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Isolated Cold Plasma Regions: Observations and their Relation to Possible Production Mechanisms

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Abstract

Regions of enhanced cold plasma, isolated from the main plasmasphere along the Explorer 45(S^3-A) orbit on the equatorial plane, have been detected using the sheath induced potentials seen by the electric field experiment. The occurrence of these regions has a strong correlation with negative enhancements of Dst, and their locations are primarily in the noon-dusk quadrant. The data support the concept that changes in large scale convection play a dominant role in the formation of these regions. Plasmatails that are predicted from enhancements of large scale convection electric fields in general define where these regions may be found. More localized processes are necessary to account for the exact configuration and structure seen in these regions and may eventually result in detachment from the main plasmasphere.

Introduction

Regions of cold plasma that appear to a satellite cutting across L shells to be detached from the main plasmasphere have been observed in or near equatorial regions on OGO's 3 and 5. Chappell, et al., (1970, 1971) found 41 dayside instances in the OGO-5 data when the plasma density rose above 10 ions/cm^3 outside the plasmapause with 76% of them occurring in the 1242-1920 L.T. sector. Most were observed between L = 5 and 9 after periods when Kp had been above 3-. They postulated the occurrence of these "detached" regions in terms of a convective flow concept in which regions would be peeled and detached in the afternoon sector by variations in the magnitude of the convective electric field. Similar profiles of a density enhancement outside the main plasmasphere were observed on OGO-3 by Taylor et al., (1970) near the bulge at the dusk meridian. Chappell et al., (1971) also reported several instances in the dusk-midnight quadrant and 3 instances near 0300 local time.

Taylor, et al. (1971) used conjugate enhancements within the ion trough at the foot of the field lines and a convection model (Grebowsky, 1970) to deduce a concept of a corotating plasmatail attached to the main plasmasphere. This large scale convection model has been improved and compared with the OGO-5 data of Chappell et al., (1971) by Chen and Grebowsky (1974) and to the OGO-4 trough data by Chen et al., (1973). Their model uses a Kp dependent convection field and traces the motion of flux tubes backward in time to determine how long since they had been outside 10 R_e (hence, open: allowing loss of the cold plasma). With any significant enhancement of Kp the model consistently predicts cold plasmatails, which more or less corotate with the earth as activity decreases. Plasma is convected toward the magnetopause in the afternoon quadrant as the increased electric field, creating the rise in Kp, reconfigures the plasmapause to lower L shells. As long as continuous, slowly varying electric fields are used, the tail will remain attached to the plasmasphere until it becomes too tenuous to exist. In considering evidence of these isolated regions that involve the ionospheric trough a certain element of question evolves as to the exact relationship between the plasmapause and the trough.

Explorer 45 (S^3-A) has provided new observations of isolated cold plasma regions in the equatorial plane. Using Explorer 45 data, Barfield et al., (1974) found during a large substorm in the main phase of a major magnetic storm that a reconfiguration of the plasmasphere occurred near the plasmapause resulting in the satellite suddenly entering a region of low density while inbound and then returning inside the plasmasphere. The inner edge of the plasma sheet moved past the satellite with field aligned currents developing, depleting or possibly energizing the cold plasma. The lower density region was assumed to be a result of these effects of the hot-cold plasma interaction. On the next orbit an isolated plasma region was observed.

In this brief report we will present other examples of isolated regions of cold plasma found in the Explorer 45 data and comment on their possible means of origin.

Observations

No quantitative cold plasma measurements were made on Explorer 45; however, the short baseline of the DC electric field experiment caused the sensors to be influenced by spacecraft sheaths at low plasma densities. The resulting sheath induced potentials were controlled by the characteristics of the sheath, thus making them sensitive to ambient plasma density and temperature changes. Model calculations and comparison to VLF data have established that the point where these sheath induced potentials saturate the detector is a good indication of the plasmapause (Maynard and Cauffman, 1973; Cauffman and Maynard, 1974). The sheath model also predicts that the saturation voltage is primarily a function of density (Cauffman and Maynard, 1974). From comparison with whistler derived densities in the equatorial plane (Morgan and Maynard, private communication), the most probable density at saturation is of the order of 30 $\bar{e}l/cc^3$.

