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THE JOVIAN TURBOPAUSE PROBE

PART 1
THE SCIENTIFIC REQUIREMENTS FOR THE JOVIAN TURBOPAUSE PROBE

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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ABSTRACT

A non-survivable probe (Turbopause Probe) is the simplest concept capable of direct measurements of the atmosphere and the interior of Jupiter. The scientific rationale and requirements for such a Turbopause Probe mission are discussed without reference to any specific year or deep space mission. A discussion of particles and fields measurements is included where these measurements are compatible with the prime mission objectives.

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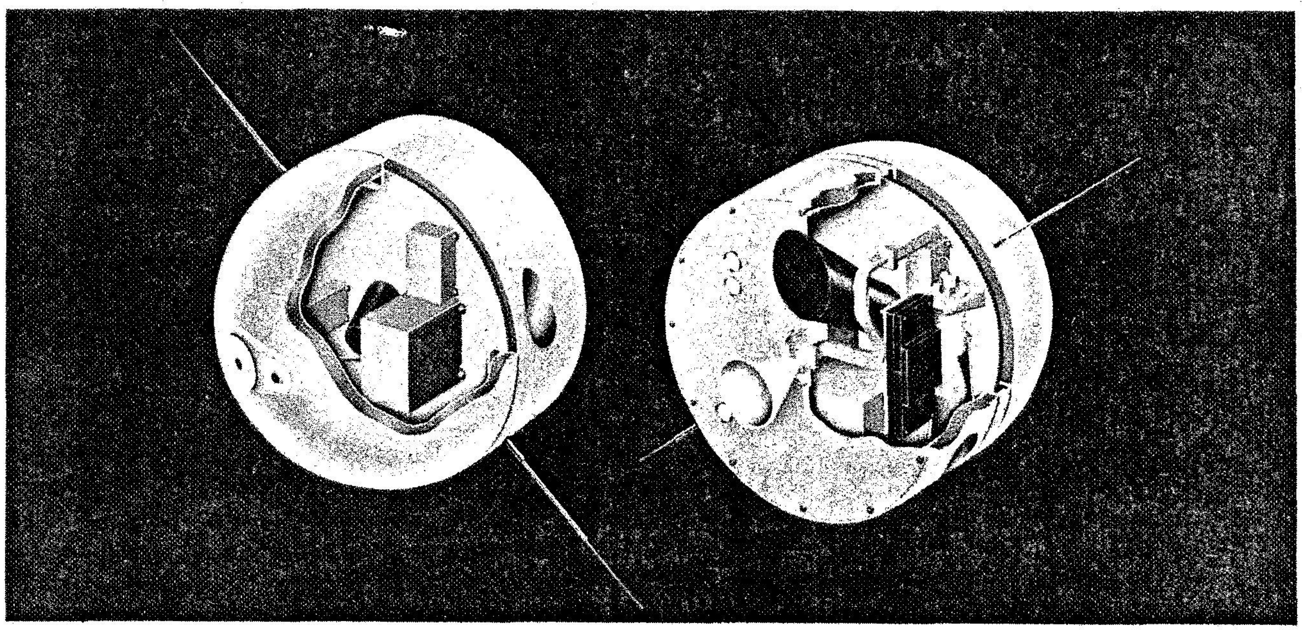

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THE SCIENTIFIC REQUIREMENTS FOR THE JOVIAN TURBOPAUSE PROBE

1.0 INTRODUCTION

In recent years much emphasis has been placed on the exploration of the outer planets. Of these Jupiter is the largest and of singular importance to planetary studies. It is the most accessible of the outer planets; it is almost of stellar mass; it probably has a significant internal heat source; its composition is close to that of the sun; and it represents a different stage in planetary evolution from that of the terrestrial planets.

The exploration of the Jovian atmosphere by remote means has proved difficult and strictly limited as to the information obtainable. Fly-by missions such as Pioneer F/G will give some additional information, but most of the questions discussed in this report will remain unanswered. The only way to gain information on neutral and ionized species far superior to that from telescopes is by means of in situ measurements from entry probes.

Such measurements, particularly those involving survivable probes, are extremely difficult. The large gravitational attraction and the high rotation rate of Jupiter results in entry velocities ranging from fifty to seventy kilometers per second. These extremely high velocities give rise to entry problems outside our present experience: a survivable Jovian entry probe is in fact beyond existing technology.

