CONF-9709316--

LA-UR-98-2730

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Author(s): See Attached

Submitted to: Correlated Phenomena at the Sun, in the Heliosphere and in Geospace
ESTEC, Noordwijk, The Netherlands
September 22-25, 1997

Los Alamos
NATIONAL LABORATORY

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SPATIAL EVOLUTION OF 26-DAY RECURRENT GALACTIC COSMIC RAY DECREASES: CORRELATED ULYSSES COSPIN/KET AND SOHO COSTEP OBSERVATIONS

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ABSTRACT

In December 1995 the Ulysses spacecraft was at a radial distance of 3 AU from the Sun and 60° northern heliographic latitude. To that time the Solar and Heliospheric Observatory (SOHO) started its mission. On board of both spacecraft particle sensors are measuring electrons, protons and helium nuclei in the MeV to GeV energy range. In early 1996 the counting rates of several hundred MeV galactic cosmic rays at Ulysses and at SOHO (Earth orbit) were modulated by recurrent cosmic ray decreases (RCRDs). The RCRDs at SOHO were found to be associated with a corotating interaction region (CIRs).

A Lomb (spectral) analysis was performed on the galactic cosmic ray flux from February 1996 to June 1996. Surprisingly, the most probable frequency is ~28 days and not 26 or 27 days, corresponding to one solar rotation. The amplitude of the RCRDs is ~2.3% on both spacecraft. The variation in the solar wind speed shows the same periodicities and is anticorrelated to the variation in the cosmic ray flux (see Richardson et al. 1996). In contrast to the RCRDs the amplitude found in the solar wind speed is four times larger at WIND (120 km/s) than at Ulysses (32 km/s). The solar wind proton density and magnetic field strength yielded no significant periodicities, neither at Ulysses nor at WIND. Comparing the RCRDs with coronal hole structures observed in the FE XIV line, we found that a single coronal hole close to the heliographic equator can account for the RCRDs observed "simultaneously" at Ulysses and SOHO. The coronal hole boundaries changed towards lower Carrington longitudes and vanished slowly. The changes of the boundaries during the investigated period could explain a 28 day periodicity.

Key words: Cosmic Ray Modulation, Corotating Interaction Regions, Coronal Holes

1. INTRODUCTION

The effects of corotating interaction regions (CIRs) on cosmic rays were first studied in detail about 20 years ago (Barnes & Simpson 1976). The three-dimensional extent of CIRs and its importance in structuring the quiet heliosphere, however, became obvious first from Ulysses observations at high heliolatitudes. A major surprise of this mission was the observation of pronounced recurrent cosmic ray decreases (RCRDs) up to polar regions (Kunow et al. 1995, Dröge et al. 1996, and Zhang et al. 1995). It had been presumed that strong 26-day variations would disappear as the spacecraft climbed to higher latitudes.

In early 1996 the galactic cosmic ray fluxes measured at the position of Ulysses at 3 AU and ~50° N and at SOHO close to Earth show pronounced solar rotational modulation of cosmic rays. At the same time a co rotating interaction region (CIR) was observed by the WIND spacecraft at Earth orbit. In this paper we investigate the spatial and temporal variation of these modulation and the correlation to coronal hole structures seen in the FE XIV synoptic maps.

2. INSTRUMENTATION

The particle observations presented here were made with the COsmic and Solar Particle INvestigation Kiel Electron Telescope (KET) onboard Ulysses (Simpson et al. 1992) and the COSTEP Electron Proton Helium INstrument (EPHIN) onboard SOHO (Müller-Mellin et al. 1995). Solar wind speed observations onboard Ulysses and WIND were made with the solar wind ion and electron spectrometer (SWOOPS) and the solar wind experiment (WIND SWE). The instruments are described by Bame et al. (1992) and Ogilvie et al. (1995).Magnetic field

Proc. 31st ESLAB Symp., 'Correlated Phenomena at the Sun, in the Heliosphere and in Geospace', ESTEC, Noordwijk, The Netherlands, 22-25 September 1997 (ESA SP-415, December 1997)

