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Simultaneous Solar-Wind Plasma and Magnetic-Field Measurements in the Expected Region of the Extended Geomagnetic Tail

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A comparison is made of simultaneous plasma and magnetic-field measurements obtained by Pioneer 7 in the expected region of the geomagnetic tail at ~1000 R_E. The results indicate that, unlike the data for the near-earth (≤ 80 R_E) geomagnetic tail, the data for the plasma and magnetic field have no unique signature of tail-associated phenomena. Furthermore, there are differences between the two types of data concerning the tentative identification of tail-associated phenomena for a number of intervals. The physical implications of these differences may be associated with anomalous transport properties that introduce turbulence in the form of mass diffusion and diamagnetic behavior adjacent to plasma eddies. As a result, the magnetopause, as it is recognized close to earth, loses its identity at far distances (>80 R_E) and combines in a turbulent and hence ill-defined way with the geomagnetic tail. Thus there would be no reason to expect a consistent tail identification on a one-to-one basis with plasma and magnetic-field observations, the criterion presently used close to earth (i.e., <80 R_E).

The length of the geomagnetic tail directly affects models of magnetospheric circulation and the access and loss of particles to the magnetosphere. It is known that the geomagnetic tail at distances of <80 R_E is well ordered and well defined (see the review by *Wolfe and Intriligator* [1970]). The first positive observational information on the extended nature of the geomagnetic tail was obtained with Pioneer 7 by *Ness et al.* [1967] and *Wolfe et al.* [1967]. Pioneer 7, launched August 16, 1966, went through the expected region of the geomagnetic tail at a distance of ~1000 R_E downstream from the earth (Figure 1). Wolfe et al. reported the observation of intermittent intervals of disturbed ion spectra. The changes in the spectra were so great that one would have expected them to be associated with wide changes in geomagnetic activity (as indicated by the *Kp* index). Since during these intervals of observation of disturbed spectra there were no such changes, it was argued by Wolfe et al. that the observation was of a more local 'geomagnetospheric wake.' On the same spacecraft Ness et al. reported magnetometer observations that could also be associated with an extended geomagnetic tail. The magnetic-field identification of the geomagnetic tail, however, is ambiguous, since the interplanetary magnetic field can often have the same configuration (solar or antisolar pointing). To eliminate this ambiguity, *Fairfield* [1968] compared magnetometer data from Pioneer 7 with simultaneous magnetometer data from Explorer 33 and 28, which were monitoring the interplanetary medium and the magnetosheath near the earth. He found, after correcting for time delays, that there were intervals during which the observed magnetic-field characteristics at Pioneer 7 were different from those at the other spacecraft and therefore indicative of tail-associated phenomena. The earlier investigations [*Wolfe et al.*, 1967; *Ness et al.*, 1967; *Fairfield*, 1968; *Intriligator et al.*, 1969] were considered to be tentative and were intended to direct attention to regions of potentially great interest. Although the previous mag-

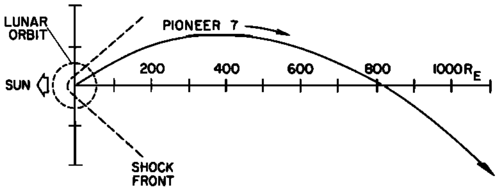

Fig. 1. Pioneer 7 trajectory, ecliptic projection. Pioneer 7, launched August 17, 1966, went through the expected region of the geomagnetic tail at 1000 R_E in September 1966. At a geocentric distance of 1059 R_E, Pioneer 7 was 28.7 R_E above the ecliptic at an ecliptic projection of the spacecraft–earth–sun angle of 189°.

netic-field and plasma observations, including those discussed below, cannot be used in a rigorous statistical sense because of their uniqueness, their importance regarding magnetic-tail metamorphosis should not be underestimated.

In this paper we compare in detail the Pioneer 7 solar-wind plasma and magnetic-field data in the region suggested by Fairfield to be of interest. The plasma data were obtained by the Ames Research Center solar-wind plasma probe, a multicollector electrostatic analyzer with concentric quadrispherical plates [*Wolfe et al.*, 1967]. The magnetic-field data were obtained by the Goddard Space Flight Center magnetometer, which is a tilted spinning flux gate, and have been taken from the paper by *Fairfield* [1968].

