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INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part II

II-5-8. Direct Observations of the Interplanetary Plasma*

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In this paper we present some preliminary results obtained with the earth satellite Explorer X (1961 kappa). This satellite was designed to measure properties of the magnetic field and of the ionized gas (plasma) over a region starting close to the earth and extending to a point where effects of the earth's magnetic field should be negligible. The orbit was very eccentric (apogee 240,000 km; perigee 300 km), and the experiments included two types of magnetometers (Goddard Space Flight Center) and a plasma probe (Massachusetts Institute of Technology). Results of the magnetometer experiments have been presented elsewhere at this meeting and in what follows we shall be mainly concerned with the plasma measurements. However it will become evident that the two sets of data should be considered together, and for this reason Dr. Heppner has presented some of the striking correlations between the magnetic field data and the plasma data at the end of this paper.

When the plasma experiments for Explorer X were planned, there were no direct experimental observations of the plasma. Indirect observations and various theoretical treatments resulted in greatly divergent views of the situation in the interplanetary region[1,2]. For this reason we attempted to design an experiment which could explore the appropriate physical quantities over a wide range. In particular, the experiment was planned to measure the flux of plasma protons, and give a crude estimate of the energy, spatial, and temporal distributions. Protons were chosen because photoelectrons complicate the measurement of plasma electrons. One can derive the bulk velocity of the plasma and the number density of charged particles from knowledge of the flux and energy distribution of the protons since the proton component carries most of the kinetic energy and determines the bulk motion of the plasma.

Instrumentation

Before discussing the experimental results it is necessary to understand the operation of the probe itself in some detail. The instrument is basically a Faraday cup mounted in the skin of the space probe. A measurement of the proton current could, in principle, be made by covering a hole in the outer conducting skin with a grid, and placing behind it a collector plate kept sufficiently negative with respect to the grid to repel the plasma electrons.

With this arrangement, the protons would flow to the collector, the electrons would flow to the grid or to other parts of the vehicle body, and a net positive current would be observed at the output of the collector. However, this measurement is not possible when the cup faces the sun, certainly an interesting direction for plasma observations, for then there is a photoelectric current of the order of 10^{-8} amp/cm^2 emitted from the collector,[3] with the same sign as that of the proton current.

Although this photocurrent can be suppressed by placing another grid in front of the collector and maintaining it a few tens of volts negative with respect to the collector, there remains a reverse photo-current produced by light reflected from the collec-

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tor onto this suppressor grid. Photoelectrons emitted from the suppressor grid travel to the collector, and this current subtracts from the proton current. Since the reverse current can be as much as 1/10 of the direct photo-current, it would prevent the measurement of proton currents over most of the range of interest. This difficulty was overcome by modulating the plasma current without modulating the reverse photoelectric current. Fig. 1 illustrates the probe: Grid 4 was kept at the potential of the vehicle skin ("ground"); grid 3 was connected to a 1.5 kc positive square wave voltage which varied between ground and E_0, thus modulating the proton flux. Grid 2 was at vehicle

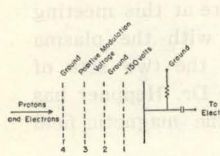

Fig. 1. Grid arrangement in cup.

potential and served as an electrostatic shield between the modulating grid and the collector. Grid 1 was maintained about 150 volts negative with respect to the collector, which was also at the vehicle potential.

When the voltage on the modulating grid was zero (the vehicle potential), the protons reached the collector, and the low-energy electrons were repelled by the negative potential on grid 1. When the modulating voltage was greater than the energy of the incoming protons, the protons could not pass grid 3; the electrons were still repelled by grid 1 since of course they acquired no net energy from grid 3. Thus, there was a pulsating current at the collector caused by the alternate arrival and non-arrival of the plasma protons. The photoelectrons from the collector and from grid 1 were not influenced by the modulating voltage because they were shielded from it by grid 2, and therefore the photocurrent gave a direct but non pulsating signal. The signal from the collector was accoupled to a high-gain, narrow band amplifier whose output therefore depended only on the pulsating (proton) component.

The flux, ϕ, of protons reaching the collector is given by

$$\phi = i/Ae \tag{1}$$

where i is the pulsating component of the collector current, A is the effective area of the collector, and e is the proton charge.