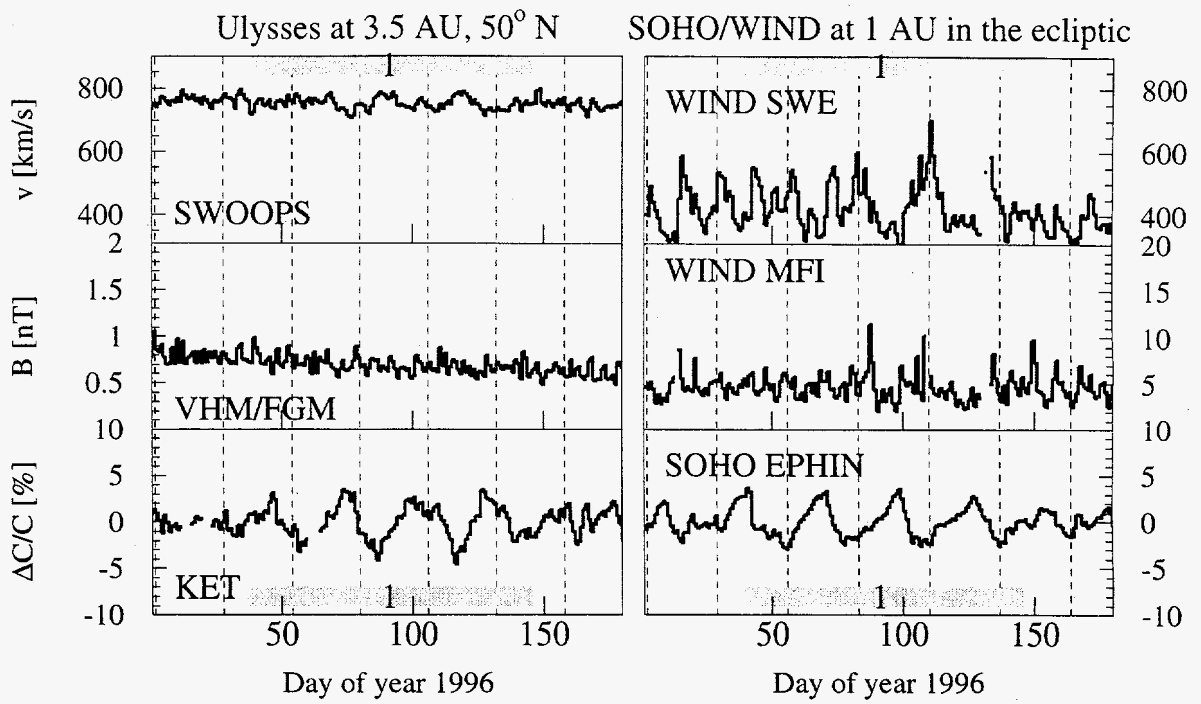

Figure 1. Daily averaged solar wind speed (upper panels), magnetic field strength (middle panels) and detrended counting rates of >100 MeV protons (bottom panels) measured by Ulysses (left, at 3.5 AU and ~50° N) and by SOHO and Wind at Earth (right). During the shaded period the >100 MeV protons are modulated on a time scale of about one solar rotation.

measurements were performed by the Ulysses magnetometer experiment (VHM/FGM, Balogh et al. 1992 and the WIND Magnetic Field Investigation (MFI Lepping et al. 1995).

3. OBSERVATION

The left panels of figure 1 shows measurements made by Ulysses at 3.5 AU and ~50° N and the right panels shows measurements made on SOHO/WIND at 1 AU. Displayed from top to bottom are the daily averaged solar wind speed, the magnetic field strength, and the detrended count rates $\Delta C/C$ of >100 MeV protons from the beginning to mid 1996. Magnetic field and solar wind data at 1 AU were taken from the WIND and particle data from the SOHO spacecraft.

As described in more detail in Kunow et al. (1997) we used the daily averaged count rates ($C(t)$) and one solar rotation averaged running means ($S(t)$) to calculate the detrended variations $\Delta C/C$:

$$\Delta C/C = (C(t) - S(t))/S(t)\,. \qquad (1)$$

The dotted vertical lines mark the time period of one solar rotation - 26 and 27 days at Ulysses and Earth. From Figure 1 it can be seen that from February 1996 to June 1996 (shaded period) the KET and EPHIN >100 MeV protons are modulated on a time scale of about one solar rotation. CIRs can be identified in characteristic changes of the solar wind speed and magnetic field strength (see Smith & Wolfe 1977). From the Ulysses magnetic field and solar wind speed data we found no any obvious CIR signature. At Earth the measurements show more complex variation than at Ulysses. In contrast to the particle data the solar wind speed and magnetic field measurements are not dominated by a single recurent structure (see Richardson et al. 1996).