A probe without a heat shield will vaporize high in the atmosphere, as if it were a meteor. The construction of such a probe will involve no new technology. Useful measurements can be made from such a probe and these measurements pertain to important scientific questions about the planet.

Calculations on the trajectory, heating and measurement capability of the non-survivable probe indicate that the entry probe may well survive to the turbopause of Jupiter and to make measurements into the mixed region of the atmosphere. Thus, a non-survivable probe can make direct measurements not only of the important upper atmosphere region but may well have a capability in the mixed region where the composition can be related to that of the mass of the planet. We suggest, therefore, that the combination of practicability and the usefulness of the data that might be obtained indicate the value of the Turbopause Probe as the first step in the exploration of the atmosphere and interior of Jupiter.

We discuss the scientific requirements of a Jovian Turbopause Probe without reference to any particular mission. The prime objective of a Turbopause Probe mission is direct measurements on the atmosphere and interior of Jupiter. However the spacecraft, which must be used to transport the probe, also has a flyby capability. Therefore, we include a discussion of compatible fields and particles science for a deep space mission.

The material on the upper atmosphere was prepared by Dr. Donald M. Hunten; the material on the bulk composition was prepared by Dr. A. G. W. Cameron; and the material on the fields and particles science for a deep space mission was prepared by Dr. W. Ian Axford.

We have not devoted effort to summarizing what is known about Jupiter for the reason that we have almost no really certain knowledge about its physical and chemical structure. For this reason it can be said that practically any information about the planet is valuable. However we must have a reason for choosing particular instruments and particular ranges for these instruments. Our general knowledge of the solar system, other planets, and telescopic studies of Jupiter are sufficient to define our needs in a rather definite way for this proposed first in situ investigation of that planet.

2.0 PROBE SCIENCE REQUIREMENTS

One may distinguish between the requirements for two specific atmospheric regions: (a) the region above the turbopause characterized by diffusive separation, and (b) the region below the turbopause characterized by an approach to complete mixing.

2.1 THE UPPER ATMOSPHERE

For purposes of this discussion, the term "upper atmosphere" refers to the region of gravitational separation of light and heavy gases, and its base is the turbopause. The upper atmosphere coincides approximately with the thermosphere and exosphere, the regions of temperature increase and constant temperature. Again approximately, the upper atmosphere is the region through which an unshielded probe can readily penetrate, though a further penetration below the turbopause is likely. A set of measurements made from a single probe should be able to define all the basic parameters of the region: the temperature, the composition and gravitational separation, and the positive-ion composition. With the last, a thorough understanding of the ionosphere will be possible, in contrast with the difficulties always encountered when only electron densities are available.

The measuring techniques required for the job are well developed for use in the earth's upper atmosphere, as are the means of relating the measurements to the atmosphere itself. Modifications are necessary to permit useful operation at entry velocities of 50 km/sec, but there is also an important simplification: as in the solar wind, the directed velocity is large compared with the random velocities, and mass analysis reduces to a simple momentum analysis.

Figure 1 shows expected concentrations of various constituents in the upper atmosphere (Ref. 1). This model of the atmosphere is for a composition with the He/H_2 ratio set at the solar value of 0.11 by volume. Figure 2 is a modification of the model shown in Figure 1 with a composition of 50% H_2 - 50% He (by volume).

These two models will then encompass a range of possible compositions in the Jovian atmosphere. The turbopause, where gravitational separation of He and H_2 begins, is taken as the origin for the height scale. (For the other gases, CH_4 and H, slightly different heights apply because their diffusion coefficients are different.)

Hydrogen atoms are produced as a byproduct of ionospheric processes; they then diffuse and mix downwards to heights where chemical processes are fast enough to permit recombination. The amount of H in the models has been adjusted to fit

