II-5. Interplanetary Plasma

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Journal of the Physical Society of Japan Vol. 17, Supplement A-II, 1962
International Conference on Cosmic Rays and the Earth Storm Part II

II-5-1. Some Aspects of the Internal Structure of a Solar Flare Plasma Cloud

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During the passage of Pioneer V through the plasma generated by the solar flare sequence of March 31–April 1, 1960, a null in the interplanetary magnetic field, having a scale of $\sim 3\times10^{10}$ cm, was noted. Arguments are presented to show the consistency of this event with various plasma-field configurations. On these bases, possible models of the interior of a solar flare plasma cloud are presented. Models having a neutral layer seem more plausible than those having isolated neutral points or field-free plasma inclusions.

Summaries of the information on the interplanetary magnetic field some millions of kilometers from the earth during March and April, 1960, and particularly during the storm of March 31–April 1, 1960, as obtained from the search coil magnetometer on Pioneer V, have been published[1,2]. We examine here a part of the interplanetary magnetic field data obtained during the flare and solar cosmic ray sequence of March 31 to April 1, 1960[1] which show a zero in the measured component of the field. For brevity, this note will deal with only a few of the arguments leading to an attempt to create a model field configuration. A more detailed description will be published elsewhere.

Fig. 1 shows each data point obtained on the transmission from the vehicle for 1246-1316 GMT on April 1. This transmission displays a minimum in which the measured field drops to a value in the neighborhood of the instrument threshold.

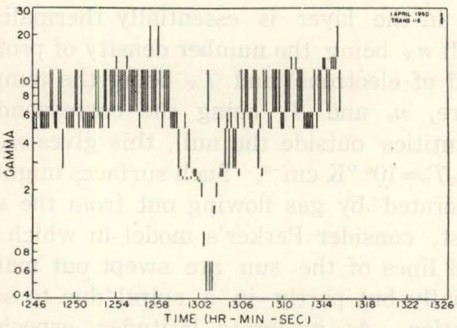

Fig. 1. Shown above is the field normal to the earth—sun line during the time discussed in the paper. The lengths of the vertical lines represent the uncertainty introduced by the digitalization and are not errors in the usual sense. A closer estimate of the field is available from the transition from one "window" to another, at which time the field must be at the switching point. The semi-logarithmic plot tends to emphasize the null. The null would be less dramatic if plotted on a linear scale.

What is observed is the component of the field normal to the spin axis of the vehicle, which at the time of interest is essentially the line to the sun. The direction of this normal component cannot be determined. During most of the transmission this component has a value of about 10γ but at 1303 it drops to 0.5–0.7γ, nearly the threshold sensitivity of the instrument, followed by a recovery to the original value. It is reasonable to question whether the recovery was indeed a return to the original field or whether there was a reversal of the field; either being consistent with the observations. Just at the minimum there is one data point that indicates momentary return to the field strength on the sides of the null. We believe that this data point is valid and is not due to noise in the system, but the structural features that it imposes on the models must be regarded as less certain than those supported by the remainder of the points. The width of the main null, between half power points, is about 5 minutes; the width of the isolated recovery is likely to be of the order of the 12 sec. interval between data transmissions. The 10γ basic field corresponds to a field energy density of 4×10^{-10} ergs cm^{-3} (or more if there is a component along the spin axis) and the decrease in energy density at the minimum is at least two orders of magnitude.

A second point of interest in this particular transmission is the wave phenomenon. These waves are probably unique to this transmission as other transmissions in the flare sequence are conspicuous by their unusually (compared to quiet sun times) steady values. The periods of these disturbances have an upper bound of some tens of seconds. It is possible that the longer periods are due to sporadic synchronism between data sampling (every 12 sec) and the wave period.*

Based upon the Forbush decrease seen by neutron monitors on earth, Fan *et al*[5] have timed the gas velocity to be some 2×10^8 cm/sec. Assuming that differential velocity in the direction of bulk plasma flow (radially outward from the sun) was small compared to this quantity, the scale of the minimum in the field, based on the 5 min. time interval between the 1/2 energy values is about 6×10^{10} cm provided that the Pioneer V spacecraft traversed the region in the direction of the field gradient. An oblique traversal would perhaps be more likely, thus reducing the scale to, perhaps, 3×10^{10} cm. It is probable that any local ordered plasma velocity was trivial compared to 2×10^8 cm/sec. Also the vehicle velocity is about 3×10^6 cm/sec in heliocentric coordinates, which is not significant when compared to the plasma velocity.

Since unambiguous field polarity information is not available, it is necessary to consider the various types of plasma activity which might account for the behavior of the field during the null. For example, could the spacecraft be observing a wave or strong

* These waves may have some features similar to the hyperwaves (perhaps "collisionless shocks") seen by Pioneers I and V at the geomagnetic boundary[3,4].

kink in the field? That waves exist in the region of the null is likely as seen from an examination of the data. However, to explain the null requires an Alfvén type of shock in which the zero would be attributed to a temporary alignment of the field direction with the spin axis of the spacecraft, since then no normal component would be observed. It is unlikely that such a kink would cause the field to go to zero and return in as symmetric a manner as the data indicates. Also, a field kink so fortuitously constituted as to cause alignment to within a few degrees of the spin axis, as is required by the large change in field, is unlikely.