Figure 1 presents data from Explorer 45 for orbit 1099 on Nov. 1 1972, during a large magnetic storm. As the satellite spins a "simusoidal" variation is seen on the detector from the sheath potentials or, in the vicinity of L = 2, from $\vec{V} \times \vec{B}$ electric fields. The data for 1/4 of every 4th spin cycle is plotted in the summary plots for both the outbound and inbound portions of the orbit. The envelope is shown over the data to clarify what regions are saturated. The orbit is drawn with a heavy line in regions where the detector is unsaturated (i.e., inside regions of higher cold plasma density by the above criteria). Saturation is indicated by a dashed line when the sinusoidal variation is limited by saturation during less than 3/4 of a cycle and by a dotted line when the wave form is limited by saturation during more than 3/4 of a cycle (nearly a square wave and indicating significantly less cold plasma density than that at first signs of saturation). The satellite moves outside the plasmapause at 8.5 hours L.T. and an L of 2.4. The density becomes quite low as L increases until a small region of cold plasma is encountered at 12.3 hours L.T. and an L of 5.1. A larger but more chopped up region is encountered starting at 13.3 hours L.T. and an L of 5.1. Saturation levels are moderate after that until the detector passes out of saturation for the remainder of the orbit at 16.2 hours L.T. and an L of 3.9. Note that within the isolated unsaturated regions, the density, and probably also the temperature, of the cold plasma are very non-uniform as indicated by the variability of the data.

Isolated cold plasma regions have been found, mainly in the noon-dusk quadrant, during most significant negative excursions of Dst throughout 1972 (see Figure 2). During the first 3 months the satellite spent most of its time in the dusk-midnight quadrant where it is possible in an $R_e = 5.2$ orbit to confuse a skirting of the bulge region with cases of isolated cold plasma. In the cases denoted by arrows it is believed that the data indicates an isolated region. A number of other cases (not shown) were interpreted as related to the bulge or very questionable. However, between April and August, the only observations of isolated regions have been associated with Dst excursions. One case, on August 12, does not seem to be associated with Dst, but may be from an irregular boundary. Strong micropulsation activity was observed in the data associated with it. The data after August was selectively scanned during Dst enhancements only. Thus these events are strongly associated with increases in magnetic activity and, hence, in the convective flow toward the dayside.

The Explorer 45 orbit, while limited to observations inside $R_e = 5.2$, does have the advantage of returning to the area approximately every $7\frac{1}{2}$ hours. Thus the development of these regions can be followed. Figures 3 and 4 present data from two cases of three consecutive orbits during two moderate negative excursions of Dst.

Figure 3 depicts data from orbits 890 through 892 during August 27, 1972. On orbit 890 the plasmapause was encountered at L = 4.0 on the outbound leg and the satellite remained outside the plasmapause until L = 3.4 on the inbound leg. During the latter part of orbit 890 Dst activity increased and on 891 the satellite remained within the cold plasma over the entire orbit except for brief periods near apogee indicating a significant shift of cold plasma in the noon-dusk quadrant toward the magnetopause. On orbit 892 as activity relaxed the plasmapause was encountered at L = 2.7 outbound (significantly lower than on 890) and at L = 3.3 on the inbound leg of the orbit. While this series of orbits does not depict an "isolated" region in the strict sense, it is instructive in representing a definite transport of plasma over a relatively short time span (compared to days as the normal filling time) in the sector where isolated regions are most often seen.

Figure 4 depicts data from a different local time: orbits 516-518 during April 29 and 30, 1972. Dst activity had been up and down previously and increased at the beginning of orbit 516. The plasmapause was crossed at L = 3.9 and 15.1 hours L.T. with an isolated region just outside from L = 4.1 to L = 4.5. The inbound plasmapause was at L = 3.7 and 20.1 hours L.T. During orbit 517 activity was variable and the detector was in and out of saturation outbound between L = 4.0 and L = 4.6 with another region of cold plasma being encountered at L = 5.0. The inbound plasmapause remained near L = 3.7. Activity decreased during orbit 518. The plasmapause was crossed at L = 3.3 and 14.5 hours L.T. outbound, and an isolated region was observed near L = 4.9 and 16.2 hours L.T. Inbound the plasmapause was crossed at L = 4.0.

