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A PLASMA WAVE INSTRUMENT FOR THE OUTER PLANETS GRAND TOUR MISSIONS*

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The instrument presently being studied by the Plasma Wave Team will measure electric and magnetic wave components over the frequency range 1 Hz to 200,000 Hz. In this report we discuss the science objectives and provide a brief description of the instrumentation.

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INTRODUCTION

We are concerned with the measurements of local plasma waves in the distant solar wind, in the plasma environments of the outer planets and satellites, at the heliosphere boundary, and in the interstellar medium. The proposed equipment can also be used to carry out VLF-ELF astronomy surveys of the outer planets. Moreover, as the TOPS spacecraft travel outward, the local wave cutoff frequency will steadily decrease so that it may be possible to detect radiation from distant sources beyond the solar system in the unexplored VLF-ELF spectral range. Thus, this experiment can contribute to all the major scientific areas of the missions, namely, Planetary, the Plasma Environment, and Interplanetary, including Interstellar.

The plasma wave instrument under consideration consists of an electric dipole, a magnetic search coil, a loop antenna, and electronic processing equipment. We intend to measure both electric and magnetic wave components over the frequency range 1 Hz to 200 kHz. The sensitivity will be high enough so that interplanetary shocks and other discontinuities will be detected even in the very dilute and cool solar wind beyond Pluto, and the dynamic range will be wide enough so that the intense emissions from the plasma environments of the outer planets (new forms of bow shock noise, local magnetospheric plasma waves, VLF emissions radiated by trapped particles, lightning whistlers, etc.) can be analyzed in detail.

Wave diagnostics are particularly well suited for the Outer Planets Missions because the wave intensity generally varies logarithmically as disturbances are encountered. In the distant solar wind the plasma density and magnetic field strength are extremely small, and it will be difficult to measure accurately small (linear) changes in plasma flow speed and density or field magnitude and direction. However, the wave experiment should readily detect local disturbances (e.g., a galactic boundary shock) even in this very dilute plasma. The feasibility of this type of instrument and the scientific value of the results obtained has been amply demonstrated near 1.0 AU by similar experiments on Pioneer, OGO, and IMP spacecraft. The forthcoming Helios probes will carry wave diagnostics close to the sun, and the TOPS payload can provide important new information in the outer solar system.

The sensors require boom mounting, and a modest EMC program is desirable. The use of RTG's simplifies this task because solar panels generally introduce significant noise problems.

SCIENCE OBJECTIVES

As the solar wind flows past the orbit of the earth into the outer solar system its properties will change, perhaps in unexpected and dramatic ways. In any attempt to understand the changing properties of the solar wind it is essential to understand the dynamic processes responsible. Both temperature and waves represent the important internal energies of a collisionless plasma. Unlike a neutral gas, the plasma cannot be fully understood without knowledge of the waves that are present. The extent to which the various wave modes are excited and their effect in exchanging energy between different populations of particles constitute the subject of plasma turbulence.

This collisionless solar wind also strongly controls the environment of any planet or satellite and the streaming plasma provides a major source of energy, momentum, and particles. However, the mechanism for interaction of the very dilute wind with the atmosphere or magnetosphere of a planet or satellite does not generally involve simple particle-particle collisions. Instead, single particles scatter from groups organized in the form of plasma waves, and the wave-particle interactions govern the interface regions.

Although many features of distant solar wind flow are not known, we can compute the anticipated wave frequencies and scale lengths that will be encountered during the Outer Planet Missions. Some results are collected in Table 1 and Figure 1, and the calculations therefore describe the characteristic properties of the streaming plasma impinging on each of the outer planets(1,2). These tabulations have been used to design our experiment and they also provide a framework for summarizing the detailed science objectives.