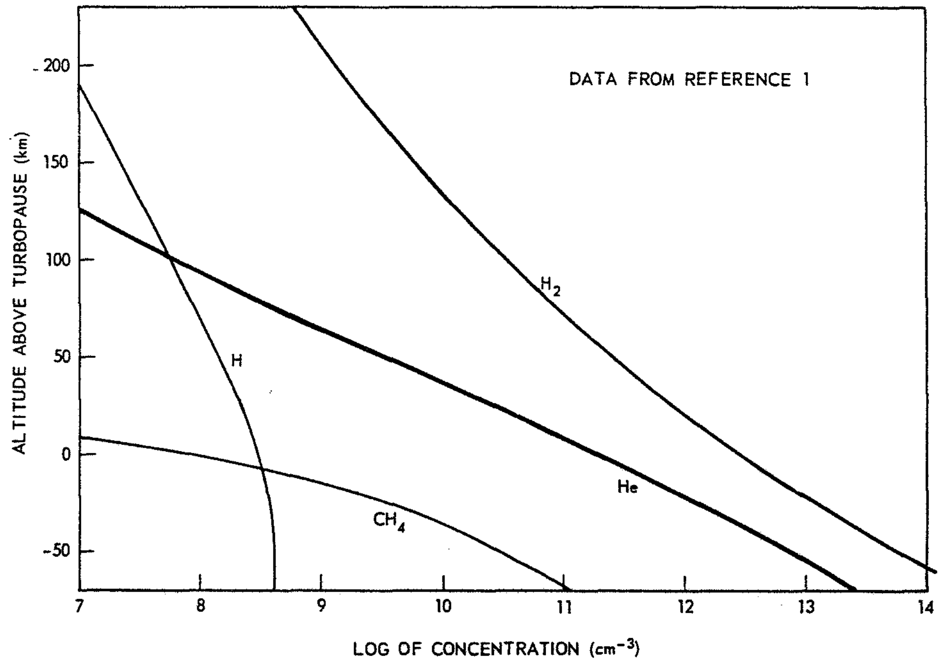

Figure 1. Number Densities of Constituents in the Jovian Atmosphere $He/H_2 = 0.11$ (By Volume)

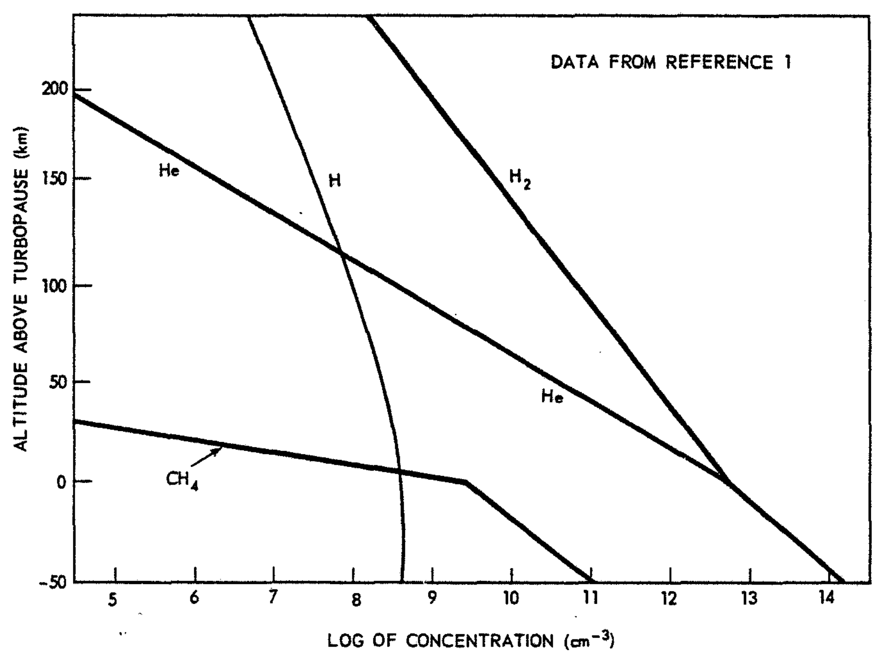

Figure 2. Number Densities of Constituents in the Jovian Atmosphere 50% H_2-50% He (By Volume)

the Lyman-alpha albedo observed from a rocket by Moos, Fastie, and Bottema (Ref. 2). In the course of this adjustment, a value is found for the eddy diffusion coefficient and therefore for the turbopause height. A refined version of this calculation will clearly be one of the most important results of a probe mission. H atoms should be observed in two independent ways: by the neutral-particle mass spectrometer, and by a dayglow photometer measuring the Lyman-alpha scattering.

As discussed in detail by Hunten (Ref. 1), we are unable at present to give a reliable prediction of the ionospheric structure for a hydrogen-helium atmosphere. Strange ions such as H_3^+ and HeH^+ may be abundant and may control the recombination. A direct measurement of the nature and concentrations of the positive ions should lead to a complete understanding, and the results will be important to studies of phenomena such as radio bursts. Most of the models for explaining these bursts require knowledge of the ionospheric conductivity and electron density (Refs. 3 and 4).