For the instrument flown in Explorer X the minimum detectable current was about 2×10^{-11} amps and the effective area of the collector (for normal incidence) was approximately 25 cm^2. Thus the minimum detectable particle flux was less than 5×10^{6} cm^{-2} sec^{-1}; the largest observable flux, determined by saturation of the amplifier, was about 5×10^{10} cm^{-2} sec^{-1}.

Assuming that the thermal velocities of the plasma particles can be neglected, the flux for normal incidence is related to the bulk velocity V of the plasma by

$$\phi = nV \tag{2}$$

where n is the number density of protons. Thus it is also necessary to measure the velocity or energy of the protons in order to determine the density.

The energy of the protons was determined by varying the amplitude of the square wave modulating voltage E_0. For a given value of E_0, the modulated current to the collector resulted from those protons with energies (in ev) less than E_0. When E_0 was less than the proton energy, protons were not stopped at grid 3, and there would then be no modulated signal at the collector. As successively higher modulation voltages were applied, the proton energy was given by that voltage at which the modulated signal first appeared. This would be strictly true, of course, only if the probe were facing in the direction of motion of the plasma. If the protons were incident at an angle θ to the axis of the probe, the value of E_0 required for modulation would be smaller than the proton energy by a factor ($\cos^2\theta$), since the component of the proton velocity in the direction of the modulating electric field is proportional to $\cos\theta$.

Six values of E_0 were used in this experiment. A 5-second measurement was made about every 2.5 minutes, and a different modulation voltage, E_0, was applied to grid 3 for each measurement. Actual values of E_0 in volts were: 2300, 800, 250, 80, 20 and 5. In addition the complete cycle included two measurements with $E_0=0$; thus it required about 20 minutes for a complete measurement cycle.

The response of the probe just described has been studied using a small linear accelerator to provide protons of known energy, and an ultra-violet source to produce the expected photocurrent. The tests on photoeffects have indicated that no modulation of the photocurrent would occur once outgassing of the vehicle was complete. This laboratory results was consistent with the results from Explorer X.

Experimental conditions for the measurements

The satellite was launched at 1517 U.T., March 25, 1961. The useful duration of the flight was limited by battery life to approximately 60 hours; this was also roughly the time to reach apogee. The satellite was spin-stabilized about an axis perpendicular to the axis (direction of view) of the plasma probe. Its rotation period was very nearly 548 milli-seconds for most of the flight and there was no precessional motion.

The response of the plasma probe is maximum when the direction of the incident particles lies along its axis of symmetry (the normal to the cup) and falls to zero at about 60 degrees off axis. Thus as the vehicle rotated, the plasma probe scanned a "window" of about 60 degrees angular width on each side of the plane perpendicular to the spin axis.

For most of the data we will be interested in the spatial orientation of the vehicle beyond 20 earth radii (R_e). The approximate geometry for this case is shown in Fig. 2. Looking down on the north pole of the

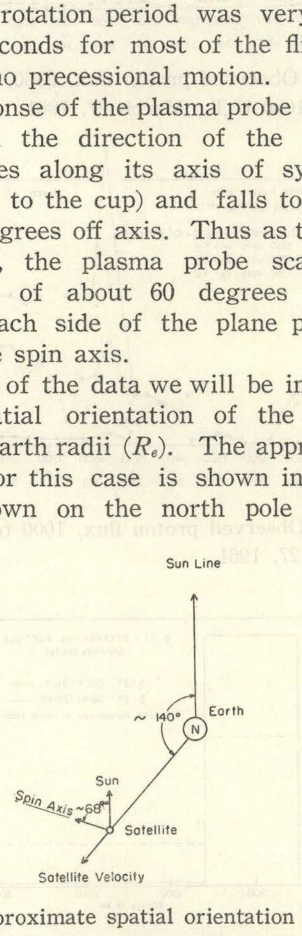

Fig. 2. Approximate spatial orientation of vehicle, looking down on the earth's north pole.

earth, one sees that the vehicle-earth line is located counterclockwise about 140 degrees from the sun-earth line. The spin axis lies approximately in the plane defined by these two directions (actually it is tipped down 15°), and makes an angle of about 68° with the sun line.