In all of the above orbits the encounter with isolated cold plasma was well sunward of the bulge in Carpenter's (1966) average plasmapause but not far from the average plasmapause of Chappel et al., (1971). They are in the lower part of the L range within which Chappell et al., (1971) see their detached regions. These statements in general apply to all detected regions after April, 1972 (regions prior to April are in the vicinity of the bulge).

Discussion

The above data leads one to a basic premise that, as mentioned by Chappell, et al., (1971), convection must be important in the formation of these regions. Chappell, et al., postulated further that somehow convection peeled the plasma away in the afternoon-dusk sector creating a completely detached region. More recently, Chappell (1974) has suggested that the detachment may result from local variations in the electric field or from a shear in the electric field set up from field aligned current shielding (see also Jaggi and Wolf, 1973, who show shielding of convection fields at lower L shells from field aligned currents at the inner edge of the plasma sheet). However, unless a local plasma depletion mechanism, local variations in the electric field, or a shear in the convection exist to separate the plasma from the plasmasphere, Kp associated increases in large scale convection will produce attached tails as calculated by Chen et al., (1973) (see also previous papers of that group mentioned in the Introduction).

In order to compare the data to convection produced effects, boundaries have been calculated from the model used by Chen et al., (1973). Their model assumes a dipole magnetic field, Stern's (1974) radial dependence for the electric field in this region (convection potential is dependent on $R^2 \sin \phi$ where R is the radial distance and ϕ is the azimuthal angle from noon), and an empirically derived Kp dependence of the magnetospheric potential. It integrates backward in time to determine how long a flux tube has remained "closed" (inside 10 R_e) and likely to have kept most of its cold plasma. In Figures 3 and 4, flux tubes that have been "closed" for 6 days or more are represented by the shaded area. A new potential dependence was used in these calculations which was derived by forcing the model to fit 35 plasmapause crossings located from 22 to 03 hours local time from OGO 3 and 5 (Chen, private communication). This potential to a certain degree accounts for the expansion of the polar cap and associated shrinking of the outer boundary (or the size of the region of sunward convection) during magnetically active periods. Previously Chen et al., (1973) and Chen and Grebowsky (1974) used a Kp dependent potential, deduced from OGO-6 electric field data (Heppner, 1973) across a fixed magnetosphere. The new potential dependence enhances the comparison by removing errors introduced by fixing the size of the magnetosphere, but the basic conclusions drawn below would still hold using previous iterations of this model and are indicative of a large scale convective process being a dominant force. Note that this model does not predict a density in these flux tubes, only that they have been "closed". The actual density is a function of an assumed filling rate and the path over which the tube travelled, which may or may not have resulted in some leakage out of the tube.

In Figure 3 the above model predicts an established plasmasphere in orbit 890 that becomes distorted during orbit 891 from the increase in activity, extending out beyond the S^3-A orbit. The model predicts that this turns into a tail structure and tends to corotate as activity decreases in orbit 892. In Figure 4 the model again predicts the distension of the plasmasphere in the afternoon quadrant as activity starts to increase during orbit 516. This distension turns into a tail during orbit 517 which corotates as activity decreases during orbit 518.

Comparisons of established boundaries, between this model and Explorer 45 data, in general show fairly good agreement (i.e., orbit 890 in Figure 3 and the inbound boundaries in Figure 4). The agreement becomes poorer in the more dynamical regions (i.e., inbound in orbit 892, Figure 3). Figure 4, in particular, illustrates that the predicted tail structures generally cover the isolated cold plasma regions defined by Explorer 45; but the detailed structure seen in the data (also shown in some of the data of Chappell, et al., 1971) is missing. Thus, loss of plasma is occurring in some of the flux tubes that the model defines as "closed". This is also true in orbit 892 in Figure 3 where Explorer 45 fails to see the inner portions of the predicted tail structure that developed during orbit 891.

