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The regular structure of shock-accelerated ∼40-100 keV electrons in the high latitude heliosphere

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Abstract. The passage of *Ulysses* through the high latitude heliosphere has given us a new insight into the interplanetary dynamical processes which are occurring, at any rate near solar minimum, in the heliosphere above the streamer belt. We report here observations of ∼40-100 keV electrons and ∼0.5 MeV protons detected by HI-SCALE from 1992-96. Apart from a few increases associated with solar energetic particle events and coronal mass ejections, the dominant events were recurrent and associated with a long-lived corotating interaction region (CIR). Furthermore, we show that for the majority of the high latitude events the acceleration region is at radial distances many AU beyond the spacecraft. Beginning with the hypothesis that the acceleration is taking place at the reverse shock of a regular, but expanding CIR, we show that the appearance of the electron increases at *Ulysses* is ordered by the right ascension and radial distance of *Ulysses* in the frame of reference corotating with the Sun. The timing of the maxima of the electron recurrences is predicted sufficiently accurately with this model, so that the accelerated electrons can be used as a clock during the high latitude phase of the mission. Although the recurrent events are not as strong in the northern hemisphere as in the south, those seen up to the middle of March, 1996 are consistent with the model when known changes in the coronal structure are taken into account.

Key words: interplanetary medium – acceleration of particles – shock waves

1. Introduction

The passage of *Ulysses* through the high latitude heliosphere has provided us with new insights into the way energetic particle acceleration occurs at corotating interaction regions (CIR). As *Ulysses* left the ecliptic plane in mid-1992 the solar wind was modulated by a recurrent high speed stream (Bame et al., 1993) which produced both forward and reverse shocks where it interacted with the slower solar wind within the streamer belt. Energetic ions and electrons were accelerated at these shocks. As the spacecraft climbed to higher latitudes the complete plasma and magnetic field signatures of the CIR were no longer detected; however, the ∼40-100 keV electron increases, and to a lesser extent the ∼0.5 MeV protons, continued to be detected in a modified form up to the highest latitudes. The strength of the increases declined as the latitude increased, and vice-versa.

The evolution of the electron and ion signatures has been discussed by Simnett and Roelof (1995) for the period covering the passage of *Ulysses* up to around 55°S. Within the streamer belt (below 30°S), simultaneous electron and ion increases were seen in coincidence with the detection of the forward (FS) and reverse shocks (RS) in the magnetic field and solar wind plasma instruments. Larger increases of both ions and electrons were associated with the RS, compared to the FS. However, after the FS of the CIR was no longer sampled directly by *Ulysses*, the electron increases were delayed with respect to the ions. Simnett and Roelof attributed both the ion and electron increases to acceleration from the RS, and they explained the electron delays in terms of direct magnetic connection to the RS of the CIR at radial distances well beyond *Ulysses* (possibly as much as 14 AU). Both electrons and ions escape upstream from the shock and the geometry is such that they move in towards the inner solar system. The electrons, which have velocities around 0.5c, are fast enough that they can enter the inner solar system, mirror, and move back to the shock for further acceleration. The ions are moving at less than 0.05c and thus propagate less effectively into the inner heliosphere against the outward convection of the magnetic field by the solar wind. Eventually, as the spacecraft approached the polar region (and even the RS signature disappeared), the ions were no longer detectable above instrument background, but the recurrent electron increases persisted.

The behaviour of the recurrent increases is important for an understanding of the structure of the interplanetary medium in three dimensions. In this paper we show that the electron increases at *Ulysses* recur as if they were a corotating structure ordered along a surface normal to the heliographic equator gen-

