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LATITUDE VARIATION OF RECURRENT MEV-ENERGY PROTON FLUX ENHANCEMENTS IN THE HELIOCENTRIC RADIAL RANGE 11 TO 20 AU AND POSSIBLE CORRELATION WITH SOLAR CORONAL HOLE DYNAMICS

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Abstract. Recurrent low energy (≥0.5 MeV) proton flux enhancements, reliable indicators of corotating plasma interaction regions in interplanetary space, have been observed on the Voyager 1 and 2 and Pioneer 11 spacecraft in the heliographic latitude range 2°S to 23°N and the heliocentric radial range 11 to 20 AU. After a period of rather high correlation between fluxes at different latitudes in early 1983, distinct differences develop. The evolution of the fluxes appears to be related to the temporal and latitudinal dynamics of solar coronal holes, suggesting that information about the latitudinal structure of solar wind stream sources propagates to these distances.

Introduction

During the decline to minimum sunspot activity of the last 11-year solar cycle (1973 to 1977) recurring enhancements of MeV-energy nucleon fluxes were found to be closely associated with plasma interaction regions corotating with the sun near the heliographic equator at distances of 1 to 8 AU from the sun (see, e.g., Barnes and Simpson [1976]). These "corotating interaction regions", or CIRs, develop at the interface between long-lived high speed solar wind streams and lower speed solar wind streams [Smith and Wolfe, 1979]. Recurrent flux enhancements most likely result from the interplanetary acceleration of keV-energy nuclei up to MeV energies by multiple interactions with the hydromagnetic shocks that often form on the leading and trailing edges of the CIRs beyond 1 AU (see, e.g., Lee [1983] and references therein). Elemental composition studies [Gloeckler et al., 1979] indicate that the keV-energy seed population is most likely the suprathermal tail of the solar wind, although solar flare accelerated nuclei which are also present can be further accelerated along with the interplanetary seed population. These recurrent flux enhancements can be used to indicate the presence of the CIRs (see, e.g., Pyle and Simpson [1977]).

The sources of high speed solar wind streams are now known to be coronal holes [Nolte et al., 1976; Schwenn et al., 1978], the longest lasting of which cover the poles of the sun during activity minimum. Equatorial extensions of the polar holes are often sources of high speed streams observed near the heliographic equator. Following the peak sunspot activity in late 1979 to mid 1980, long-lasting holes reappeared in the sun's corona [Webb et al., 1984; *Solar-Geophysical Data Reports*], allowing investigations of the association between coronal hole and solar wind stream dynamics and the interplanetary acceleration of nuclei to MeV energies to be extended into the outer solar system using data from the Voyager and Pioneer spacecraft.

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Spacecraft Observations of Recurrent Phenomena

This study is based on daily samples of the average counting rate of protons in the energy range ~0.6 to 17.5 MeV (~0.4 to 15.5 MeV) from nearly identical Low Energy Telescopes of the Cosmic Ray Subsystem on the Voyager 1 (2) spacecraft [Stone et al., 1977] and the counting rate of ~0.8 to 1.6 MeV protons from the Goddard - University of New Hampshire Cosmic Ray Experiment aboard the Pioneer 11 spacecraft [Van Hollebeke et al., 1978]. Spacecraft distance from the sun (R), latitude (Θ), and longitude (Φ) in an inertial heliographic coordinate system are listed in Table 1 for the start and end of the analysis period. Pioneer 11, midway between the Voyagers in radius, is closer to Voyager 2 in longitude (<7° separation) but is closer to Voyager 1 in latitude (~5° to 9° separation).