Table 1

Obstacle	Physical Radius (km)	Distance from Sun (AU)	N (cm^{-3})	T (°K)	B (γ)	ψ	Debye Length	$\frac{c}{\omega_p^+}$	$r_+ \equiv \frac{A_+}{\Omega_c}$
Earth	6,378	1	5	5×10^4	5	45°	6.9m	103 km	50 km
Mars	3,380	1.524	2.1	3.3×10^4	2.88	58°	8.6m	157 km	70 km
Jupiter	71,351	5.2	0.185	9.8×10^3	0.69	79°	16m	535 km	160 km
Saturn	60,400	9.54	0.055	5.25×10^3	0.375	84°	21m	980 km	216 km
Uranus	23,800	19.18	0.018	2.6×10^3	0.187	87°	26m	1,970 km	308 km
Neptune	22,200	30.07	0.006	1.6×10^3	0.12	88°	37m	3,100 km	384 km
Pluto	3,000	39.44	0.003	1.3×10^3	0.09	89°	45m	4,050 km	440 km
Heliopause		50(?)	0.002	10^3	0.07	89°	49m	5,140 km	495 km

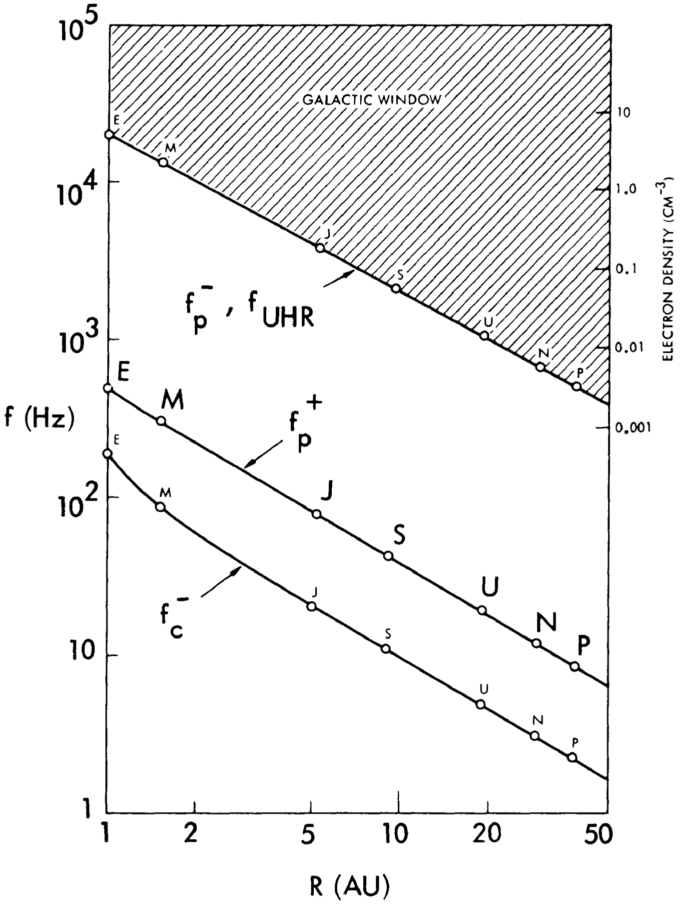

Figure 1

Interaction of Planets and Satellites with the Solar Wind

The Jovian planets are physically very large, but it is likely that they are still dwarfed by their magnetosphere-shock-tail systems. There are two reasons for this: a) the distant solar wind pressure that confines the planetary field is greatly reduced; b) in the case of Jupiter, and perhaps other outer planets, the intrinsic magnetic field is very large in comparison with that of Earth. It has been estimated(2) that the subsolar magnetopause for Jupiter is at 53 R_J, with the shock at $r = 74\ R_J > 5 \times 10^6$ km. In Fig. 2 we sketch a possible configuration of the Jovian magnetosphere based on this estimate, and it can be seen that the tail might be expected to extend over 1 AU downstream. This means that the planetary encounter is of extremely long duration as far as plasma wave measurements are concerned. The time between first encounter with the shock and closest approach to Jupiter may be as long as 1.5 days, and the exit across the tail will also be lengthy. Thus the Plasma Wave Experiment will have an excellent opportunity to monitor a large number of distinct planetary phenomena.