Upper-atmospheric measurements are important in themselves, but an even greater interest is attached to them if they can be related to the mixed atmosphere below the turbopause. Furthermore, it is useful to have several methods of inferring the location of the turbopause; penetration is of little use in itself unless we know that penetration has occurred. Fortunately, at least two methods exist, and one of them has already been used with earth-based measurements. The more direct technique is simply to look for the presence of a heavy gas such as methane. Its scale height is so small relative to that of H and He that its mere appearance ensures that the turbopause cannot be far below. A very reliable correction can then be made to the He/H_2 ratio. The second method is to use the ratio H/H_2 at any height. Hydrogen atoms are produced at a known rate in the ionosphere; their diffusion and mixing down to the lower atmosphere is controlled by exactly the same processes that control the upward mixing of heavy gases.

2.2 THE BULK COMPOSITION OF JUPITER

The clouds of Jupiter appear to be crystals of NH_3 and their temperature is about 160°K: very few substances are in volatile form above them. The most important of these are H_2, He, and CH_4. Recent spectroscopic determinations indicate that these may be present in solar proportions, but the errors are large (Ref. 5). In any case, the proportions are approximately solar, so that planning for a Jupiter mission can logically proceed on that assumption as a first approximation. Any departure from that assumption will probably involve easier detection of the heavier elements.

The neutral atom or molecular mass spectrometer provides an opportunity to make deductions about the general composition of the planet. We make the following assumptions:

1. The planet is of essentially solar composition, as suggested spectroscopically for the C/H ratio, and also as seems reasonable from the low temperature and high mass of the planet.

2. Nonvolatile elements will form molecules and collect into assemblies at least as large as dust particles, and hence they cannot be separately detected by a mass spectrometer.

3. The remaining isotopes of possible interest, having abundances at least as great as 10^{-6} H_2, are H^1, D^2, He^3, He^4, C^{12}, C^{13}, Ne^{20}, Ne^{22}, Ar^{36} and Ar^{38} (see Table I).

From these considerations it is suggested that it would be wise to monitor the following mass numbers with the mass spectrometer:

Mass Number	Substance
1	H^1
2	H_2^1
3	H^1D^2, He^3
4	He^4
16	$C^{12}H_4^1$
20	Ne^{20}
21	Ne^{21}
22	Ne^{22}
36	Ar^{36}
38	Ar^{38}

Some channels should also be monitored for control purposes where nothing is expected.

The He/H ratio is of special interest for a number of reasons. If helium is enriched relative to the sun, this would imply some rather drastic conditions in the formation of Jupiter, such as extremely low temperatures (unlikely) or extensive selective evaporation (possible, as may have happened in Uranus and

Neptune). If the ratio is solar, then we have to exploit the opportunity to measure this ratio more accurately than we can do on the sun itself. Helium may have been made by cosmological nucleosynthesis and possibly enriched in the pre-solar interstellar medium by stellar nucleosynthesis. Cosmological nucleosynthesis makes about 28 per cent by mass in a closed universe and 22-24 per cent in an open universe. Present solar models (Ref. 6) require 22 per cent helium, but this number is uncertain because of possible errors in stellar opacity calculations. Current difficulties in detecting solar neutrinos may require a rather low solar abundance of helium. If the C/H ratio turns out to be solar, then one would have confidence that the He/H ratio is also solar, and its value would be very important in this cosmological context.

One of the controversies likely to be settled by these measurements is the site of the nucleosynthesis of the light elements. It has been proposed (Ref. 7) that D^2, He^3, Li, Be, and B were made by high energy spallation processes in the primitive material of the solar system. On this picture, these elements should be present only in the inner solar system and not in Jupiter. Cameron has frequently criticized these ideas on various astrophysical grounds and believes that approximately the abundances of D^2 and He^3 given in Table I should be found in Jupiter. The signal at mass three will enable us to judge between these conflicting views.

Table I

This table of dominant neutral isotopes in the mixed portion of the Jovian atmosphere is based mainly on solar and carbonaceous chondritic (Type I) compositions.