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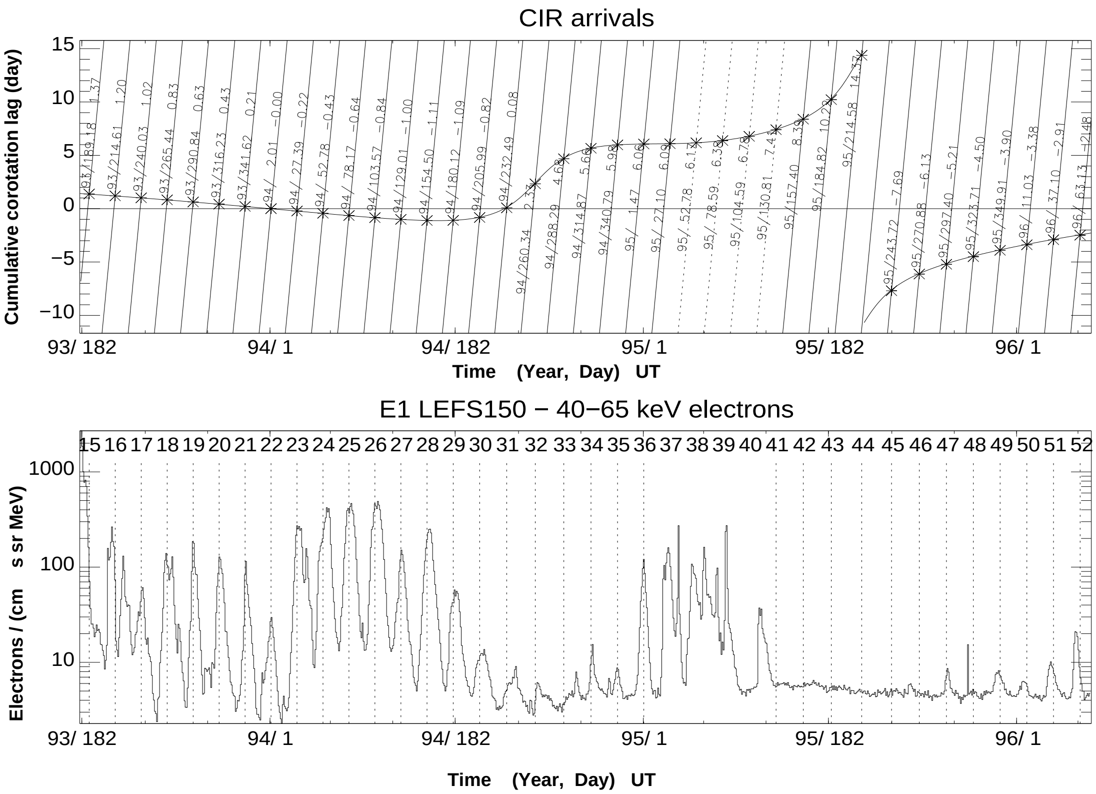

Fig. 1. Upper panel: The cumulative corotation lag for the CIRs expected at *Ulysses*, taking into account the radial distance and right ascension of *Ulysses* and a solar wind velocity of 750 km/s. The origin for zero days lag is arbitrarily chosen to be the peak intensity of CIR 22 (on day 2.0 of 1994), when *Ulysses* was at 3.83 AU and at RA -87.6°. The curve represents the cumulative phase shift due to the trajectory of *Ulysses* and the numbers attached to each rotation are the dates when a 750 km/s Parker spiral surface would intersect the orbit, together with the cumulative lag. The slanting lines give strict corotation with a period of 25.6 days (determined by requiring agreement with the maximum of recurrence 36 on day 1.5 of 1995). Lower panel: The daily averaged intensity-time history of the 40-65 keV E1 electron counting rate from 29 June 1993 to 13 March, 1996. The vertical dotted lines are plotted at the intersection of the *Ulysses* trajectory with the corotating Parker spiral surface.

erated by Parker spirals for a constant solar wind velocity, all originating from the same coronal heliographic meridian. Using this timing model, it is possible for us to correct for the the motion of *Ulysses* in right ascension and radial distance and therefore predict when the electron increases should be observed. We find that within the statistical uncertainties of the data the increases do in fact behave in a clock-like fashion, thus confirming the interpretation of Simnett and Roelof (1995) that the magnetic field lines form a well-ordered and predictable structure in the interplanetary medium. This regular behaviour is most probably due to the fact that the high-latitude observations were made during the declining phase of the solar cycle when there was a long-lived extension of the south polar coronal hole towards low-latitudes. The phase of the clock is determined by the longitude of this coronal-hole extension.