Magnetic-field and plasma data plotted versus time from Pioneer 7 on September 27 and 28, 1966, are shown in Figure 2. The top three graphs display the magnetometer data; the field orientation is solar directed or antisolar directed for $\varphi = 0°$ and $\varphi = 180°$, respectively. The bottom two graphs show the solar-wind proton number density and the proton bulk velocity. The values shown for the proton number density have error bars of plus or minus several hundred per cent due to the non-Maxwellian nature of some of the data (see text below and Figure 3). The two horizontal lines in the middle of the figure [*Fairfield,* 1968] indicate intervals during which Pioneer 7 was considered to be encountering tail-associated phenomena based on the comparison of magnetic-field data from Pioneer 7 with the magnetic-field data from Explorer 28 and 33. Similarly, the solid bars indicate intervals during which the spacecraft was considered to be encountering tail-associated phenomena as determined from the plasma data by examining the individual ion (energy per unit charge) spectra. The open bars denote disturbed or changing individual ion spectra, and a definite identification of whether they represent tail-associated phenomena or disturbed interplanetary plasma cannot be made until simultaneous interplanetary solar-wind data from another spacecraft are available (see summary).

Examples of the ion spectra are shown in Figure 3. One spectrum is taken every 48 sec. Each graph shows the results of the eight successive spectra starting at the time indicated on the right of the graph. In the first graph (1040 UT) the first seven spectra are similar in shape to many solar-wind proton spectra [*Intriligator et al.*, 1969] even though the magnitude of the flux is depressed. The eighth is not shown, however, since there was no measurable proton flux. The second graph (1046 UT) shows the continued absence of measurable flux. This absence of flux persists until ~1103 UT, and we consider it to be indicative of tail-associated phenomena (see the solid bar in Figure 2). The results of Fairfield's study of the simultaneous magnetic-field data on the same spacecraft and on the two other spacecraft do not, however, indicate that Pioneer 7 is encountering tail-associated phenomena (i.e., there is no horizontal line immediately below the magnetic-field results at this time). Thus this is an interval for which a detailed examination of the individual ion spectra shows that the spacecraft is encountering tail-associated phenomena, whereas the study of the magnetic field yields no such results. A similar result is indicated in Figure 2 between ~1430 and ~1500 UT and possibly at ~2100 UT.

On the other hand, there are also a number of intervals during which Fairfield's study of the magnetic-field data implied the presence of the spacecraft in a region of interest (possibly the magnetic tail) but where an examination of the individual plasma ion spectra identified these spectra more with the familiar solar wind (i.e., ~1400 to ~1430 UT, ~1540 to ~1600 UT, ~1610 to ~1700 UT or possibly to ~1720 UT, and ~1810 to ~1910 UT). To study this last time interval, the individual ion spectra from 1801 to ~1815 UT are shown in Figure 3. We consider all eight spectra in the third graph

(1801 UT) and only the first three spectra in the fourth graph (1807 UT) to be associated with the extended tail region. Clearly, the last five spectra in the graph are associated with a different plasma regime: they are quite similar to 'typical' solar-wind ion spectra. This finding illustrates why the solid bar in Figure 2 denoting tail-associated phenomena does not extend beyond $\sim$1810 UT.

In Figure 2, there are also some intervals of agreement between the two types of data. For example, from $\sim$0700 to $\sim$1030 UT the spacecraft is not in the tail. From $\sim$1720 (or possibly $\sim$1700 UT) to $\sim$1810 UT, both sets of data agree that the spacecraft is in the tail. From $\sim$1400 to $\sim$1900 UT, however, it is clear that the agreement is not good between the two sets of data concerning when tail-associated phenomena are being encountered.

SUMMARY

The simultaneous plasma and magnetic-field data presented above clearly indicate that the characteristics of the geomagnetic tail can be very different in the extended regions of the tail ($\sim$1000 R_E) from those in the near-earth regions (<80 R_E). Unlike the near-earth tail data, the plasma and magnetic-field data have no unique signature. There are also intervals of differences concerning the tentative identification of tail-associated phenomena. By taking the total numbers of hours identified as the extended tail by the magnetic-field and/or plasma data in Figure 2 to be 100%, these discrepancies in identification can be examined more quantitatively. Approximately 88% of this time (the total possible tail time) was identified as the extended geomagnetic tail by Fairfield from his study of the simultaneous magnetic-field data from three spacecraft. Whereas, on the basis of an examination of the individual plasma ion energy per unit charge spectra associated with the plasma data, approximately 27% of this time (or at most 47% if all of the open bars are actually tail data) can be identified as the extended geomagnetic tail. From looking in more detail at specific time intervals, one sees that for approximately 60% of the time (the total possible tail time) shown in Figure 2 the usual criteria fail unambiguously to identify the geomagnetic tail. This discrepancy in identifying the geomagnetic tail by the heretofore standard method is also shown by the fact that for only $\sim$18% of this time (or at most 38%, again depending on the plasma data