4. DATA ANALYSIS

To investigate the periodicity of the RCRDs at both spacecrafts we performed a spectral analysis method developed by Lomb (1976) for $\Delta C/C$, for the solar wind speed v, and for magnetic field strength B . Figure 2 shows in the upper panels the measured $\Delta C/C$ (black curves) and solar wind speed (grey curves) profiles measured at Ulysses (left) and at Earth (right). The lower panels display the result of the spectral analysis, the Lomb periodigram, for $\Delta C/C$ and v. For each frequency in the range of 10^{-2} to 0.5 day^{-1} the corresponding spectral power in the data was calculated. The probability, that frequencies with a power above the upper horizontal dashed line are random, is below 0.1%. The peaks in the periodigram at frequencies corresponding to ~28 days, close to one solar rotation, is significant. Possible explanation for a difference between an expected period of 26 days at Ulysses and 27 days at SOHO versus the 28 days found, will be given later, when we discuss single events more in detail. When we perform the same spectral analysis on the magnetic field strength and proton density, not shown here, no signifcant periodicity was found, ia. clear

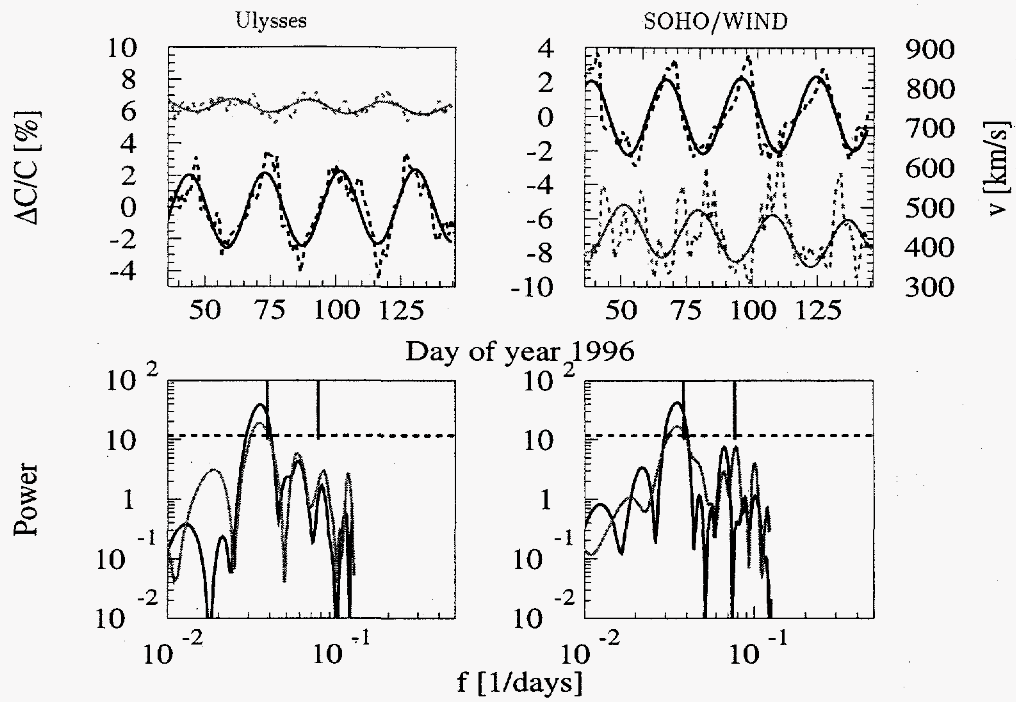

Figure 2. Particle and solar wind measurements of Ulysses (left) and SOHO/WIND (right). The upper panels show the measured $\Delta C/C$, and the solar wind speed and their approximation by a sinusoidal. Note that for Ulysses the solar wind speed are the upper curves and for SOHO/WIND the lower curves. The lower two panels show the Lomb periodigrams for the solar wind speed and $\Delta C/C$. The two vertical lines in each periodigram mark frequencies of 26 and 13 day periodicities.

	Ulysses 3.5 AU, 50° N	SOHO/WIND 1 AU in the ecliptic
$f(\Delta C/C)$/days $A(\Delta C/C)$/%	28.9 (2.3±0.4)	28.5 (2.2±0.3)%
$f(B)$ $f(\rho)$	nspf nspf	nspf nspf
$f(v)$/(days) $A(v)$/(km/s)	28.9 32	28.4 120
phase $\Delta C/C$ to v	~180°	~180°

Table 1. Fit parameter f, A and phase for four RCRDs, magnetic field strength B, proton density ρ, and solar wind speed v observed by Ulysses and SOHO/WIND. nspf stands for no significant period found.

local signature of a CIR were appearent, neither at Ulysses nor SOHO/WIND.