We make a distinction between this timing model and the actual magnetic configuration of the middle heliosphere. Although Pizzo (1994) has shown that a CIR will expand poleward as it moves to large radial distances, the distance-scales on which this occurs are much greater than those implied by the delays in the electron arrival times; therefore the actual magnetic connection to the RS of the CIR (the likely site of the electron acceleration) cannot occur via Parker spirals lying on cones of constant heliolatitude. Rather, we believe that it actually occurs via the more complex field configuration suggested by Fisk (1996) in which high latitude field lines are brought to lower latitudes in an ordered manner. The demonstration that the connection to the CIR RS via this latter field model results in a phasing similar to the timing model presented here is left to another study (Roelof and Simnett, *in preparation*). Our purpose in presenting the timing model is to demonstrate the extremely ordered spatial distribution of the shock-accelerated electrons, and to show that they act as a "clock" for the remote connection from *Ulysses* to the distant RS of the CIR.

We have extended the analysis up to 13 March, 1996, when 6 recurrent electron increases had been detected in the northern hemisphere. The last of these, which had a maximum electron intensity around 28 February, 1996, was delayed around three days from the maximum in the ions. There are two other events seen so far in the north which we believe are not CIR-associated. The event between rotations 40/41 is a solar event. We suspect the small electron increase between rotations 45/46 following