Although the model has many drawbacks in the assumptions and in the time scale of the input variations, the comparison does confirm that convection is a basic underlying process in the formation of these regions. To explain the observed structure in and near the isolated regions, it is necessary to add to large scale convection more localized processes. Mechanisms such as the local reconfiguration observed by Barfield, et al., (1974) or spatially limited variations in the convection electric fields may account for the variations and, in some cases, cause complete detachment. As these regions convect farther and farther away from the main plasmasphere in moderate active to active periods, it is likely that these mechanisms will cause detachment (see Chappell, 1974). One should be cautions about any shear mechanisms that require a reversal of large magnitude electric fields as such events are not common near the plasmapause in the satellite electric field data (see Gurnett, 1970; Heppner, 1973).

Recently Burch and Chappell (1974) have observed that a number of the Explorer 45 events have occurred at the inner edge of the plasma sheet. This is partially the result of the hot plasma being influenced by the same convective processes (Grebowsky and Chen, 1974), but may also be a further indication that the hot-cold plasma interaction is important in the structure of these regions.

Chappell (1974) found a bias toward moderate Kp (3 to 5) in the occurrence of events on OGO-5, and that no correlation with Dst existed, leading to a conclusion that the origin of these regions was substorm oriented. The definite association with Dst observed here points more to large scale convection changes and a magnetic storm orientation. A bias is present in these data, however, from our low 5.2 R_e apogee which limits our observation region and prevents observations when the plasmasphere is expanded during very low activity periods. The events are from areas relatively close to the main plasmasphere, in the afternoon-evening sector where these isolated regions must originate.

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Figures

Figure 1: Explorer 45 electric field experiment data showing the location of the observed isolated cold plasma regions on November 1, 1972 and the data from which these regions are deduced (see text).

Figure 2: A plot of Dst for 1972 (Sugiura and Poros-private communication) also showing the locations of Explorer 45 cases of observed isolated cold plasma regions.

Figure 3: Data from three orbits on August 29, 1972, showing the development of an isolated cold plasma region. The shaded area represents those field lines that have been "closed" for 6 days or more as defined by the large scale convection model (see discussion). The outer boundary encloses field lines that have been closed for 4 days or more. The heavy orbit trace denotes regions where the experiment is unsaturated indicating higher cold plasma density while the lighter dotted and dashed traces represent degrees of saturation as discussed in the text.

Figure 4: Data from three orbits on April 29 and 30, 1972, depicting the time evolution of an isolated cold plasma region. The shaded area represents those field lines that have been "closed" for 6 days or more as defined by the large scale convection model (see discussion). The heavy orbit trace denotes regions where the experiment is unsaturated indicating higher cold plasma density while the lighter dotted and dashed traces represent degree of saturation as discussed in the text.