For the further analysis we used the most probable frequency f to determine the Amplitude A and Phase of the RCRDs. The result of this analysis is displayed in the sinusoidal curves (upper panels of Fig. 2) and summarized in Table 1.

The amplitude A of the RCRDs is 2.3±0.4% at Ulysses (3.5 AU, ≈50° N) and 2.2±0.3% at 1 AU in the ecliptic and is within the uncertainties independent of the spacecraft position, indicating that the galactic cosmic ray flux is modulated uniformly by the same CIR in the inner heliosphere. Note, that

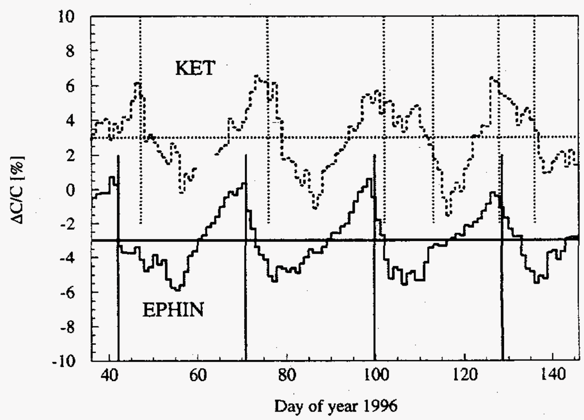

Figure 3. Daily averaged detrended >100 MeV proton count rates. EPHIN and KET data are the solid and dashed lines, respectively. The vertical lines mark the onset of individual RCRDs seen by SOHO at Earth and Ulysses.

t_0 @ Earth	t_0 @ Ulysses	Δt	$(\Delta t)_{\text{exp}}$
Day of year 1996		days	days
41	47	6	5
70	75	5	4
99	102	3	2
127	127	0	1
	113		
	136		

Table 2. Approximated onset times for the RCRDs seen by EPHIN and KET. $(\Delta t)_{\text{exp}}$ and Δt are the expected and measured time lack between both spacecraft calculated under the assumption that the first four RCRDs are caused by a corotating stream ($v \sim 750$ km/s).

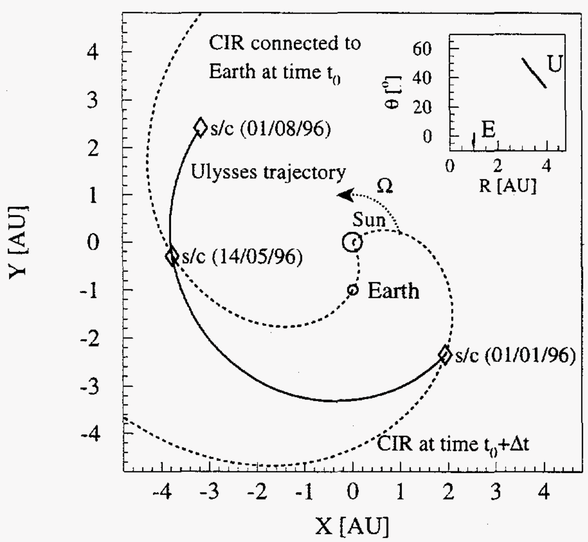

Figure 4. Position of Ulysses (solid line) from January 1996 to August 1996 in a reference frame with a fixed Sun-Earth position. The dashed lines represents the Archimedian spirals of a fast wind stream (750 km/s) corotating with the Sun. The insert shows the latitudinal variation of Ulysses (U) during this time period heading towards the heliographic equator.

the absolute >100 MeV proton flux is ~12% higher at Ulysses than at Earth (Heber et al. 1997). In contrast to the RCRDs the amplitude of the solar wind speed variation is four times larger at Earth (120 km/s) than at Ulysses(32 km/s). We find this result to be in contradiction to the idea that the solar wind speed variation alone is causing the RCRDs (Richardson et al. 1996).