The phase of the plasma probe signal with respect to the sun was recorded for each plasma measurement by an optical aspect sensor.[4]

Summary of experimental results and conclusions

The results of the experiment can be summarized as follows:

1. Between approximately 1.3 R_e and 2.9 R_e a signal was present at all energy modulation levels. The signal was strongly modulated by the spin of the vehicle and certainly arose from the presence of a relatively cold stationary plasma in this region. No detailed analysis of these data has been made.
2. Between 2.9 R_e and 21.5 R_e no signal was observed. The absence of a detectable signal during this period confirms the results of the laboratory tests on the photoelectric effect.
3. At about 21.5 R_e a flux of positive particles of about 4×10^8 cm^{-2} sec^{-1} at a mean energy of about 500 ev was observed for the first time. During the remainder of the flight, these particles were observed most of the time. However, there were large fluctuations in intensity between the minimum detectable value and about 10^9 cm^{-2} sec^{-1}. The flux shows a striking correlation with the magnetic field; roughly speaking, the presence of plasma coincided with a relatively weak magnetic field which fluctuated in magnitude and direction; the absence of plasma was associated with a relatively strong steady field.
4. The energy spectrum of the particles was peaked at about 500 ev, but the shape of the spectrum showed large variations. Combining the flux and energy measurements, the typical number densities range from 6 to 20 protons per cm^3.

5. The particle flux showed a periodic variation because of the rotation of the vehicle. Maximum intensity was observed when the angle between the axis of the probe and the sun-vehicle line reached its minimum value (about 20°) i.e., when the probe faced as nearly toward the sun as was possible. The position of the maximum and the "shape" of the signal show that the plasma arrived from the general direction of the sun.

Discussion of the experimental data and results

We now consider the experimental data on which these conclusions are based. Figs. 3, 4, 5 and 6 show the particle flux as a function of time and of distance from the center of the earth. The variations of intensity which were mentioned in (3) above are plainly evident. Different energy ranges are indicated as noted in the caption, and it can be seen that the spectrum appears to shift in energy. It must, however, be remarked that the data presented in these graphs are in a very preliminary form. Some of the points are subject to much greater errors than others, mainly because of noise in the received telemetry signal. Since it is probable that the accuracy can be greatly improved, it has seemed unprofitable to evaluate errors for the individual points.

An interesting feature of the record is evident in Fig. 6. Beginning at about 1512 U.T. on March 27, the flux increased markedly and the energy spectrum shifted toward higher energy. The shift of the

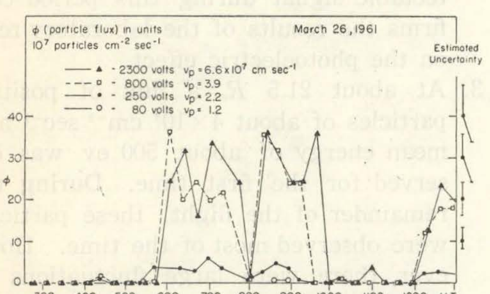

Fig. 3. Observed proton flux, 0300 to 1300 U.T., March 26, 1961.

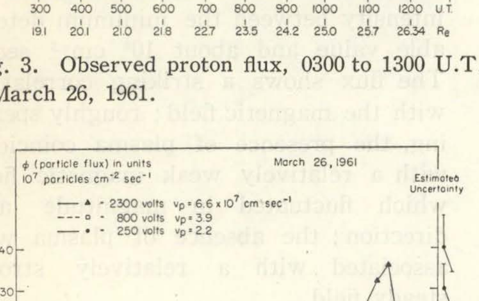

Fig. 4. Observed proton flux, 1300 to 2350 U.T., March 26, 1961.

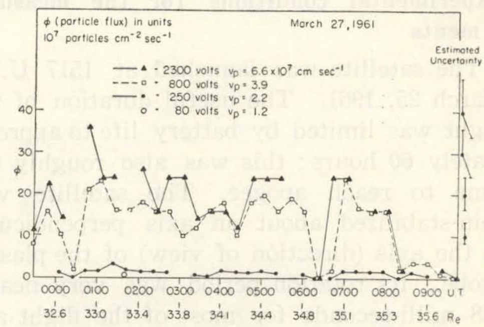

Fig. 5. Observed proton flux, 2350, U.T., March 26 to 1000 U.T., March 27, 1961.

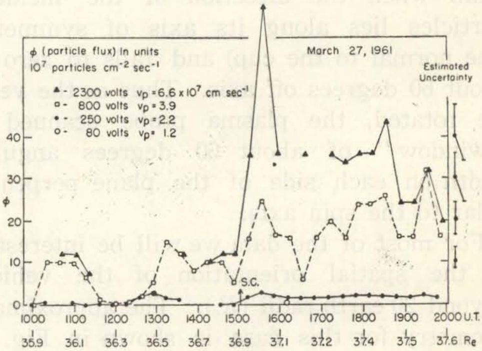

Fig. 6. Observed proton flux, 1000 to 2000 U.T., March 27, 1961.