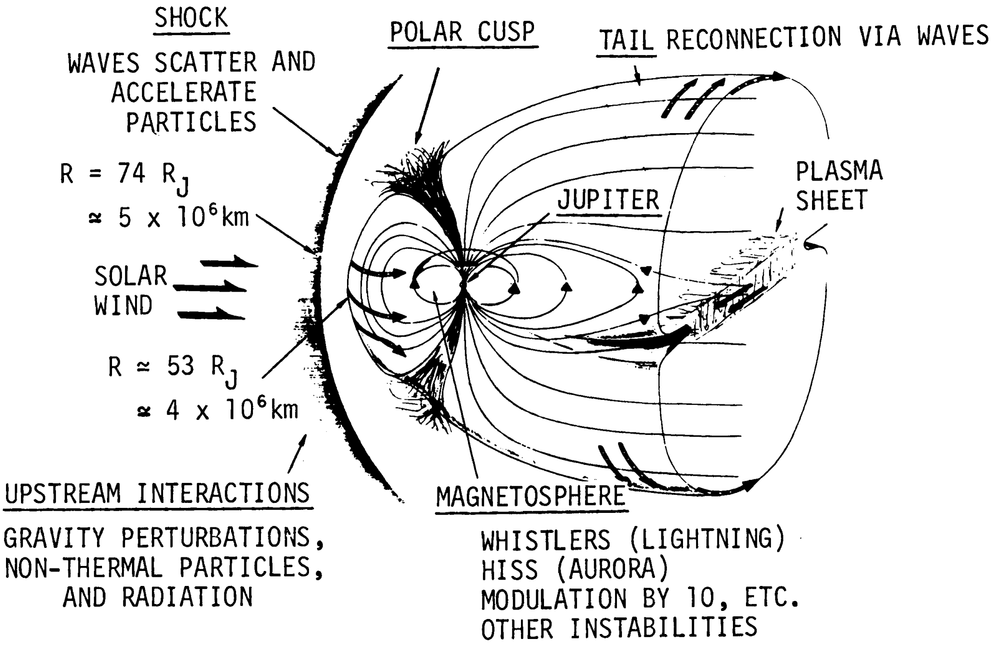

Figure 2

- If the planet has a Jovian-type magnetosphere then we will determine what wave-particle interactions produce the shock, give rise to viscous drag, allow particle diffusion into the magnetosphere, and cause local acceleration and precipitation. Since the solar wind itself will change drastically as R increases, it is expected that new forms of interactions will be present at the outer planets.

- For weakly-magnetized planets or satellites, we will determine if the solar wind flows directly into the upper atmosphere or if wave-particle interactions generate an ionization layer and a detached shock. The oncoming wind can supply particles and thermal energy, and can provide important atmospheric loss mechanisms. Thus this study bears directly on the analysis of the dynamics of the planetary atmosphere.

- If a large planetary magnetic tail is formed, local wave excitation will determine the tail stability and the reconnection rate. Waves produce an effective (turbulent) electrical conductivity that leads to field annihilation. This is significant because a Jovian tail, for example, could extend more than 1 AU behind the planet, and thus Jupiter (or the other major planets) could influence a vast region of interplanetary space. However, wave-particle interactions control the reconnection rate and these extended planetary magnetic tails could differ greatly from that of Earth because different plasma instabilities are operative.

- Completely new kinds of interactions are likely at Uranus and Pluto. A Uranus magnetic dipole moment would very likely point toward the oncoming wind(3), while the scale size of Pluto is unusually small in comparison with some characteristic wavelengths (see Table 1).

The Distant Solar Wind

When interplanetary investigations at 1 AU were started, the highest priority aims were to detect the existence of a continuous streaming wind and to determine the average properties. This task has largely been accomplished at 1 AU, and new emphasis on solar wind studies beyond 1 AU must be directed to the analysis of <u>how</u> the basic plasma properties change with distance. This means that we must study the microscopic changes and determine the causes of the gradients. No satisfactory understanding of the distant wind will be achieved without knowledge of local wave-particle interactions(2).

Fortunately, this experimental study is quite feasible, although the distant wind is dilute and cool. The proposed plasma wave instrument will be able to detect and identify any reasonable wave-particle interactions out to at least 50 AU (see Figs. 5, 6 and the associated discussion).