In the following paragraph we will give further evidence that the RCRDs seen by EPHIN and KET are caused by the same CIR. Figure 3 shows the daily averaged detrended count rates of >100 MeV protons seen at the position of Earth (solid line) and Ulysses (dashed line). The vertical lines mark the approximate onset times of RCRDs seen by KET and/or EPHIN. These times are listed in Table 2. Note, that the shape of the RCRDs for KET is smoother than for EPHIN. Let us assume that a single CIR is causing a RCRD at Ulysses and at Earth. The

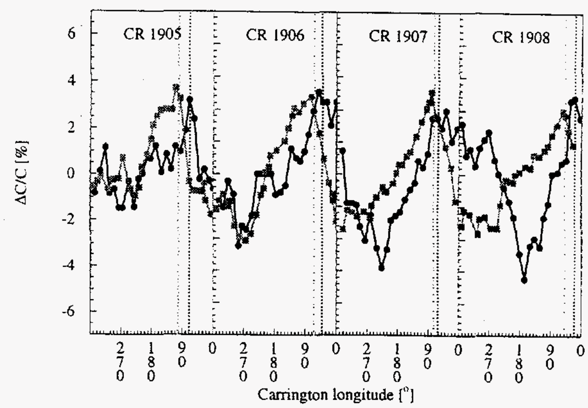

Figure 6. Daily averaged, detrended >100 MeV proton count rates for Carrington rotation 1905 through 1908. For every Carrington rotation the longitude is counted from right to left and time from left to right. All RCRDs seen by EPHIN are close to 90° Carrington longitude.

relative position of both spacecraft, as shown in Figure 4, and the large scale, maybe tilted, CIR geometry then would determine the recurrent temporal variations (see Gosling et al. 1995). The solid line in Figure 4 shows the trajectory of Ulysses projected onto the ecliptic plane in a reference frame for a fixed Sun-Earth system. The two dashed curves represent the magnetic connection of Earth and Ulysses in January 1996 to the sun assuming a solar wind speed of 750 km/s. In this example a RCRD caused by this stream will first pass the Earth and later Ulysses. The delay Δt depends on the solar wind speed v, the radial distance Δr and the longitudinal distance $\Delta\phi$ of both spacecraft. From Figure 4 it is obvious, that Δt is decreasing with increasing time. Using a solar wind speed of 750 km/s we expect that the RCRD caused by this stream will be measured at Ulysses and Earth at the same time on 14. May 1996. The expected and measured time lags, calculated under these assumptions, are listed in Table 2 and compatible with each other.

To identify the associated coronal holes that could be attributed to the CIRs and the RCRDs at both spacecraft, Figure 5 shows FE XIV Carrington maps of the Sun for Carrington rotation 1905 through 1908 (day 19 through 127). Coronal holes are marked as white areas bordered by black. To compare the cosmic ray data with the synoptic maps we calculated the corresponding Carrington longitude of both spacecraft based on the locally measured solar wind speed. The black and gray curves in Figure 6 display the detrended cosmic ray count rates measured by the KET and EPHIN instruments as a function of Carrington longitude. In Figure 6 the longitude is increasing from right to left for every Carrington rotation. Note, that in this representation time is increasing from left to right. The vertical dashed lines mark the approximate onset longitude of the RCRDs seen at KET (dashed lines) and EPHIN (solid lines). The RCRDs seen by EPHIN are relatively stable and located at ~60 to 90°. In comparison with Figure 5 these RCRDs can be attributed to a coronal hole seen close to the heliographic equator. The magnetic field measurements on WIND show that this