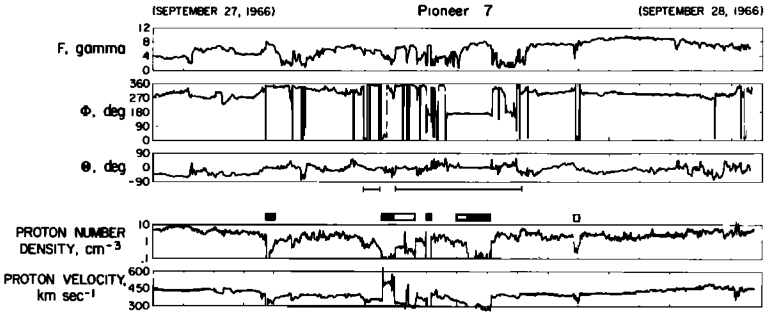

Fig. 2. Simultaneous magnetic-field and plasma data in the expected region of the extended geomagnetic tail ($R \sim 900$ R_E). The first three graphs [*Fairfield*, 1968] show the magnitude of the magnetic field F in gammas and the azimuthal (in the ecliptic plane) orientation φ and the polar (perpendicular to the ecliptic plane) orientation θ in degrees. The horizontal lines below the magnetic-field data indicate intervals of data that Fairfield considered to be in the tail. The last two graphs are the plasma number density in protons per cubic centimeter ±200% and the streaming velocity in kilometers per second. The rapid changes in the plasma distribution function (time aliasing) give rise to the large errors associated with the number density determination. The solid bars indicate time intervals of tail-associated data based on an examination of each proton flux as a function of energy per unit charge (E/Q) spectra (cf. Figure 3). The open bars indicate that an examination of the individual proton spectra yielded ambiguous results.

in the open bars) both the magnetic-field and plasma data agree that tail-associated phenomena might have been encountered. Simultaneous magnetic-field and plasma data from several other days have been examined and yield similar results. A word of caution is noted: the statistics given above are, of course, less than rigorous, since the spacecraft made only one pass through the region expected to be occupied by the geomagnetic tail. Since there exist no other data from which one might accumulate more meaningful statistical information, the figures given above must be interpreted only in a general way.

This evidence that the criteria used to identify the nature of the extended geomagnetic tail should be different from those used for the near-earth tail is convincing, particularly when one recalls again that the magnetic-field identifications of the tail regions used here were those from the study of Fairfield of simultaneous magnetic-field data from three spacecraft. This