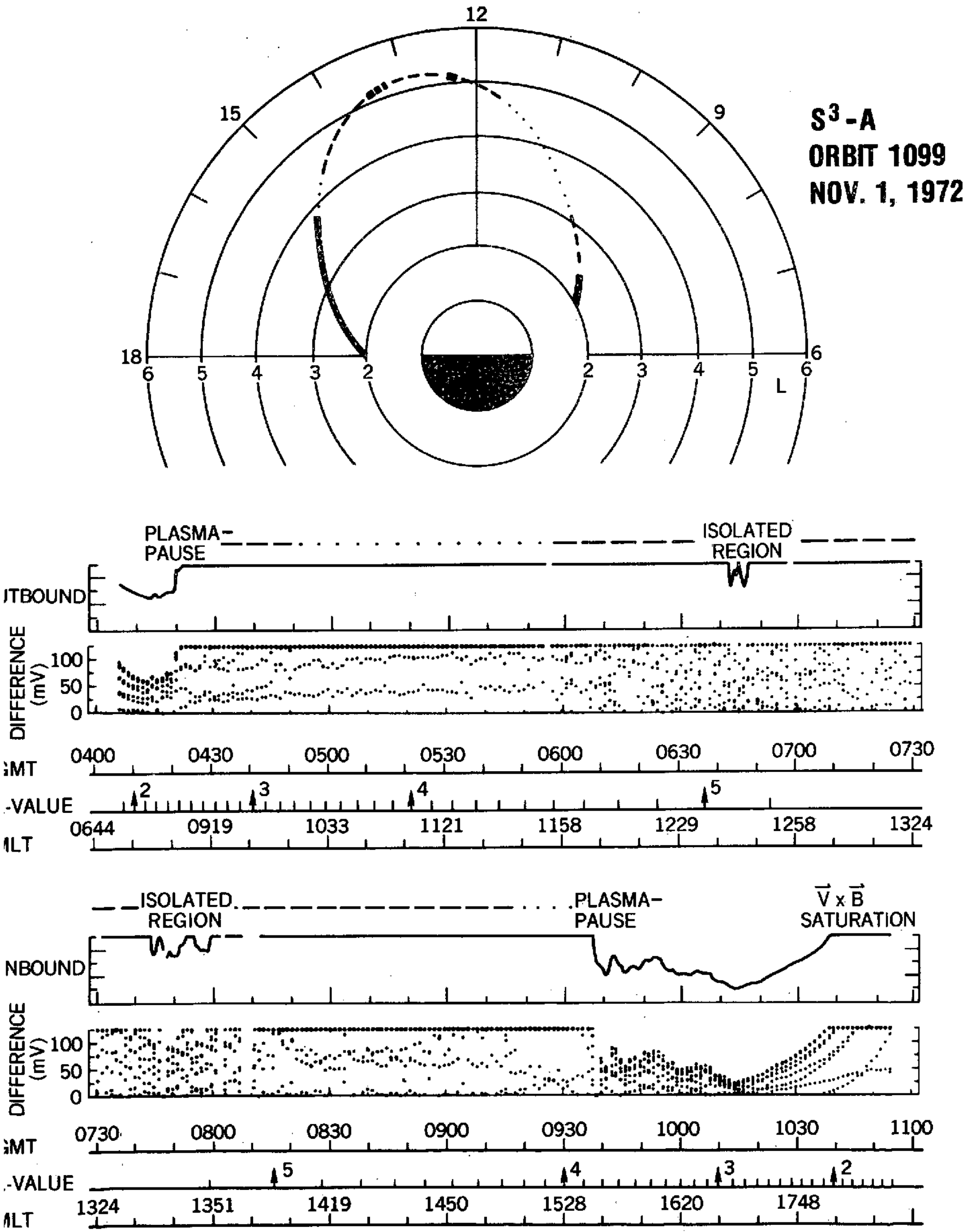
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Figure 1