Approximately 450 days of ≥0.5 MeV-energy proton observations starting in early 1983 appear in Figure 1. To facilitate comparisons, the observation times of spacecraft data have been translated back to the sun assuming a sun-spacecraft propagation delay corresponding to a corotating flow with a constant speed of 500 km/s and are plotted against Carrington Solar Rotation number. An average radial propagation speed of 500 ± 35 km/s was derived using spacecraft radial and longitudinal positions, a solar rotation period of 25.38 days, and measured delay times between correlated recurrent features. (The features at rotation 1734 and 1736 are possibly modified by the appearance of solar flare particles and have not been used in the computation of the speed). Since the spacecraft were close in longitude (<23°), the small additional adjustment for corotation delay was unnecessary in the figure. Features associated with a CIR characterized by 500 km/s line up vertically at the three spacecraft. Recurrent features at Pioneer 11 and Voyager 1 which are associated with a higher speed corotating structure appear to the left of a vertical alignment with Voyager 2, slower characteristic speed structures appear to the right. Similarly, latitude variations of the boundary and width of a solar wind stream's source region cause fluctuations around this vertical organization.

Temporal periodicity is apparent at each spacecraft

TABLE 1. Trajectory Information

	Voyager 2	Pioneer 11	Voyager 1
R	11.0 - 14.2 AU	13.1 - 16.1 AU	15.1 - 19.8 AU
Θ	2.4°S - 0.8°S	11.7°N - 14.3°N	17.1°N - 23.1°N
Φ	327.1° - 348.4°	329.6° - 342.6°	315.6° - 325.7°

throughout this time period. This is in direct contrast to observations from Pioneer 10 during the rise to maximum solar activity, when no recurring features were observed beyond 14 AU [McDonald et al., 1981]. During the first twelve solar rotations shown in the figure, the average periods of the recurring proton flux enhancements in the spacecraft reference frames are 25.8 ± 1.0 days for Voyager 2, 26.2 ± 0.8 days for Pioneer 11, and 25.9 ± 0.6 days for Voyager 1. These averages were determined by visually estimating the centroid of each flux enhancement and assuming a ± 1 day uncertainty in each estimate. Hereafter, the periodicities will be referred to collectively as "26-day" variations.

Double peaks on a number of recurrent flux enhancements may indicate the presence of either the forward-reverse shock pair on a single CIR or single shocks on two or more merging CIRs. Two to four stream structure evident in geomagnetic data ($\sim$1 AU) during 1983 suggests that the single 26-day recurrent structure beyond 11 AU is due to a number of closely spaced, or merged, CIRs (see, e.g., Burlaga et al. [1983]) in which slower flows have been swept up and assimilated by a faster flow.

Three fairly distinct intervals are apparent in Figure 1. During Interval 1, lasting until mid-rotation 1737, the counting rates at all three spacecraft are highly correlated and are dominated by a common 26-day recurrence. The recurrent nature of the proton flux enhancements indicates that CIRs are most likely present, enforcing an ordered structure throughout this region of the heliosphere. The salient point of these observations is the periodicity of the recurrence, not an exact correspondence of the intensity-time profiles, since MeV-energy flux is known to vary somewhat along a CIR (see, e.g., Christon [1981], Figure 2).

Interval 2, from mid-rotation 1737 to mid-rotation 1744, is identified by counting rates at all three spacecraft lower than those observed during Interval 1. A common 26-day recurrence is still apparent, although, at times the peaks are barely visible at Voyager 1. On the average, the relative decrease in peak counting rates at Voyager 1 and at Pioneer 11 is approximately twice the relative decrease at Voyager 2. Since Pioneer 11 is closer to Voyager 1 in heliographic latitude but closer to Voyager 2 in distance and longitude, the similarity between Pioneer 11 and Voyager 1 observations indicates that the overall variation in the fluxes is most likely latitudinal, and not radial or temporal in nature.