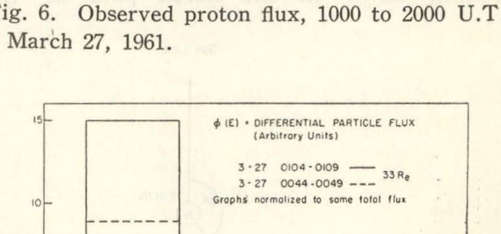

Fig. 7. Typical proton energy spectra.

energy spectrum is confirmed by the change in the shape of the observed signal; this point is considered below. This change followed a sudden magnetic storm commencement observed on the earth at 1503 U.T. on March 27. Typical energy spectra are shown in Fig. 7, and an example of the shifted spectrum for the period following 1512 U.T. on March 27 is shown in Fig. 8.

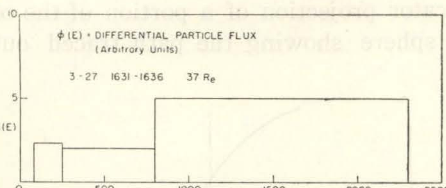

Fig. 8. Energy spectrum of protons, 1631-1636, U.T., March 27, 1961.

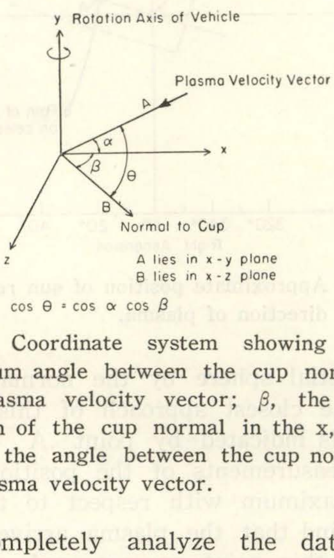

Fig. 9. Coordinate system showing α, the minimum angle between the cup normal and the plasma velocity vector; β, the angular position of the cup normal in the x, z-plane; and θ, the angle between the cup normal and the plasma velocity vector.

To completely analyze the data it is necessary to know the angular response of of the probe in detail. Consider the coordinate system shown in Fig. 9: The cup axis lies in the x-z plane and rotates about the y-axis; its position in the x-z plane is measured by the angle β. The plasma velocity vector lies in the x-y plane, and makes an angle α with the x-axis. The angle between the cup axis and the plasma velocity vector is θ. In evaluating the response as a function of β three principle effects must be considered. First, there is a $\cos\theta$ correction for the projected area in the beam direction. Second, the collector is not infinite in extent but is approximately the size of the front opening of the probe. Thus the circular image of the front window moves across the circular collector as θ increases and the effective collector area is the region where the collector and image overlap. Finally, the transmission of the grid structure depends on θ.

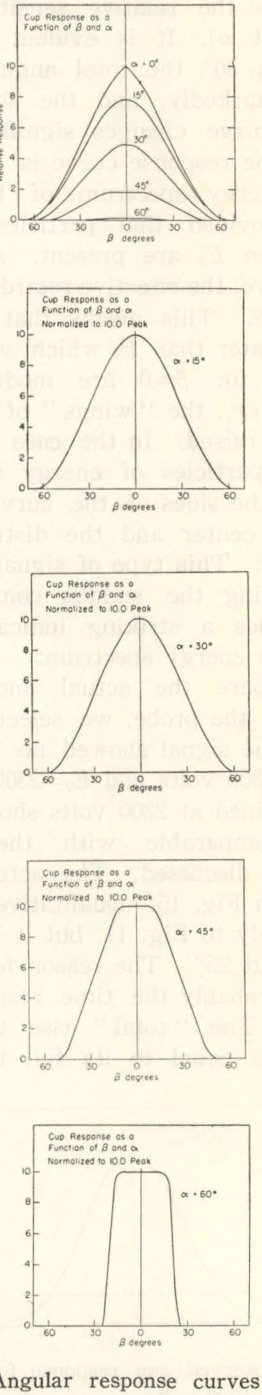

Fig. 10-14. Angular response curves of cup for different values of α.