Isotope	Abundance	Isotope	Abundance
H 1	3.44×10^{10}	N 14	2.94×10^{6}
D 2	5.2×10^{6}	Ne 20	1.85×10^{6}
He 3	7.6×10^{5}	Ne 22	1.80×10^{5}
He 4	2.53×10^{9}	Ar 36	8.4×10^{4}
C 12	1.20×10^{7}	Ar 38	1.6×10^{4}
C 13	1.35×10^{5}		

The Ne/Ar ratio in Jupiter will be of particular value to current calculations in nucleosynthesis theory. The relative abundance of most of the isotopes in the range silicon to calcium can be quantitatively predicted by the process of explosive silicon burning (Ref. 8). This predicts a certain abundance for the Ar^{36} and Ar^{38} isotopes, and the ratio corresponds to that observed. Ne^{20} is made by explosive carbon burning, a different process, and the abundance listed in Table I is based on the relative abundances of oxygen and neon in solar cosmic rays. These relative abundances happen to agree with the Ne/Ar ratio in gas-rich chondritic meteorites, which is encouraging. But the abundance ratio in Jupiter will be a much more definitive test of these theories.

One of the major mysteries in current meteorite research is the Ne^{20}/Ne^{22} ratio (Ref. 9), which can vary between 3 and 14, the terrestrial ratio being 11. The solar ratio is not known, although it may be deduced from the gas content of lunar dust. Even in this case, doubt may remain that a lunar value for this ratio in the solar wind is truly representative of the sun. The Jovian value for this ratio is likely to be the same as solar even if heavier elements have been enriched in Jupiter, and the determination of this ratio then helps to establish the theories for the processes which can alter this ratio in the neon implanted into the meteorites. This is particularly important, because the Ar^{36}/Ar^{38} ratio does not suffer similar variations, and hence the neon has an important story to tell us about the early history of the solar system if these processes can be determined. There is so little neon in the earth's atmosphere that there is little assurance that the terrestrial Ne^{20}/Ne^{22} ratio represents anything; the neon on the earth may have been captured from the solar wind.

There is also an interesting situation concerning He^3. The signal at mass 3 may be HD as well as He^3, so that it is highly desirable that this mass be separated into its components. The He^3/He^4 ratio is usually near 3×10^{-4} in gas-rich chondritic meteorites, but there is a big spread in this ratio in gas-rich carbonaceous chondritic meteorites (Ref. 10), the ratio varying from 1 to 4×10^{-4}. If deuterium in the early solar system had the D/H ratio characteristic of the terrestrial oceans, then the early sun had to pass through a deuterium-burning phase in which the sun was fully convective. In this process about 3×10^{-4} He^3 relative to He^4 would be formed from the deuterium, and the products of the deuterium-burning would reach the solar surface and be ejected in the solar wind. Hence a determination of the He^3/He^4 ratio in Jupiter would establish the primordial value and would also help to establish the process whereby helium was implanted into the gas-rich meteorites.

It may be seen from these various considerations that mass spectrometer measurements near or below the Jupiter turbopause could give information about the composition and structure of Jupiter of great importance for the reconstruction of the early history of the solar system.

3.0 FIELDS AND PARTICLES SCIENCE FOR A DEEP SPACE MISSION

3.1 INTRODUCTION

Experiments designed to measure particles and fields in the magnetosphere of a planet such as Jupiter are likely to be poorly matched to the requirements of interplanetary measurements. For example the magnetic field strength in the Jovian magnetosphere might be as large as 1-10 gauss, whereas in interplanetary space beyond the orbit of Jupiter, the magnetic field strength is expected to be 1-10 microgauss. Energetic particle experiments are similarly mis-matched; in the Jovian magnetosphere the experiments must be designed to cope with large fluxes of energetic trapped protons (J (> 1 MeV) $\simeq 10^{7\pm3}$ cm^{-2} sec^{-1}), electrons (J (> 2 MeV) $\simeq 10^{7\pm2}$ cm^{-2} sec^{-1}) and possibly α-particles, whereas in interplanetary space the expected cosmic ray fluxes are very much smaller (J (>1 MeV) $\leq$ 10 cm^{-2} sec^{-1}) and consequently require instruments with much larger geometric factors. The anisotropies of magnetospheric and interplanetary energetic particles are of a different nature, and in the case of galactic cosmic rays it is of the utmost importance that composition measurements be made with considerable care since the information to be gained is of great astrophysical significance. In the case of the low energy (~1 keV) plasma, the interplanetary measurements involve the solar wind (i.e., highly directed fluxes of the order of 10^5 - 10^7 ions cm^{-2} sec^{-1} beyond 5 AU) whereas magnetospheric fluxes should be essentially isotropic and probably much more intense. The composition of the solar wind is of great interest, not only as far as protons and alpha particles are concerned, but also ions such as $^4He^+$, $^3He^{++}$, $^{12}C^{4+}$, $^{12}C^{5+}$, $^{16}O^{6+}$, $^{16}O^{5+}$ and so on, since the composition may change with increasing heliocentric distance. Finally there are very large differences in the intensities of electromagnetic radiations to be expected in the vicinity of the outer planets compared with those to be expected in interplanetary space.