Interval 3 (after mid-rotation 1744) is characterized by peak flux levels at each spacecraft comparable to those in Interval 1, although now the intensity-time profiles are distinctly different. The interleaving of two 26-day recurrences results in the apparent 13-day periodicity continuing from late in Interval 2 throughout Interval 3. The interleaved 26-day recurrences most probably result from distinct solar sources well separated in heliographic longitude. Strong 13-day recurrences appearing at Voyager 2 and at Pioneer 11 during rotations 1742 and 1743 do not appear at Voyager 1. Thirteen-day peaks during rotations 1744 and 1745 are strongest at Voyager 1, barely discernible at Pioneer 11, and absent at Voyager 2. Since temporal shifts due to radial propagation have already been removed, the staggered appearance of these 13-day series is another indication that distinct latitudinal differences exist and persist as the solar wind propagates into the outer solar system. These observations of distinct latitudinal differences are consistent with near-sun observations of sharp latitudinal solar wind stream boundaries [Schwenn et al., 1978; Mitchell et al., 1981].

Correlation with Coronal Hole Dynamics

Figure 1 also displays estimates of He 10830Å coronal hole boundaries plotted versus central meridian observation time (identified by Carrington solar rotation number). These inferred coronal hole boundaries and photospheric magnetic polarity information, both derived from earth-based observations, are included in the Hα solar synoptic charts published monthly in *Solar-Geophysical Data Reports.* Coronal holes appearing in regions of dominantly north (south) solar magnetic polarity are shaded (unshaded).

The dominant near equatorial coronal hole during Interval 1 is a long-lived ($\sim$7 solar rotations) equatorial extension of the north polar hole. Numerous mid-latitude and equatorial coronal holes, as well as an equatorial extension of the south polar hole, are also visible. Equatorial extensions of polar holes are most often associated with the highest speed solar wind near the heliographic equator [Hundhausen, 1977], and higher speed streams are known to dominate control of the interplanetary medium [Burlaga et al., 1983]. Since two of the spacecraft are north of the equator, the equatorial extension of the north polar coronal hole seems to be the most probable source of the corotating plasma feature controlling the interplanetary medium in the region of the spacecraft. For part of Interval 2 (rotations 1738 to 1744), the north polar extension recedes to well above 45° while two south polar extensions grow, reaching toward the equator, coincident with decreased flux levels at Voyager 1 and Pioneer 11 and with the continuing presence of moderate flux levels at Voyager 2. This suggests that the high speed streams at Voyager 1, at $\lesssim$20°N latitude, may emanate from mid-northern latitudes, while those responsible for the continuing moderate flux levels at Voyager 2 may be from a combination of the new equatorial extensions of the south polar hole and the continuing near equatorial holes of northern polarity. Finally, from rotations 1745 to 1747 during Interval 3, the north polar coronal hole re-extends to the equator while, at the same time, the intensities of the