The angular response curves for different values of α are shown in Fig. 10 through Fig. 14. In computing these functions, a parallel monoenergetic beam of particles with energy less than the modulating voltage E_0 was assumed, and the curves were normalized to the same peak height (Fig. 10 also shows the relative sensitivities as a function of α). It is evident that for α larger than 30° the total angular width is reduced markedly, and the shape of the response curve changes significantly. The shape of the response curve is also affected by the energy spectrum of the incident plasma provided that particles of energy greater than E_0 are present. As we mentioned above, the effective retarding potential is $E_0 \cos^{-2}\theta$. This means that particles of energy greater than E_0 which would not be modulated for $\beta=0$ are modulated as β increases; *i.e.*, the "wings" of the response curves are raised. In the case where there are many particles of energy close to but above E_0, the sides of the curve are raised above the center and the distribution has two humps. This type of signal was observed following the sudden commencement, and provides a striking indication of the shift in the energy spectrum.

To compare the actual and predicted response of the probe, we selected a region in which the signal showed no increase between $E_0=800$ volts and $E_0=2300$ volts. The signal obtained at 2300 volts should then be directly comparable with the computed curves just discussed. The actual response is shown in Fig. 15. Qualitatively it corresponds closely to Fig. 11, but it is somewhat wider, about 25°. The reason for the extra width is probably the time response of the amplifier. The "total" rise time of the amplifier is equal to its fall time and is equivalent to about 25°.

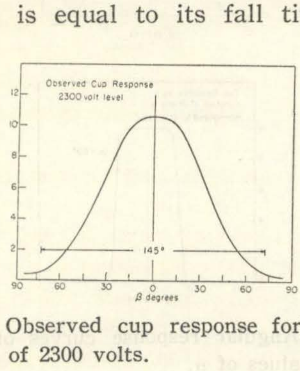

Fig. 15. Observed cup response for modulation voltage of 2300 volts.

As discussed above, our observations are consistent with the assumption that the particles entered the cup in a parallel stream. Our data enable us to give angular limits on the apparent location of the source of the plasma. The spin axis of the vehicle had a declination of -15° and right ascension of 289°, and the cup looked out in directions perpendicular to the spin axis. Fig. 16 is a mercator projection of a portion of the celestial sphere showing the path traced out on the celestial sphere by the normal to the cup. The closest approach of this line to the sun is indicated by point .A We have made measurements of the position of the signal maximum with respect to the point A, and find that the plasma arrives within ±10° of this point as measured along the path of the cup normal. The accuracy of this measurement should be improved by subsequent analysis to ±5°.

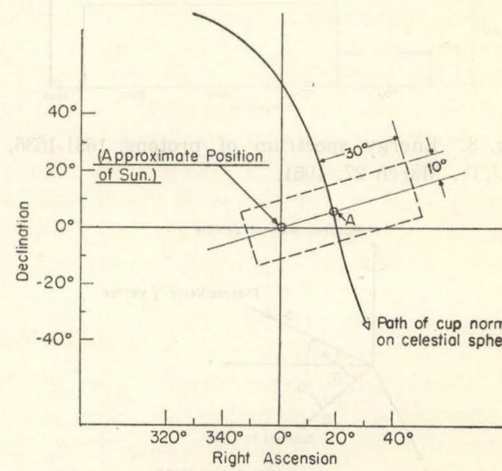

Fig. 16. Approximate position of sun relative to arrival direction of plasma.

The shape of the signal enables us to estimate roughly the arrival of the plasma in a plane perpendicular to the plane swept out by the cup normal. At present we estimate that this angle was within 30° of the point A. The signal shape definitely excludes much larger angles, but is relatively insensitive to particular choices of angles less than 30°. The particle fluxes reported above were computed assuming that the plasma entered the cup at a minimum angle of 30°. This correction increases the flux by a factor of 1.4 over what would be calculated on the assumption that the plasma entered normally.

Measurements of particle fluxes have also been made with ion traps carried by Russian space probes[5]. The most extensive data have been reported from Lunik II which encountered a flux of positive particles beyond $14R_e$. The measured flux varied between 2×10^8 and 10^9 cm^{-2} sec^{-1} and persisted until the capsule hit the moon. No information concerning the directionality of the particles or their energy spectrum was reported.

It is our understanding that the orbit of Lunik II essentially overlaps that of Explorer X. A comparison of the results is interesting: The measured fluxes are practically identical, and the results from Lunik II show that the positive flux persists beyond the region of the Explorer X measurements.

In conclusion, the authors wish to acknowledge the generous assistance and cooperation given to them by personnel of the Goddard Space Flight Center. The reduction of experimental data has been performed mainly by Mr. R. Talbot and Mr. D. Gudehus.