Another possibility is that the null is due to a field-free bubble of gas. The assumption of a hydrogen plasma having a temperature $\geq 10^4$ °K and the measured scale size of $\lambda \sim 2\times 10^{10}$ cm lead to a decay time $\geq 10^{14}$ seconds[6] if one uses the conductivity of a quiet field-free plasma. This provides a lifetime far in excess of the time for such a bubble to come from the sun. This argument is, however, suspect because the existence of plasma waves may increase the resistivity a large amount.[7,8] There is no good theoretical method at the present time by which the effective resistivity could be calculated. Dungey[9] shows that for a field-plasma interface, the interpenetration is exponential with the field decreasing into the gas. There does not seem to be a strong argument for exponential slopes as seen in the data, particularly with the required positive curvature on either side of the zero. Unless the bubble is very thin compared to its dimensions parallel to the field lines, the latter would be crowded together just outside the bubble. However, no such increase in field strength is indicated by the observations. By far the most telling argument against interpreting the null as a bubble in an otherwise regular field is the fact that such a bubble, with its concave boundary, is unstable. Interchange instabilities would diffuse the field through the bubble and each sub-bubble produced would lengthen and become more slender due to the magnetic pressure as well as suffer further interchange instabilities. Thus its life should be very short and the model does not seem attractive.

On the other hand, if the vehicle goes close enough to the center of an X-type neutral point, one should observe the null, the symmetry, the regions of nearly constant field, and the waves, which seem likely to be excited in such a region. The probability of observing such a null would be increased if it were more nearly a neutral surface, with equal and opposite fields on the two sides, separated by a thin transition region in which the necessary currents flow and in which there is increased gas pressure to balance the field pressure outside. If the gas in the layer is essentially thermalized, with n_N being the number density of protons (and of electrons) and T_N being the temperature, n_0 and T_0 being the corresponding quantities outside the null, this gives $n_N T_N - n_0 T_0 \approx 10^6$ °K cm^{-3}. Such surfaces might be generated by gas flowing out from the sun. First, consider Parker's model in which the field lines of the sun are swept out mainly radially but partly in a spiral due to solar rotation. At moderate latitudes, especially near spots, the sun's magnetic field is very irregular with alternating regions of north and south polarity. When the field is swept outward, neutral surfaces will extend out from the boundaries of all such regions. As the field spirals, it developes a component that can be observed by the magnetometer. Since the gas flow is radial, the structure is swept past the magnetometer. Gold's model, the magnetic bottle or tongue, is based on a similar model of the basic solar field, but contemplates conditions before the gas has carried a loop of field lines essentially to infinity. With Gold's model it is possible either to generate a neutral surface along the center of the tongue or to have field everywhere; the field lines turning, crossing the central surface, and running back on the other side. This latter sub-case is not excluded by the observations since if in turning the field became nearly parallel to the spin axis, it would not be observed. However, as argued above, such alignment is unlikely, in which case the model requires that the tongue was created by a jet of gas that carried all the lines beyond the earth rather than by one that carried some lines only a short distance out from the sun.

The resistivity opposing the currents in a neutral layer of the type we have been considering will mean that gas flows into the layer across the field lines. It is the pressure of the gas that balances that of magnetic field outside the layer. But as gas accumulates, an unstable situation will develope, the gas tending to collect in bubbles. These bubbles will suffer interchange instabilities and tend to diffuse into the magnetic field. Thus X-type neutral points and neutral lines will be set up which will behave in the manner discussed by Sweet[10] and Dungey[11]. These instabilities should produce waves in the neighborhood of the neutral region and the interchange instabilities will allow threads of field to enter the neutral region, thus providing a possible explanation of the brief field peak observed inside the null. The X-type neutral points and lines will lead to a reconnection of the field lines. This should lead to the production of loops of magnetic field that are not connected with the sun and that are swept outward by the plasma flow. When these processes are allowed for, the models of Parker and of Gold may become more nearly similar; Gold emphasizing the effect of a single discrete explosion from a small region of the solar surface and Parker emphasizing a wind that is more continuous in time and over the solar surface. Gold's model refers only to disturbed conditions; but null surfaces should be a feature of Parker's model both for disturbed and for quiet conditions.

This discussion, based as it is on a single, incomplete observation, must be regarded as speculative. But since the neutral surfaces are plausible components of popular models of solar disturbances, it seems reasonable to give added credence to those aspects of these features that are consistent with this observation. Further observations are obviously needed to confirm these features, to determine the frequency with which they occur, and to explore further their details.

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Discussion

Gold, T.: I think there is a poor possibility of the neutral sheets being distorted sufficiently to see a bulge sweep over the vehicle, thus giving two points of intersection.

Sonett, C. P.: It is easy to draw a figure so that a bulge gives the two points of intersection, but more difficult to make the central peak so narrow.

Parkinson, W. D.: Is the dotted line in your model a plane on which the magnetic field is zero, or on which it is perpendicular to the direction of sensitivity of the vehicle?

Sonett: Observationally it is impossible to be sure. I have regarded it as a plane of zero field.

Biermann, L.: The time scale of the field reversal being of the order of 5 min., one might be tempted to think of filaments of $\sim$10,000 km diameter, extending largely radially away from the sun (30 km/sec, vehicle velocity$_{\perp}r_{\odot}$, $\times$300 sec yields 9,000 km). There is some still somewhat indirect evidence for the existence, in interplanetary space, of filamentary structures from radio astronomy and from cometary physics, which, however, needs further investigations.

Sonett: The observations would be consistent with this model too.