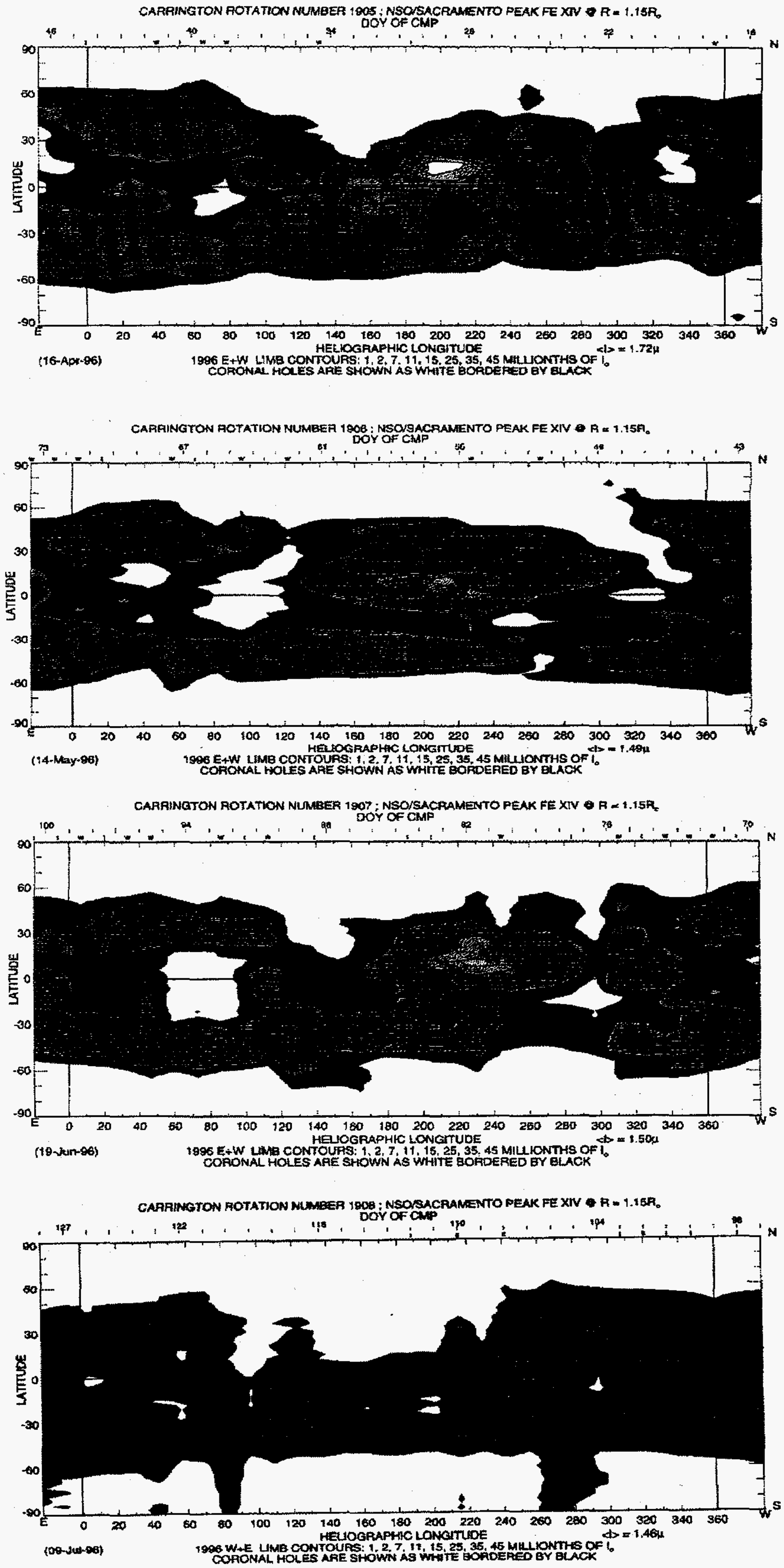

Figure 5. FE XIV maps for Carrington rotation 1905-1908.

recurrent fast stream has a southern polarity. During Carrington rotation 1905 and 1906 also a RCRD close to 60° longitude is observed with KET. Considering the fact, that both spacecraft are at different latitudes, the measured cosmic ray spatial/time profiles agree very well during these two rotations. As can be seen in Figure 5 the coronal hole boundaries are changing from one rotation to the next. This temporal changes could be in principle responsible for the measured ~28 day periodicity. During rotation 1907 and 1908 the signature of this RCRD is getting weaker. From rotation 1906 through 1908 the structure of the coronal boundaries was reorganized. In qualitative agreement with the temporal evolution of the RCRDs observed by KET.

5. SUMMARY

We analysed four RCRDs observed by KET on Ulysses and EPHIN on Soho in early 1996. We conclude tentatively that these RCRDs are caused by the same CIR. The fast stream had its origin in a coronal hole at ~90°. The temporal evolution of this coronal hole may be responsible for a somewhat longer, 28 day instead of 26/27 day, periodicity. Because of the large latitudinal separation of both spacecraft one would not expect to find such a good agreement. The results can be summarized as follows:

1. a periodicity of ~28 days for these RCRDs at both spacecraft,
2. an amplitude of ~2.3% independent of the spacecraft position.
3. the same periodicities in the solar wind speed
4. an amplitude of 120 and 32 km/s, respectively, in the solar wind speed, depending on the spacecraft location.
5. a phase of 180° between solar wind speed and the RCRD (see also Richardson et al. 1996)
6. a correlation between RCRDs and temporal variations of coronal hole structures in the Suns corona as seen in the FE XIV line.

ACKNOWLEDGEMENTS

This work was partly supported by Deutsche Agentur für Raumfahrtangelegenheiten (DARA) under Grant No. 50 ON 9106.

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