Emissions from the Planets

We know that Jupiter is an intense source of high frequency electromagnetic (EM) waves. We have every reason to believe that intense local EM and electrostatic (ES), or space charge waves, will also be generated at many or all of the characteristic or resonant frequencies in the plasma environments of all the outer planets. Our wave experiment will allow this excitation to be detected and identified, and we should, for example, be able to determine which planets have auroral activity.

- One of the questions of great biological and atmospheric significance covers the possibility that lightning occurs in another planet. For planets with magnetospheres, we should be able to detect lightning signals as they propagate to the TOPS spacecraft in the whistler mode.

- Our local measurements of the plasma environments of the planetary satellites should provide important new information on the mechanism for modulation of radio emissions (e.g., by Io). It is frequently argued that the satellite generates local instabilities that lead to modulation of the decametric emission(4), and it seems highly unlikely that unambiguous answers will be obtained by TOPS unless simultaneous local plasma wave measurements are made. Moreover, TOPS will be capable of flying very near other satellites of Jupiter (Ganymede, Callisto) and Saturn (Titan, Iapetus), and it should be possible to investigate other forms of satellite-stimulated plasma instabilities.

- If Uranus does have a planetary field, the topology of the magnetosphere(3) will be so distinct from that of Earth or Jupiter that completely new categories of emissions are likely to be found.

The Heliosphere Boundary

If the solar wind terminates in a shock transition, the plasma wave experiment will provide a clear and unambiguous identification of the event. Plasma wave experiments have already detected fast-mode collisionless interplanetary shocks for a wide range of Mach numbers, and detection of enhanced wave levels has also been used to identify slow-mode and reverse shocks in the solar wind.

Even if the heliopause boundary is thick and there is no shock transition(5), there will be a region in which the solar system magnetic field merges with the interstellar field. Merging requires dissipation, and wave-particle interactions provide the only plausible dissipation source in this very dilute plasma.

INSTRUMENTATION

General Description

We propose to measure AC electric and magnetic field levels over the frequency range 1 Hz to 200 kHz. A single electric dipole will be employed, and a permeable core search coil, together with an air core loop antenna will be used for the magnetic field sensors. The signals will be processed in several ways. A multichannel spectrum analyzer for E and an identical one for B will give continuous coverage with high temporal resolution. A narrowband sweeping receiver that can be commanded to examine E or B signals will provide high frequency resolution and greatly enhanced sensitivity. A waveform capture channel will utilize the TOPS core storage to record short segments of the entire waveform for the most energetic transients.

The sensors are to be mounted on the plasma wave boom (included in the baseline TOPS spacecraft) and the mounting is shown in Fig. 3. The electric field dipole is 24" long, and it consists of a pair of spherical wire grids (4" diameter) mounted on ends of fiberglass rods. The magnetic search coil-preamplifier package is also 24" long. Both permeable core and air core coils are proposed, since they are mutually complementary. The former has superior sensitivity at frequencies below 5 to 10 kHz, and the sensitivity of the latter is superior at higher frequencies.

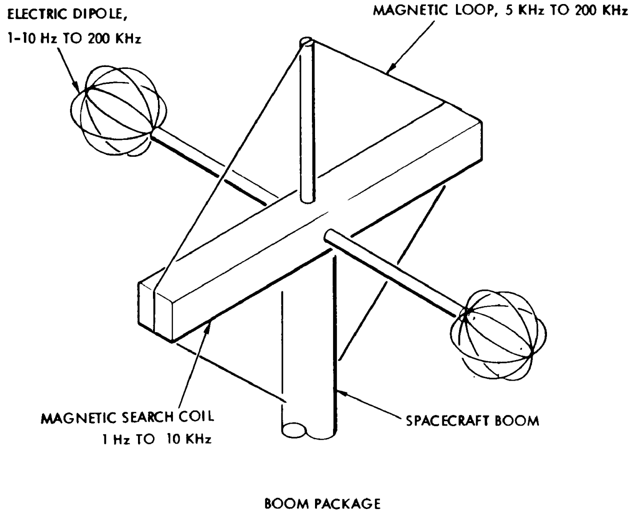

Figure 3

The block diagram is shown in Fig. 4. Each multichannel spectrum analyzer is an array of bandpass filter-amplifier-compressor channels. The output to be telemetered from each channel is a measure of the highest amplitude detected since the previous telemetry sampling. The narrowband sweeping receiver will provide supplementary spectral information from either the E or B sensors, upon command. The scan will necessarily be slow because the amplifier must have time to settle at the selected center frequency, but the amplitude sensitivity and frequency resolution will be very high.