From these considerations it appears that we should examine the possibility of instrumenting at least one spacecraft to perform interplanetary measurements as its primary task. We wish to point out that in fact such a spacecraft should be designated as an interstellar probe, since there is a very good chance that if it can reach a heliocentric distance of the order of 30-50 AU in the ecliptic plane the interstellar medium will be encountered for the first time. In order to make this journey as rapidly as possible, a Jupiter swing-by is advisable.

3.2 THE INTERACTION OF THE SOLAR WIND WITH THE INTERSTELLAR MEDIUM

It is believed that the solar wind terminates as a supersonic flow through a roughly spherical shock transition which occurs at a heliocentric distance where the ram pressure (ρV^2) is equal to the inwards pressure of the interstellar medium ($P_0 \approx 4 \times 10^{-13}$ dyne cm^{-2}). If the interstellar gas surrounding the solar system is fully ionized, then the solar wind density varies inversely as the square of the heliocentric distance ($\rho \propto 1/r^2$) and the velocity V is constant. Taking as typical values, $\rho = 10^{-23}$ grams cm^{-3} at 1 AU, and V = 400 km/sec, we find that the shock transition would occur at 140 AU. Beyond the shock there would be a very extensive region ($\gtrsim 10^3$ AU in radius) of hot plasma moving subsonically and into the wake of the solar system (Ref. 11). If the heliosphere were as extensive as this model suggests it would be almost futile to attempt to detect the shock transition and the interstellar gas beyond the heliosphere using the spacecraft under consideration here. However, there are good reasons for believing that the situation is quite different, and that the shock transition and the interface with the interstellar medium occur at a heliocentric distance of only ~30-50 AU.

In the presence of a neutral interstellar "wind" the heliosphere should be affected markedly, both within the region where the solar wind exists as a supersonic flow, and outside where it is subsonic and is blown back into the wake of the solar system. It is expected that the interstellar wind has a density of 0.1-1 cm^{-3} and a relative velocity of ~ 20 km sec^{-1} moving in a direction toward the constellation Vega, ~ 53° out of the ecliptic (Refs. 12 and 13).

The most important process involved in the interaction of the solar wind plasma with the neutral component of the interstellar gas is charge exchange between solar wind protons (initially having a velocity of ~400 km sec^{-1}) and the 20 km sec^{-1} interstellar hydrogen (Ref. 14). This produces a shower of energetic hydrogen atoms which leave the solar system, and slows the solar wind markedly as a result of the momentum loss to the plasma. Preliminary calculations suggest that for typical solar wind fluxes of 2×10^8 cm^{-2} sec^{-1} near the earth, the solar wind must terminate within 50 AU and possibly as close as 30 AU from the sun. The effect of charge exchange on the shocked plasma beyond the transition is to cool it to a temperature of $\sim 4 \times 10^4$ °K and to drag it into a tadpole-tail wake behind the solar system.

Apart from its effect on the momentum and temperature of the solar plasma, this interaction can be detected in at least three ways: (1) by scattering of solar Lyman-α photons from the interstellar neutral hydrogen, and from the energetic neutral atoms produced by the charge exchange reaction; (2) by the appearance of singly-ionized helium and other species (from the interstellar gas) in the solar wind (Ref. 13); (3) by a change in the flow characteristics of the solar wind plasma which would be evident in its velocity and density and also in the magnetic field (Ref. 15). There already exists evidence involving Lyman-α measurements and measurements of He^+ ions in the solar wind which supports the hypothesis that the solar wind is interacting with a neutral interstellar gas along the lines described (Refs. 16, 17, and 18).