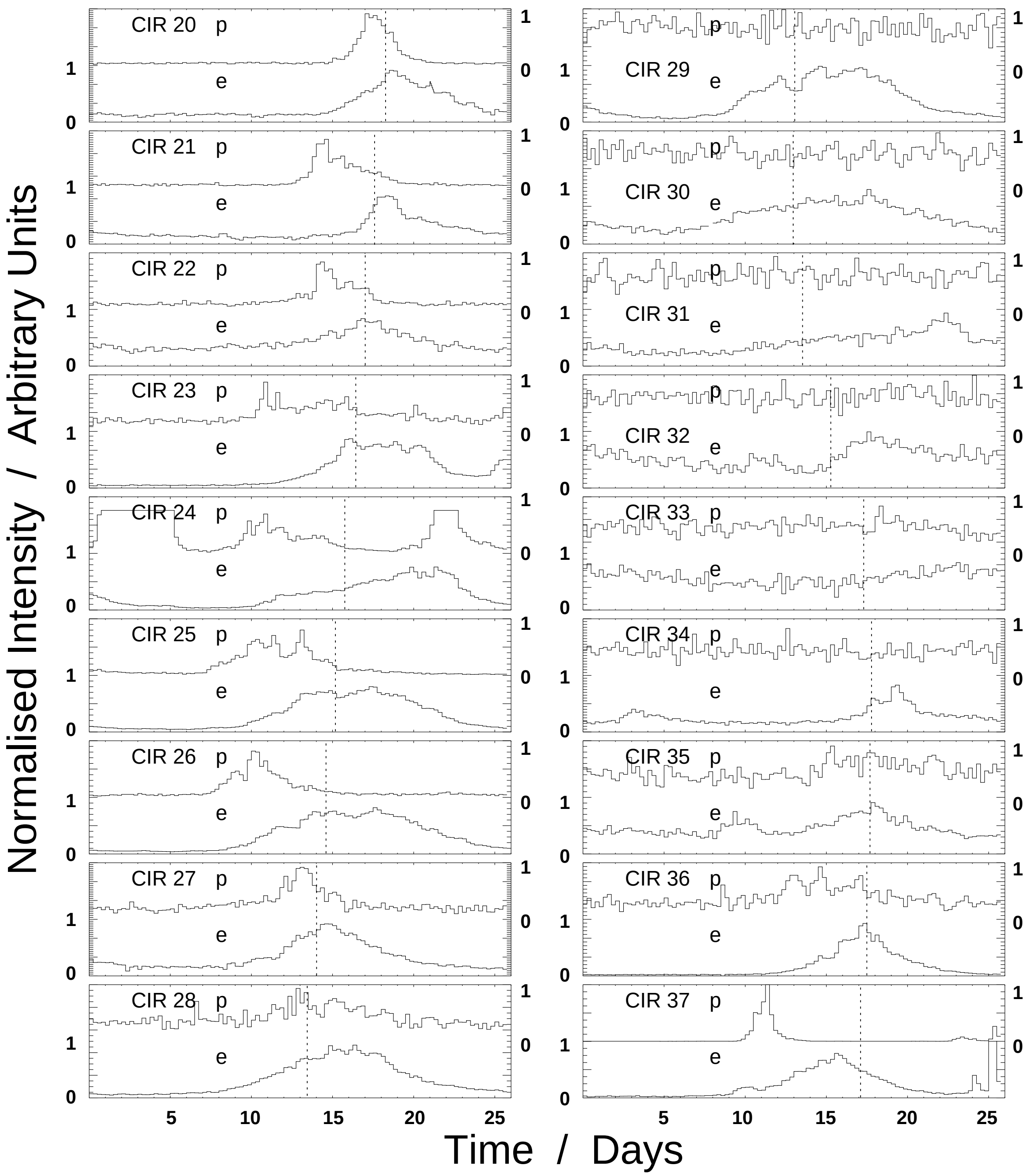

Fig. 2. The relative timing between ∼50 keV electrons and ∼0.5 MeV ions for the recurrent events between 25 October 1993 and 4 February, 1995. The data are 6-hour averages, plotted in 26.0 day blocks; the intensity scale has been normalised to the maximum intensity of the recurrent events and is in arbitrary units. In electron events with associated ion increases (CIR 20-28 and 37) the DE1 deflected electron channel is plotted; in the other events without the possibility of ion contamination, the LEFS150 E1 channel is plotted; the ion channel is always W1. The vertical dotted lines mark the arrival times predicted by the timing model.

the north polar pass is also a solar electron event (at 73°N). This conclusion is based on the intensity-time profile which has a decay time an order of magnitude longer than the rise time, plus the anisotropy of ∼2:1 at the peak of the event in favour of electrons coming from the solar direction (LEFS60/LEFS150).

2. The analysis procedure

The observations we discuss here were made with the Heliosphere Instrument for the Spectrum, Composition and Anisotropy at Low Energies (HI-SCALE; Lanzerotti et al., 1992) from 29 June, 1993 to 13 March, 1996. In particular we are using the 40-65 keV electron channel from the LEFS150 detector (referred to as E1), the 38-53 keV magnetically-deflected