The waveform sampling mode of operation will be used to capture in SDS memory a digitized two-second snapshot of E or B field waveforms having frequency components up to 1000 kHz. The most intense waveform will be telemetered to Earth as frequently as possible (the intervals are dependent on the TOPS telemetry rate), and the entire signal will be available for audio-frequency analysis. This channel will provide a dramatic form of "sound track" from the outer planets in the sense that we will literally be able to listen to emissions from these very distant objects.

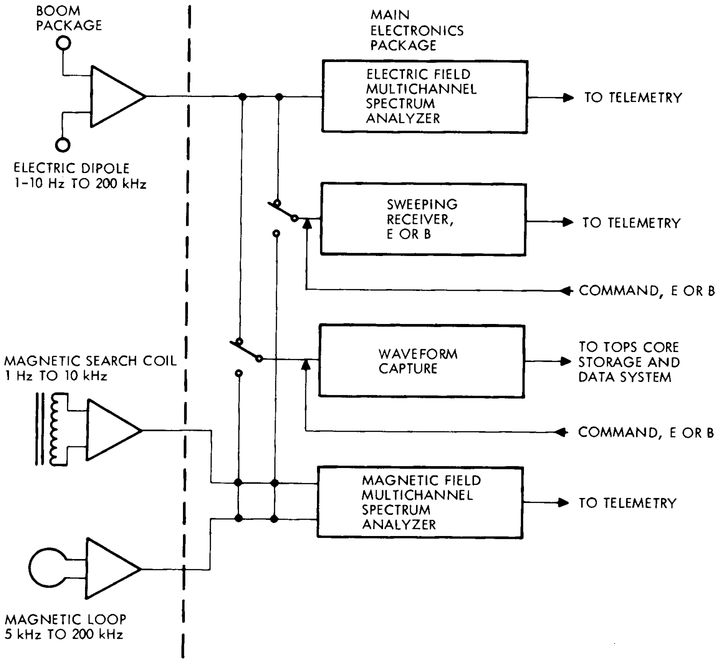

Figure 4

Sensitivity and Dynamic Range

As shown in Table 1, the distant solar wind is a plasma with very low temperature and density, and a small dc magnetic field. However, in various regions near the Earth, plasma wave experimenters have already successfully measured wave characteristics in regions with grossly similar properties. The ionosphere has $T < 10^{3}$°K, and the plasma trough and distant tail have $N \lesssim 10^{-2} - 10^{-3}$ particles/cm^3. At interplanetary field nulls and in the tail neutral sheet we have found intense waves when the dc field strength is less than 100 milligamma. It is true that no one of these near-earth regions has a simultaneous combination of small T, N, and B, so that they are not immediately representative of the distant solar wind. However, we have surveyed regions with large variations in the individual plasma parameters, and we are confident that we can scale the anticipated wave amplitudes for a situation in which N, T, and B are all small at the same time.