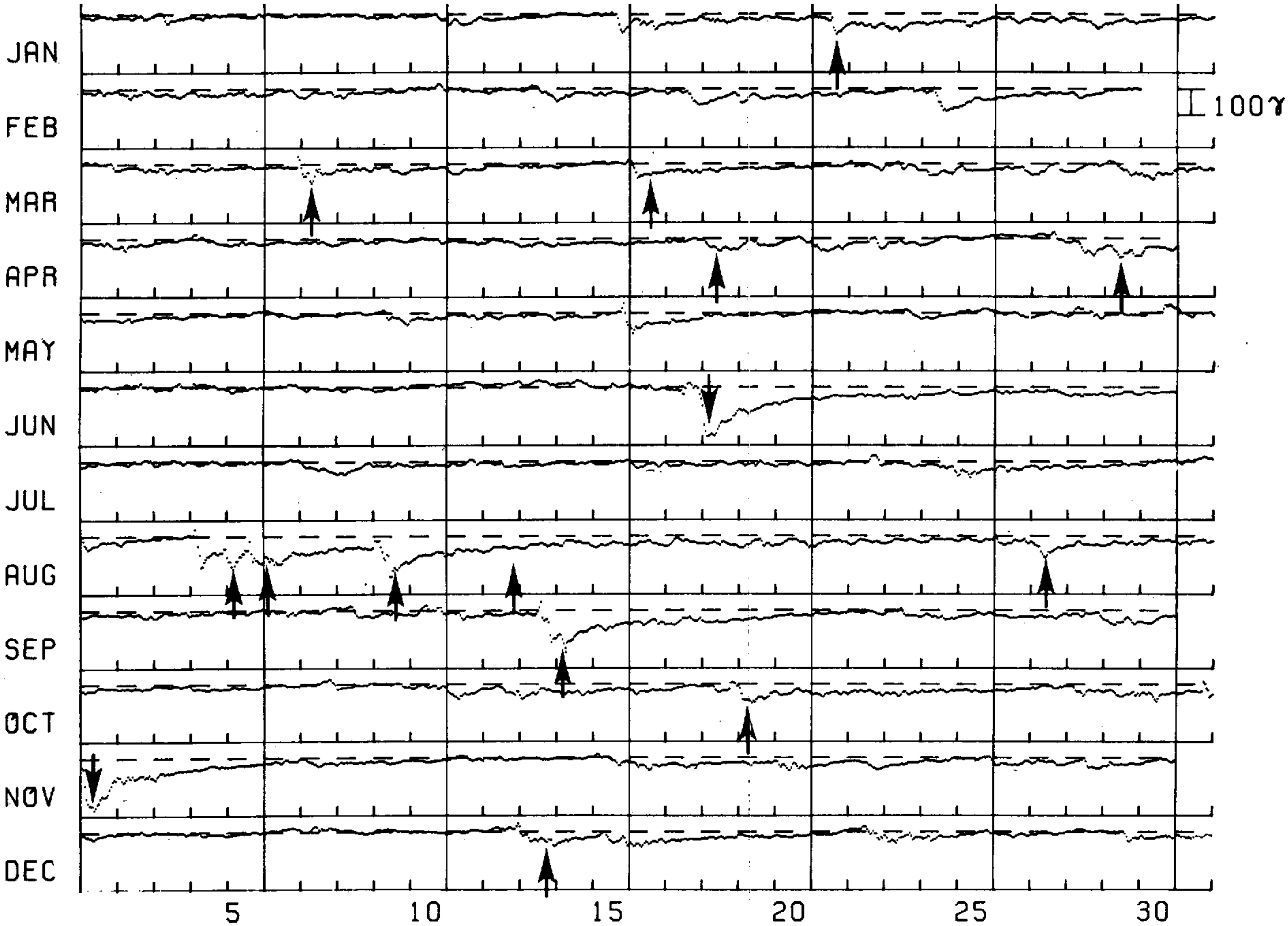
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Figure 2