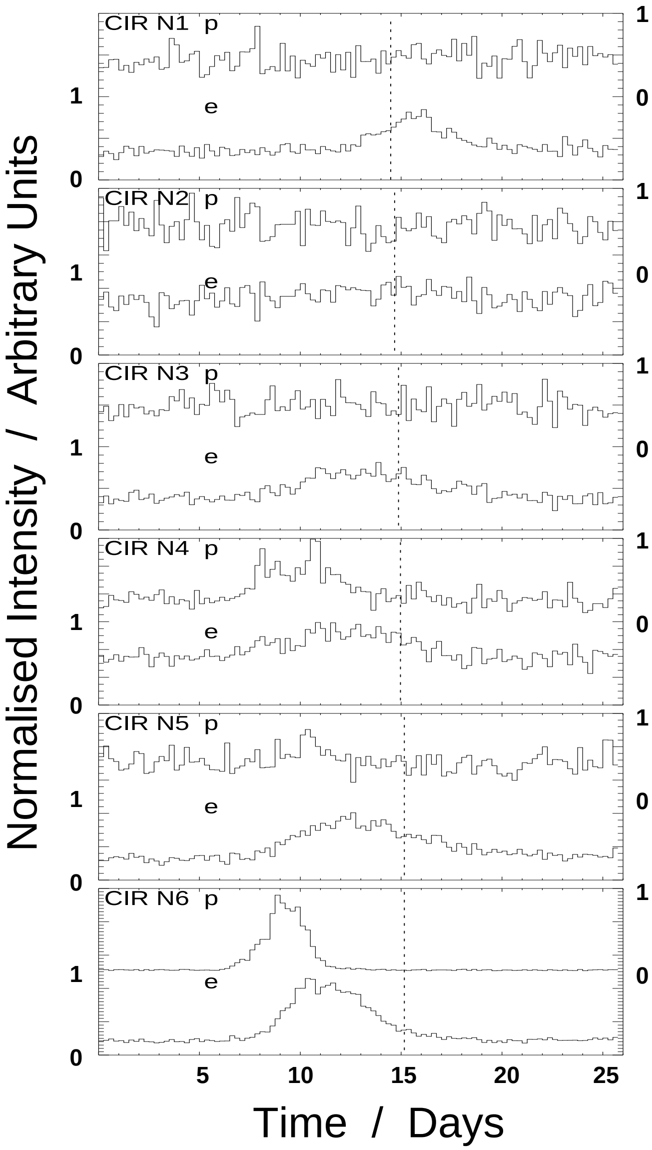

Fig. 3. The relative timing between ∼50 keV electrons and ∼0.5 MeV ions for the recurrent events between 10 October 1995 and 13 March, 1996. The format is identical to that of Fig. 2, but the phase of the zero days has been adjusted by 13.0 days to bring the peaks closer to the centres of the plots. The LEFS150 E1 and CA60 W1 channels are used in all panels.

electrons coming through the LEMS30 aperture (DE1) and the 480-966 keV proton channel from the CA60 detector (W1). The angle between the axes of the detector collimators and the spacecraft spin axis is indicated by the number in the aperture name (e.g. LEFS150 views particles arriving at $\sim$ 150° to the spin axis).

Fig. 1(lower panel) shows the daily intensity-time history of the spin-averaged E1 counting rate. The recurrent increases are numbered according to the sequence started by Bame et al. (1993) when the regular high speed streams were detected by *Ulysses* in mid-1992. The passage of *Ulysses* through the streamer belt in early 1995 encompasses rotations 37-39 and any recurrent events during this period are merged with the generally-enhanced particle fluxes associated with the streamer belt. We therefore concentrate mainly on rotations 15-37 during the southern polar pass. There is a consistent shape to the electron increases which is present throughout, even though it is somewhat "ragged" at the highest latitudes. Note that the south polar pass was at rotation 32, the equatorial crossing around rotation 38, and the north polar pass at rotation 43.

The spacecraft heliographic ephemeris gives us the radial distance, r (AU), the heliolatitude, β, and the right ascension α. We assume that the solar wind speed is constant at $v_{\rm sw}$ = 750 km/s everywhere outside the streamer belt (latitudes $\sim \pm 20°$); this is a reasonable approximation given the narrow range of observed values (Phillips et al. 1995). We also have to fix the phase of the recurrences and determine the effective sidereal rotation rate, ω, of the corona. For convenience we choose zero phase lag to occur at the peak in the recurrent electron event 22 on 2.0 January, 1994, when *Ulysses* was at r_0 = 3.83AU, $\alpha_0 = -87.6°$ and $\beta_0 = -48.5°$. We then require that the timing model should agree one year later with the maximum of recurrence 36 (as *Ulysses* approached the streamer belt after the south polar pass) on 1.5 January 1995. This choice fixes the sidereal rotation period at 25.6 days, which corresponds to a synodic period of 27.5 days which is comparable with the Carrington period of 27.3 days (25.4 sidereal) and lies within the range of coronal rotation rate observed by Nash (1991). The corotation angular lag at any given location (r, β, α) is then given by

$$\Delta\phi = (\alpha - \alpha_0) + \omega(r - r_0)/v_{\rm sw}.$$

This may be put in terms of the arrival time lag at *Ulysses*:

$$\Delta t = \Delta\phi/\omega.$$

From the spacecraft ephemeris and the equations above we have calculated the corotation lag as a function of time; this is plotted as the curve in the upper panel of Fig. 1. The sloping lines across this panel are a line of unit slope passing through 0 at our selected origin of time (2 January 1994) and repeated at 25.6 day intervals (they are shown dotted in passage through the streamer belt where this timing model is not applicable). The predicted arrival time of the particles at *Ulysses* is then given by the intersections of these lines with the corotation lag curve; these are marked with asterisks. The dotted vertical lines in the lower panel are then the projections of the intersections (asterisks); these have been omitted in the streamer belt. We find that with this approach there is a remarkable fit through the peaks of the majority of the electron events from 15-37. The only poor fits are around the highest latitudes. There are three significant solar events in this data set, close to CIR 15, 23 and 24, which accounts for the extra features seen in the electron data at these times. In addition, there are some solar particle "inter-events" between the recurrences visible in late 1993 (Roelof et al., 1995).