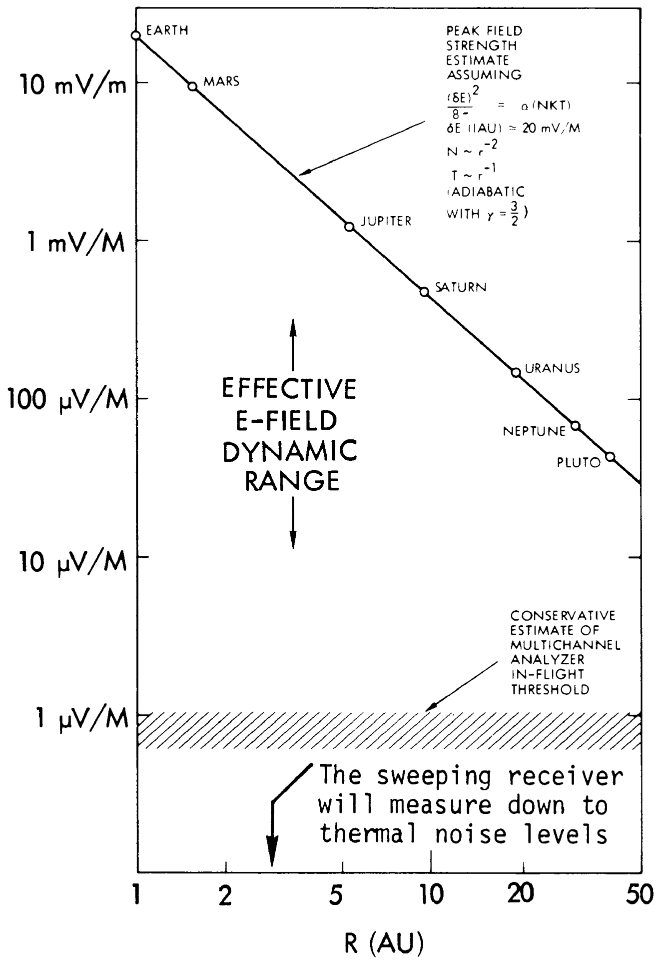

Figure 5

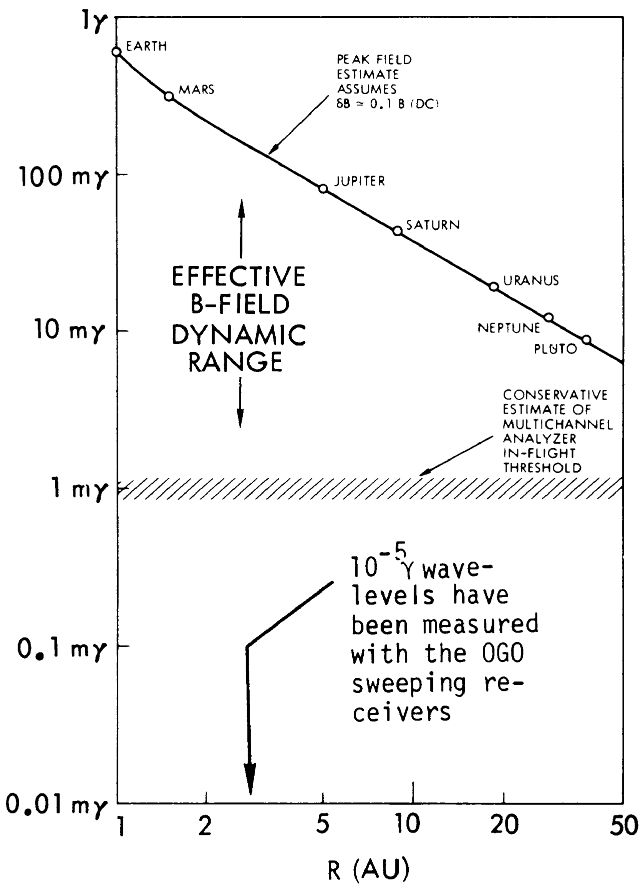

Figure 6

The most crucial measurements are those made in the distant solar wind and at the bow shock crossings for the outer planets. We assume that typical 1 AU values [$\delta E(\max) \simeq 20$ millivolts/meter and $\delta B(\max) \simeq 0.1\, B(dc)$] can be scaled using $[\delta E(R)^2]/8\pi = \alpha[N(R)\kappa T(R)]$, where α is a constant, and $\delta B(R) \simeq 0.1\, B_{dc}(R)$. In this case Figs. 5, 6 show how $\delta E(\max)$ and $\delta B(\max)$ vary with R. It can be seen that even for R = 50 AU, with conservative broadband spacecraft noise level estimates, the relatively insensitive multichannel analyzers should still provide an order of magnitude in effective dynamic range. For the sweeping receiver, even greater sensitivity is expected.

We conclude that presently developed and tested sensors and circuitry have more than adequate sensitivity to detect weak shocks and other local disturbances in the distant solar wind. Much stronger signals will also be found at planetary encounters, and the overall dynamic range will be adequate so that the characteristics of these signals can also be measured.

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