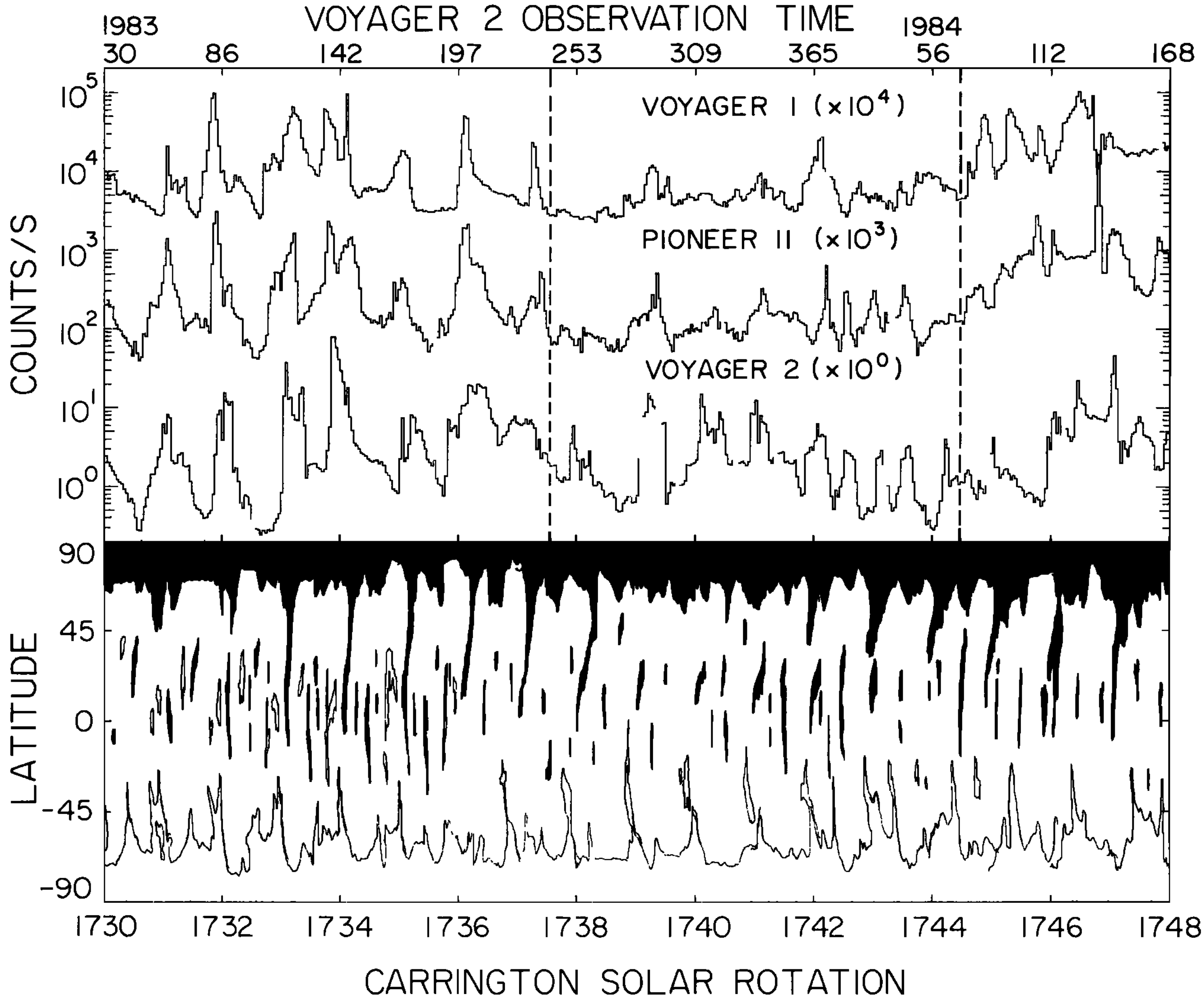

Fig 1. Upper panel: counting rates of ≥0.5 MeV-energy protons from the Voyager 1 and 2 and Pioneer 11 spacecraft are plotted versus observation time translated back to the sun (Voyager 2 time is indicated) and identified by Carrington solar rotation number. Dashed lines separate the three analysis intervals discussed in the text.
Lower panel: He 10830Å coronal hole boundaries are plotted versus Carrington solar rotation number.

recurrent flux enhancements reach levels comparable to those in Interval 1.

Summary

Correlated, recurrent enhancements of ≥0.5 MeV-energy proton fluxes are observed at all three spacecraft for approximately six solar rotations in early 1983, demonstrating that long-lasting structuring of the interplanetary medium by solar wind streams and their CIRs can persist over a latitude range of ~20° out to ~17 AU. Major differences in the intensity of recurrent proton flux enhancements then continue for over ten solar rotations from mid-1983 into 1984, showing that large-scale differences can also exist over a latitude range of only ~20°. Additionally, recurrent proton flux enhancements occurring twice per solar rotation are observed out to at least 19 AU, indicating that CIRs do not necessarily merge within this radius.

The recurrent flux enhancements, which depend upon the dynamics and structure of the heliosphere in the outer solar system, and their apparent correlation with coronal hole dynamics suggest that structuring of the interplanetary medium is still generally controlled by coronal hole dynamics out to ~20 AU and up to 23° latitude from the heliographic equator.

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