Once *Ulysses* has gone into the northern hemisphere the high speed solar wind is now intersecting structures related to the structure of the corona in the northern hemisphere. Examination of the events after rotation 45 indicates that (a) there are still events present, (b) they are recurrent (c) they are less intense than those in the south.

We now look at the ion increases. Simnett et al. (1994) showed that once *Ulysses* had left the streamer belt the electron increases lagged behind those of the protons. Their analysis stopped at CIR 21. In Fig. 2 we extend the comparison of the relative timing of the electron and proton increases, plotted on an exact 26-day cycle, keeping the same 26 day sequence for the zero days as Simnett et al. (1994). Thus the absolute phase of the electron events slides within the 26-day window according to the phase shift in the upper panel of Fig. 1. Here the intensity is plotted normalised to a maximum, in arbitrary units, simply to illustrate the timing differences. (The times of the maxima predicted by the timing model are indicated by the vertical dotted lines in the figure.) The left panel covers CIRs 20-28, up to the time when the proton increases cease to be significant. In CIR 24 there were proton events associated with coronal mass ejections and these have been truncated to emphasize the proton increase at phase 10-15 days. In the right panel the proton increases are not present above background in CIRs 29-34, but possibly reappear in CIR 35, and definitely in CIR 36. CIR 37 contains a solar particle event which starts at phase 9 days in the electrons, with a strong proton event following. However, the recurrent electron increase is clear, reaching maximum intensity around phase day 16. There was an additional impulsive solar electron event at the end of the period covered by CIR 37 which has been suppressed.

Fig. 3 is a similar plot for the six electron events so far detected in the northern hemisphere through late 1995 and early 1996, a 13-day shift in the phase of the zero-days of the plots relative to a continuation of the 26-day period of Fig. 2 has been introduced to bring the peaks of the electron events near to the centre of the panels; we have numbered these increases N1-N6. Remarkably, the phasing of their maxima (up to N5) is within a few days of that predicted by the timing model whose parameters were set during the **southern** polar pass in 1994. Thus (as can be seen in Fig. 1) N1 can be identified with recurrence 47 etc. For a simple-minded picture with a time-stationary coronal structure this would appear to imply a North-South mirror symmetry of the solar-wind structure about the heliographic equator. However when we examine the NSO/Sacramento Peak Fe XIV synoptic maps (Solar Geophysical Data) we see that there were major changes in the boundaries of the polar coronal holes between Carrington rotations 1892 (Jan/Feb 1995) and 1898 (July 1995); in particular the northward extension of the southern hole at a Carrington longitude of $\sim 330°$ (which had persisted since at least mid 1992) disappeared, while a southward extension of the northern hole appeared a few rotations later at a very similar Carrington longitude. These equatorward extensions will generate stream-stream interactions between the fast solar wind from the coronal hole and the slow solar wind from the streamer belt; it is this interaction which develops into the CIR as it propagates outward into the heliosphere.