S^3-A
AUGUST 27, 1972

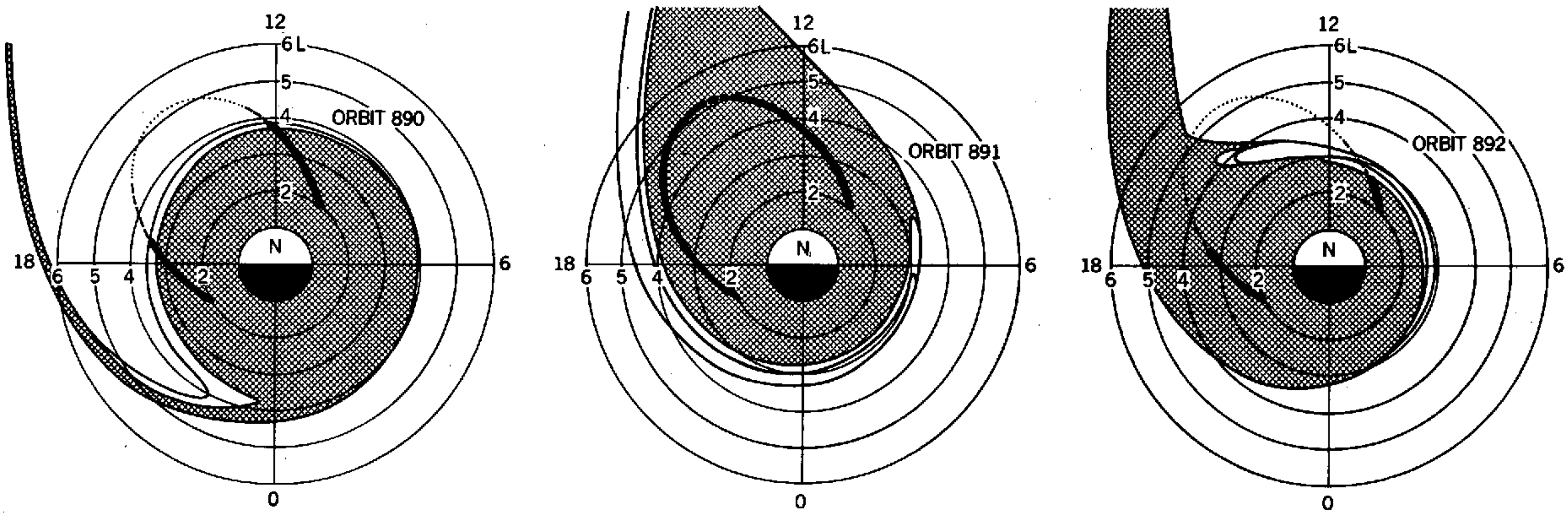

Figure 3

S^3-A
APRIL 29-30, 1972

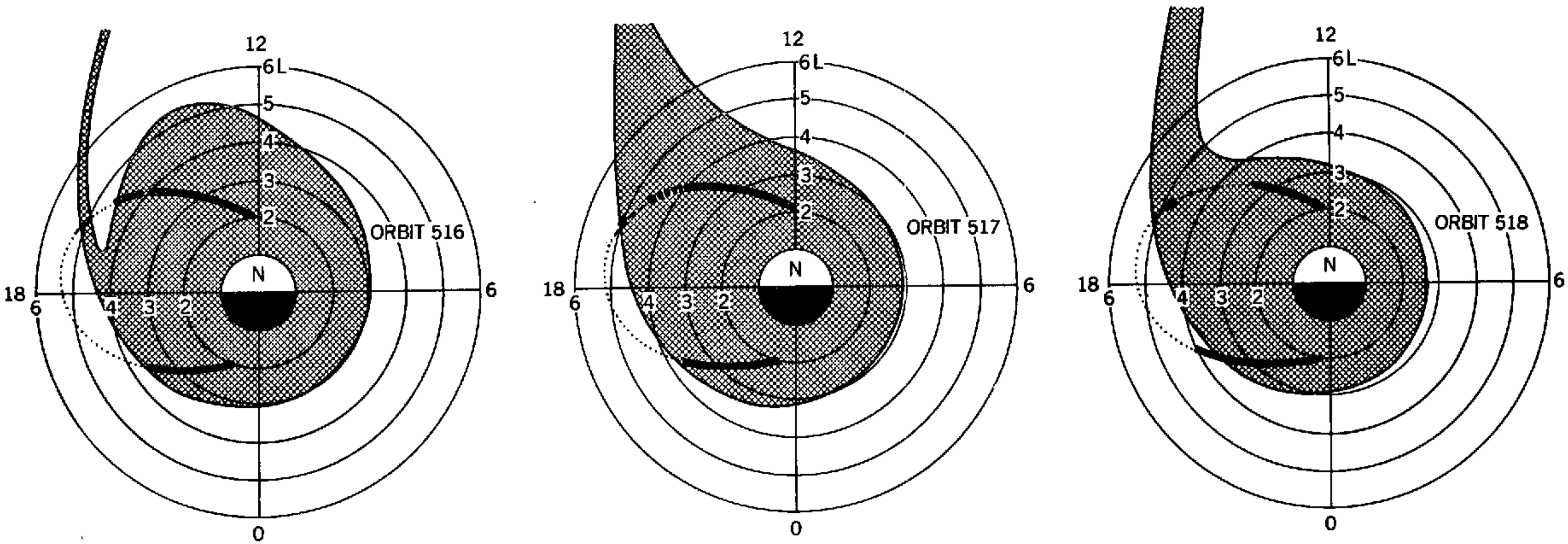

Figure 4