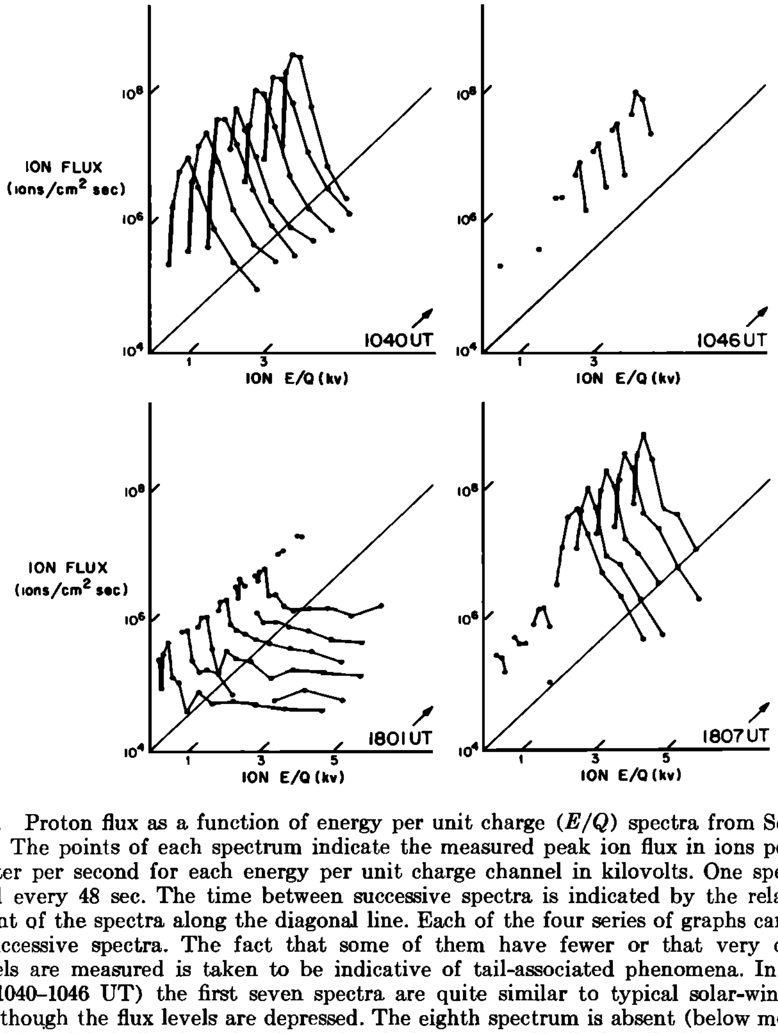

Fig. 3. Proton flux as a function of energy per unit charge (E/Q) spectra from September 27, 1966. The points of each spectrum indicate the measured peak ion flux in ions per square centimeter per second for each energy per unit charge channel in kilovolts. One spectrum is obtained every 48 sec. The time between successive spectra is indicated by the relative displacement of the spectra along the diagonal line. Each of the four series of graphs can contain eight successive spectra. The fact that some of them have fewer or that very depressed flux levels are measured is taken to be indicative of tail-associated phenomena. In the first graph (1040–1046 UT) the first seven spectra are quite similar to typical solar-wind proton spectra, though the flux levels are depressed. The eighth spectrum is absent (below measurable flux levels) and is indicative of tail-associated phenomena. Similarly, all eight spectra in the second graph (1046–1052 UT), all eight spectra in the third graph (1801–1806 UT) and the first three spectra in the fourth graph (1807–1813 UT) are examples of tail-associated phenomena. The last five spectra in the fourth graph, however, are more similar to typical solar-wind spectra.

study should remove much of the ambiguity associated with the identification of the geomagnetic tail from magnetic-field data, since the interplanetary field can have the same orientation as the geomagnetic field. The ambiguity associated with identifying tail-associated phenomena for the few intervals of the open bars from only the plasma data can be eliminated by a study of simultaneous plasma parameters from Pioneer 7 and parameters from an additional spacecraft in the vicinity of the earth. A detailed study of several sets of simultaneous data (magnetic-field, plasma, and even low-energy cosmic-ray data) for the extended tail could either yield completely new criteria or establish one type of data as the best indication of tail-associated phenomena in this region. It is also possible that such a study would indicate that there are many problems in trying to correlate individual features of short time duration over such extended distances. In this event the most reliable criteria for identifying the extended tail may come from the detailed examination of one type of data for the more subtle changes indicative of this phenomenon.

The detailed comparison of magnetic-field and plasma data given above can be used to improve the speculation on the actual physical processes responsible for the observations in this extended region. One might suggest that the plasma diffuses into the tail as a result of anomalous transport properties introduced farther upstream in the well-defined magnetopause by various plasma instabilities [cf. *Eviatar and Wolf*, 1968]. Thus, in the regime of turbulent plasma processes, there is no reason to expect a consistent tail identification on a one-to-one basis with plasma and magnetic-field observations, as used closer to earth for magnetic-tail identification.

If this suggestion is adopted, it is a straightforward step to concepts of viscosity, thermal and mass diffusion, and resistivity within the magnetopause boundary layer, as discussed initially by *Axford and Hines* [1961]. The concept of vorticity diffusion (see *Dryer and Heckman* [1967] for estimates of this boundary layer growth in the downstream direction) can be used up to a point where instabilities (Kelvin-Helmhotz) cause transition to a turbulent layer. Then momentum and energy exchanges in space and time become rampant. Eddies grow (just as the jet trails in our own atmosphere) and move downstream, sometimes in an oscillatory pattern (von Karman vortices). All this presupposes the acceptance of another extrapolation of a fluid mechanics idea to the present case, which is, of course, more complex because of the possible presence of plasma eddies (or 'blobs') separated by plasma-free regions. Thus the so-called 'differences' may be compatible in reality if the physics suggested above is applicable.

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