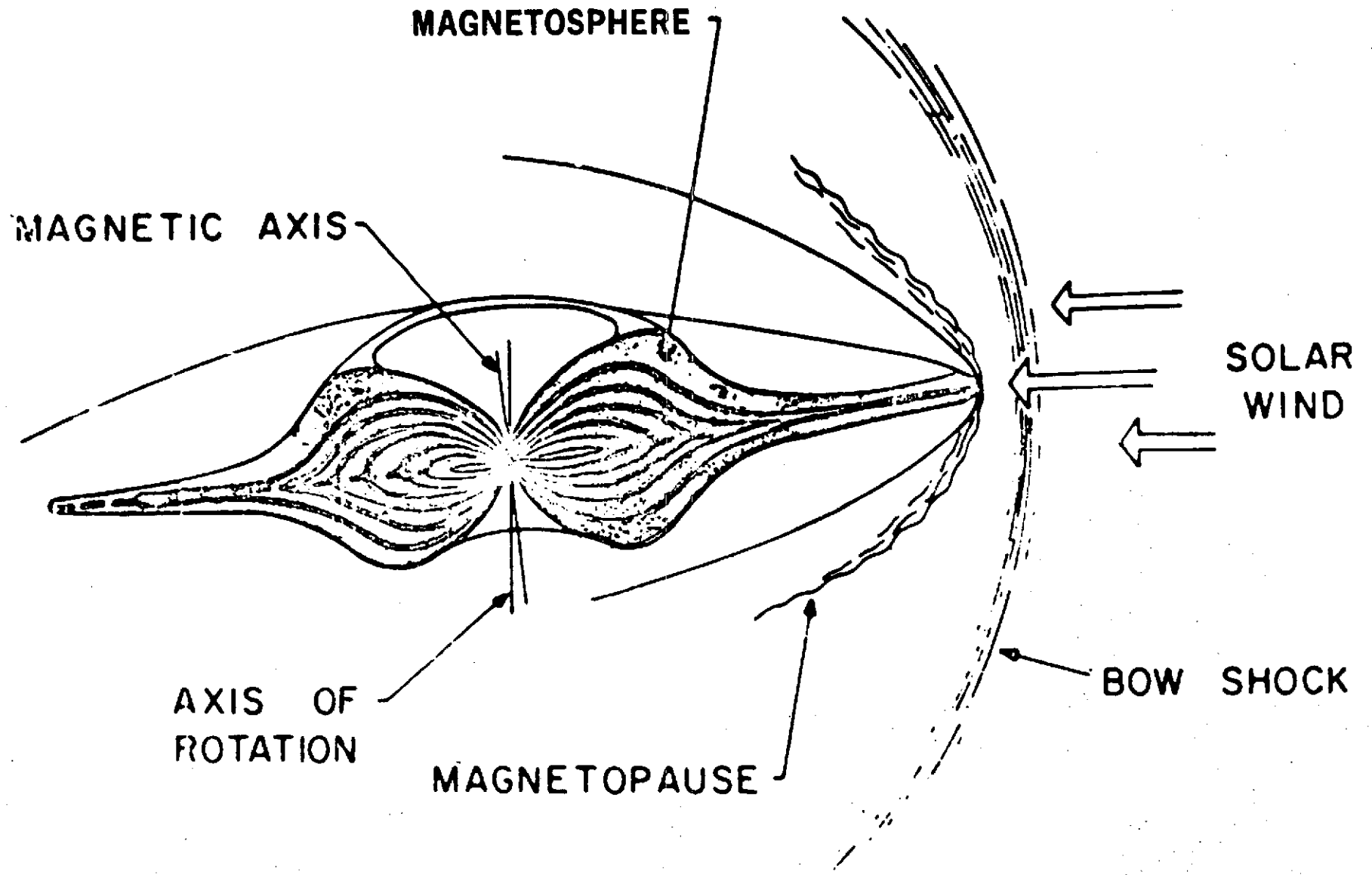


Fig.6