It is evident from the above discussion that a well-designed solar wind experiment in the outer solar system must be capable of giving good energy/unit charge spectra for total fluxes of the order of 10^5 ions cm^{-2} sec^{-1}, and also if possible to measure the flux of energetic neutral hydrogen atoms. Since the solar wind is very cold at large distances from the sun, an electrostatic analyzer should give a satisfactory composition determination (Ref. 19). Some consideration will have to be given to the problem of observing the properties of the subsonic plasma beyond the shock transition since this is required in order to establish the position of the shock transition. Observations of the distribution of intensity of scattered solar Lyman-α and other relevant lines would also be of interest. The possibility of detecting the interstellar neutral wind directly should also be investigated.

3.3 THE INTERPLANETARY MAGNETIC FIELD

At great distances from the sun the magnetic field strength near the ecliptic plane is expected to have the form $B_r = B_0 (a/r)^2$, $B_\phi = B_0 a^2\Omega/rV$, where B_0 is the radial field strength at a nominal distance $r = a$, and Ω is the equatorial rotation speed of the sun. Thus for typical values of the solar wind speed the spiral angle $\chi = \mathrm{Tan}^{-1} B_\phi/B_r$ is such that $\chi \sim 45°$ at $r = 1$ AU. Beyond the orbit of Jupiter we expect $\chi \sim \Omega r/V$ and $B \sim B_\phi \propto 1/r$. At the orbit of Jupiter, therefore, we expect to find $\chi \sim 80°$ and $B \sim 10^{-5}$ gauss if the field strength at the earth is 5×10^{-5} gauss. That is, at great distances the magnetic field in the ecliptic plane must be essentially azimuthal with the field strength varying inversely as distance from the sun. If the shock transition occurs at 30 AU, the field strength in front of the shock should be about 1.5×10^{-6} gauss, and behind the shock perhaps 3×10^{-6} gauss.

Obviously such small fields are difficult to measure with the usual techniques, but a loop on the rotating spacecraft might serve the purpose very well, and in addition provide some indication of the degree of turbulence of the field. In this respect it is interesting to note that the magnetic field will be almost perpendicular to the spacecraft's spin axis if the latter points toward the sun. One might expect some evidence for the 'sector' pattern of the interplanetary magnetic field to still be evident at great distances from the sun. Observations of fluctuations in the field are of interest since they can be related to cosmic ray scattering, which is in turn one of the important problems to be investigated on deep space missions.

The magnetic field might offer a clear means of detecting the position of the shock transition, and also it probably offers the best means of detecting the transition between solar magnetic field and interstellar magnetic field since the solar plasma characteristics at this interface are likely to be such that it is difficult to detect the plasma at all. Electric field probes of the type flown on recent Pioneer spacecraft might also provide a useful means of detecting the shock transition as well as indicating the general nature of the noise in the plasma.

3.4 COSMIC RAYS

Observations of the behavior of the low energy end of the cosmic ray spectrum (i.e., particle energies $\lesssim$ 300 Mev/Nucleon) will provide some of the most important information that can be derived from a deep space probe. Such observations will establish the interstellar spectrum of cosmic rays which is at present completely unknown at these low energies. The spectra of the various components of the cosmic radiation other than protons (i.e., e^+, e^-, He^3, He^4, Li, Be, B, C, N, O, Ne, F, Si, Fe, etc.), if they can be measured will tell us a great deal more than we know at present about the origin of the particles, and also help us to understand the nature of solar modulation (Ref. 20). The problem of the cosmic ray gradient in the solar system will also be solved on this mission provided one or more spacecraft equipped with an identical set of detectors is flown at the same time in the inner solar system. By learning about the radial gradient and knowing the unmodulated cosmic ray spectrum, we should be able to finally resolve the modulation problem.

It has been suggested that some of the low energy cosmic rays seen near the earth are of solar origin (Ref. 21). We should be able to tell if this is the case by watching these particles disappear as the spacecraft moves away from the sun, and be replaced by a different component of galactic origin. It has also been suggested that low energy cosmic rays might be accelerated at the shock transition or in the disturbed region beyond; a genuine interstellar probe which penetrates as far as the interstellar medium beyond the solar wind region should give an immediate answer to this question. Finally it is clear that some very interesting information will be gained concerning transient events, such as Forbush decreases, and solar cosmic ray events.

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