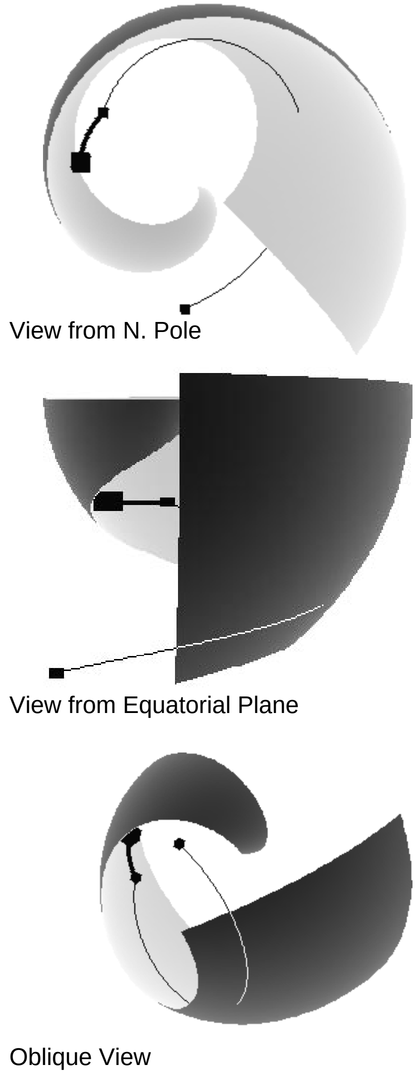

Fig. 4. The reverse shock associated with an expanding CIR in three dimensions (suggested by the model of Pizzo, 1994). The large rectangle indicates the position of *Ulysses* when it is closest to (but just below) the poleward edge of the reverse shock; the small squares delimit a field line originating some four days later along the *Ulysses* orbit (when the maximum electron intensity would be observed from a stronger region of the shock). The heavy arc represents schematically the motion of *Ulysses* while the light arc represents the field line connecting *Ulysses* to the shock at the time the particles are detected.

Although the proton increases do not rise above background until N4 the delay of the electrons is still present, as it was in the southern hemisphere. The latest event N6 is the first increase where the electron intensities are an order of magnitude above background. This occurred at a latitude of 45°N; the comparable latitude in the southern hemisphere was around CIR 21. Examination of the lower panel in Fig. 1 thus shows that there is a striking asymmetry between the two hemispheres; given the major restructuring of the polar hole boundaries which occurred during the *Ulysses* fast latitude scan, this asymmetry could be attributed to a temporal evolution at all latitudes. However, the reappearance of the recurrent events in the northern hemisphere shows that the same type of physical process must be occurring in both hemispheres above the streamer belt in association with the CIRs.

3. Discussion

The connection of *Ulysses* to the CIR is probably a combination of the expansion of the CIR as it moves out in radial distance (Pizzo, 1994) plus the ordered latitudinal transport of magnetic field lines according to the Fisk (1996) model. The presentation of the configuration of heliospheric field-lines predicted by Fisk's field model would require a calculation beyond the scope of our discussion here. However, we can at least illustrate our concept of the essential element, the direct magnetic connection from *Ulysses* to the acceleration region bounded by the reverse shock of the CIR. This is possible because the configuration of the CIR itself is determined by the solar wind stream-stream interaction and is not dependent (to first order) on the configuration of the global heliospheric field. Fig. 4 shows a three-dimensional representation of the RS of an expanding CIR. At low latitudes, the CIR actually sweeps across *Ulysses*, and Simnett et al (1994) showed that in this case the proton and electron intensity maxima were coincident. At latitudes above the streamer belt the CIR is no longer detected by *Ulysses* and the charged particles accelerated by the reverse shock of the CIR, at radial distances beyond *Ulysses*, have to travel back into the inner solar system in order to be detected. Simnett and Roelof (1995) argued that the protons, if they were seen at all, could best be seen when *Ulysses* was first connected to the reverse shock, whereas the electrons, on account of their relativistic velocity, had enough time to enter the inner solar system, mirror and return to the shock for further acceleration, probably several times. The protons are moving too slowly inward against the outward convection by the solar wind to effectively reach *Ulysses* with high intensities. Therefore the peak electron intensity is *delayed* from that of the protons, and at high latitudes the protons are not seen above instrument background.

The data from the northern hemisphere, shown in Fig. 3, are in agreement the timing model we have presented. However the north-south mirror symmetry of the solar wind stream structure required to give the agreement in phasing between the two hemispheres appears to be a fortuitous result of a temporal change in the boundaries of the polar coronal holes. In any case, the recurrent particle events show that at least in the approach to solar minimum, the middle heliosphere, say from a few to 10-20 AU, is dominated by the CIRs, which are the main source of mildly-relativistic electrons and sub-MeV protons. The fact that the high-latitude 40-100 keV electron increases recur so regularly in both the northern and southern hemispheres over an epoch of more than 2 1/2 years from mid-1993 into early 1996 means that the global middle heliosphere, which they probe so effectively because of their velocities (> 0.3c), is highly ordered during the decline of the solar cycle.

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