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Disscussions (II-5-7 and 8)

Rossi, B.: If I may, before opening the discussion, I would like to spend several minutes to be checked by the vice-chairman to point out a kind of general physical features which seem to emerge from the experiments reported by Dr. Heppner and Dr. Bridge. (The contents of the opening speech are similar with those in II-6 and the separate manuscript was not provided.)

Sonett, C. P.: Would you consider that the conditions in interplanetary space during this time were representative of quiet interplanetary times in view of the disturbances which Heppner showed on a slide?

Heppner, J. P.: From observatory magnetograms, the magnetic field at low and middle latitudes at the earth's surface was quiet for at least a week preceding the flight and remained that may until the time of the sudden commencement. There were the usual magnetic bays in the auroral zone but their intensity was in general weak to moderate.

Sonett: Large disturbances were noted for some two to four hours prior to the SC at auroral stations. Does this not represent the possibility of disturbed interplanetary conditions?

Heppner: The activity in the auroral zone prior to the sudden commencement was typical of an average night in which one gets a $+\Delta H$ disturbance in the pre-midnight hours and a $-\Delta H$ disturbance in the post midnight hours. The disturbances prior to the SC were not large relative to average conditions in the auroral zone.

Dungey, J. W.: Could the zero reading in the quiet regions be interpreted as static plasma?

Bridge, H. S.: Yes, provided that the flux is less than 5×10^6 particles cm^{-2} sec^{-1}. Since the vehicle velocity is low, a flux of this order might correspond to a number density of about 50 particles cm^{-3}. The difficulty is to reconcile such static regions with adjacent regions of higher velocity.

Parker, E.N.: In which of the two types of region—plasma predominance and field predominance—do you see the "garden hose" field?

Heppner: The field fits the "garden hose" model the best when it is the most intense and stable and plasma is not detected.

Biermann, L.: What is the angle itself between the mass velocity of the plasma, the direction of the magnetic field and the radius vector to the sun?

Heppner: The magnetic field direction during the most stable periods was essentially that of a radial field with a spiral (or "garden hose") angle of 25° to 55°. During the unstable periods the angles vary considerably.

Dessler, A. J.: Can you comment on whether or not your measurements are consistent with the STL results that have been interpreted as a quiet day ring current?

Heppner: As stated in our presentation there is evidence that a field source exists in the region of the slot or in the inner part of the outer radiation belt. This is much closer to the earth than the ring currents reported by the STL experimenters. We do not see evidence for a ring current beyond 3 *Re* along our trajectory, that is, beyond the shell which would include the maximum of the outer belt at the equator. At distances greater than 8 *Re* along the trajectory the field deviates from the theoretical field and one might try to explain this as being caused by a ring at great distances, however, considering the agreement between measured and computed fields between 4 and 8 earth radii this would be difficult.

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INTERNATIONAL CONFERFNCE ON COSMIC RAYS AND THE EARTH STORM Part II

II-5-9. Some Theoretical Aspects of Interplanetary Plasma

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I would like to discuss some aspects of the interplanetary plasma. These remarks are based on some work which has been done in recent years by Biermann and myself[1] and also by some other colleagues of our Institute.

In connection with the comets which have ionized tails, Biermann[2] pointed out, early in the fifties, that the stationary interplanetary medium is identical with the corpuscular radiation of the sun and that the matter which has been seen sometimes by the zodiacal light should not be regarded in a static equilibrium. In recent years Parker[3] developed a hydrodynamical theory of this corpuscular of the sun which now is very often called the solar wind. He could show that such solar wind is a natural consequence of the conditions in the solar atmosphere. The first measurements from satellites and space probes confirm the above mentioned indications that the solar wind really exists.

Since the intensity and the velocity of the solar wind is determined by the physical states of the solar atmosphere, I would like to discuss first the conditions in these regions to indicate the source of the energy of the corpuscular radiation. In the second part of my talk I would like to mention some other observational evidence, especially those from comets which seem to be important for the understanding of the interplanetary plasma. Finally, some theoretical conclusions will be discussed.

The corpuscular radiation is the most important energy loss of the solar corona. Assuming a flux of about 10^9 ions/cm^{-2} sec^{-1} at one astronomical unit, which corresponds to about 20 ions cm^{-3} with velocity of about 500 km sec^{-1}, such a value gives an energy flux at the solar surface of about 10^5 ergs cm^{-2}