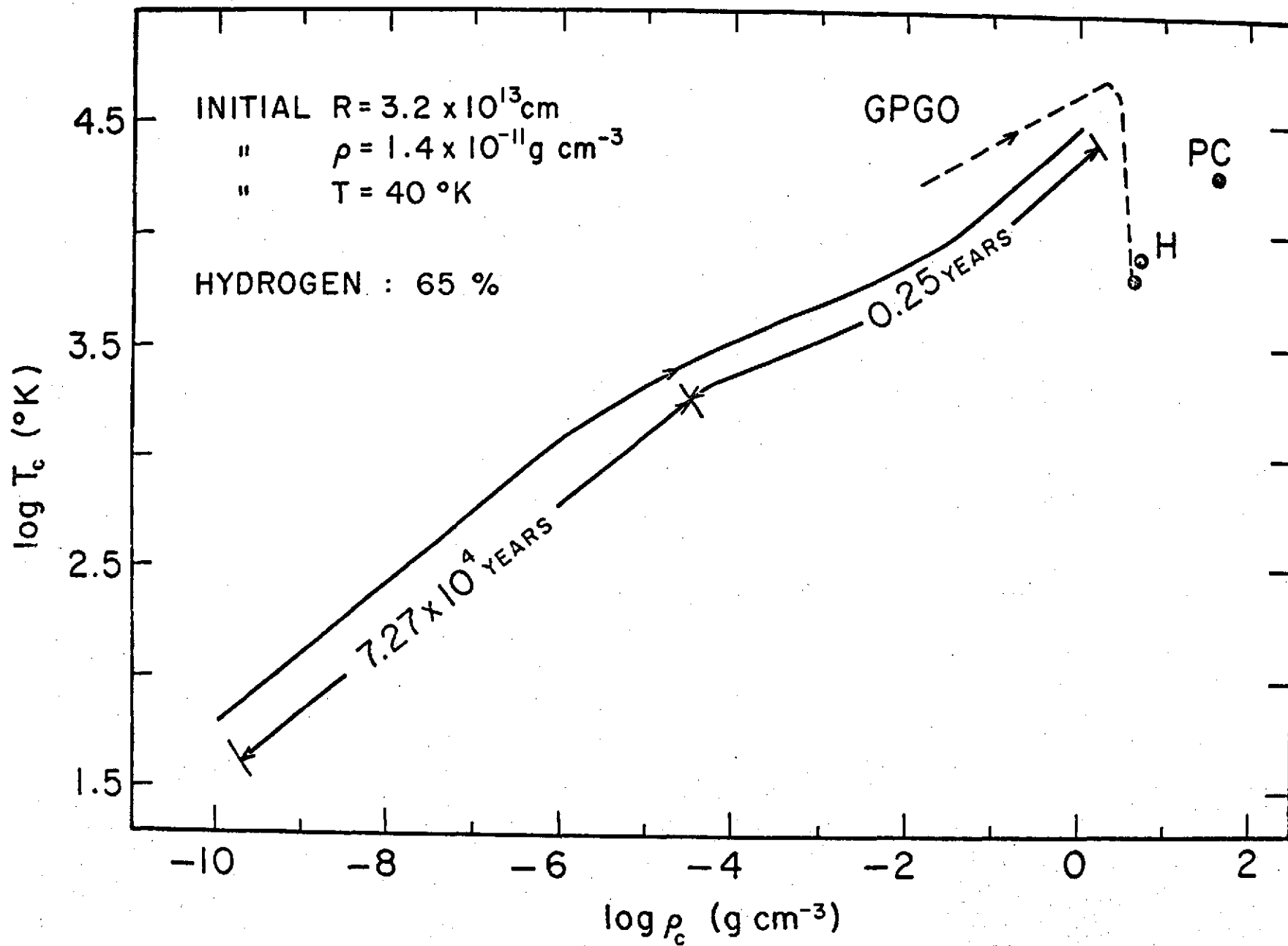


Fig. 7