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Coronal diffusion and high solar latitude recurrent energetic particle increases

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Abstract. Ulysses observations have demonstrated that energetic particle flux increases are not only found to be associated with the regularly appearing recurrent fast streams seen at mid solar latitudes but also that they persist with the same periodicity of occurrence to at least 64° latitude, well into the region where no accompanying plasma speed enhancement is obviously present. We discuss various models for this high latitude phenomenon including acceleration within a lower latitude fast stream with diffusive escape polewards in latitude or the return of flux from a region beyond Ulysses, but conclude that anisotropy data and other evidence on interplanetary diffusion coefficients support solar coronal acceleration at microflare sites followed by diffusion in a network of coronal paths characterised by large field magnitude gradients.

Key words: acceleration of particles – Sun – corona – Sun – particle emission – Sun – flares – Sun – magnetic fields

1. Introduction

A major discovery by Ulysses has been the persistent, recurrent series of high speed streams driving corotating interaction regions (CIR's) seen between 13° and 40° South heliolatitude (Bame et al. 1993). Energetic particle increases are found to coincide with each CIR, (Keppler et al. 1995a). These increases persist to 64°S in the case of 0.5-1.0 MeV protons (Keppler et al. 1995b) and to 75°S in the case of $\geq 50 keV$ electrons (Lanzerotti et al. 1995), even though the solar wind shows little residual trace of the regular 26-day periodicity above 40°. Regular fluctuations of full amplitude ∼200 km/s are seen in the fast stream zone, but at higher latitudes, the wind steadies to a mean ∼ 750 km/s with the fluctuations reduced to ∼ 50km/s full amplitude. Any interpretation of these Ulysses based observations naturally turns to the diffusive shock origin explanation (Palmer and Gosling, 1978, Fisk and Lee, 1980) for the original, ecliptic plane data from Pioneer 10 and 11 which located peaks in the accelerated flux of 1 MeV protons on the forward and reverse shocks of CIR's (McDonald et al. 1976, Barnes and Simpson, 1976). The theory supposes that an interplanetary 'seed' population-probably the solar wind ions-is accelerated at each shock to form a quasi-steady state distribution, convected out by the stream but slowly growing in amplitude as the shock becomes more effective. Thus escape from this accelerator could be the cause of particle enhancements above latitudes where CIR's are seen. However, simple numerical studies have cast doubt on the ability of the observed shocks to bring about a sufficiently fast acceleration to allow MeV particles to appear in a typical sun-spacecraft transit time. This was noticed independently by Moussas et al. (1982) and Bialk and Dröge, (1993) and emphasised by Lim et al. (1996). These last authors are among those who suggest a genuinely solar coronal acceleration process as the major source of acceleration. If this is the case, coronal diffusion, as in prompt solar particle events, (McCracken et al., 1971), should play an important role in determining the latitude spread of the energetic particles seen by Ulysses. In the following, we proceed to consider in more detail the alternatives of interplanetary escape from the known regions of fast stream particle increases or solar acceleration and coronal diffusion as possible models for the high latitude, Ulysses data.

2. Observations

The data to be discussed has been obtained from the EPAC experiment on Ulysses (Keppler et al. 1992). It consists of 4 identical, three-element semiconductor telescopes mounted at different angles relative to the spacecraft spin axis so that, by virtue of the spin rotation, about 80 % of the 4π solid angle is covered during 8 sector sampling. The geometry factor for

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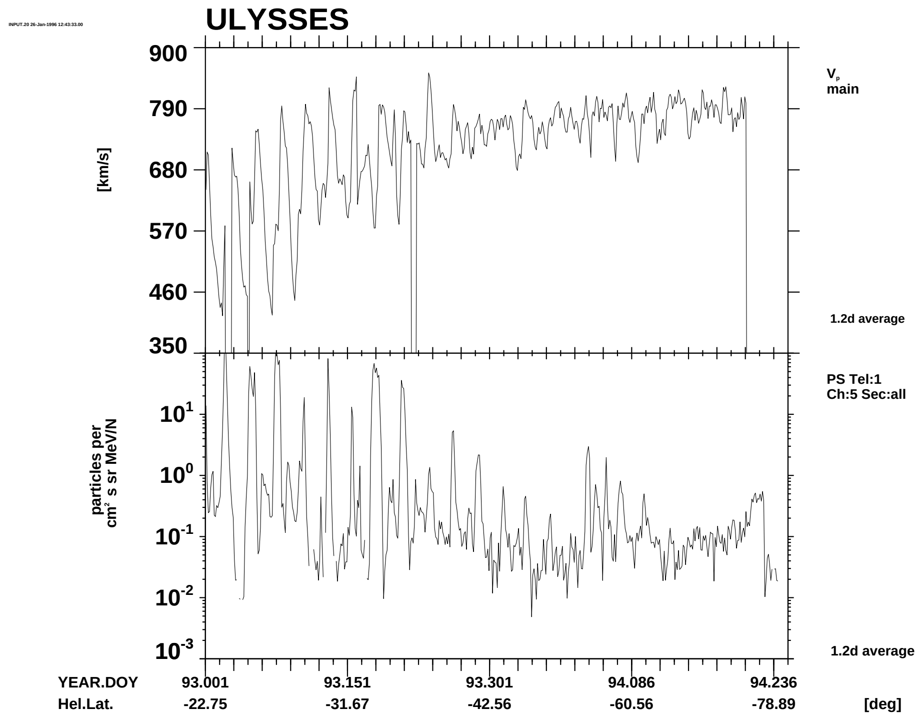

Fig. 1. 0.5-1.0 MeV omnidirectional protons and solar wind speed plotted against heliolatitude for the southern solar pass, 1993-1994.

0.3 to 1.5 MeV protons and 0.4 to 6 MeV/N heavy ions is 0.08 $cm^2 ster$. Energy and charge resolution are achieved by use of the range-energy loss technique in the front two detectors. Electrons are nominally measured in two channels, $0.1 \leq E \leq 0.38$ MeV and $E \geq 0.18$ MeV, although this second channel actually has a predominant response to relativistic protons during quiet times when far from Jupiter. RTG background is unimportant for the data to be described here.

Fig. 1 provides an overview of the phenomenon to be explained, showing the 0.5-1.0 MeV omnidirectional EPAC flux and the solar wind speed plotted against Ulysses heliolatitude for 1993 and 1994, through to the maximum of the southern solar pass. As pointed out by Phillips et al. 1995, in the streamer belt up to $\sim 35°$ a recurrent series of forward and reverse shocks with velocity excursions between 400 and 800 km/s denote the presence of a well-defined high speed stream with an equatorial extension of a south pole coronal hole as source. Beyond this latitude, forward shocks die out although some reverse shocks persist to $-58°$ and while some evidence for the existence of CIR's remains throughout this region, the wind fluctuations are confined to 700-800 km/s. The regular series of energetic proton increases persist to latitude $-67°$, although the peak intensity reduces by up to 4 orders of magnitude.

Figs. 2 and 3 show the first order, Compton-Getting corrected anisotropy of 0.5-1.0 MeV protons, plotted at 12-hourly intervals for the duration of the proton peaks at $-35°$ and $-42°$ respectively. The X component represents the plasma frame radial outward flow, the Z component is flow to the north and the Y component completes a right-handed coordinate set. Both for Fig. 2, on the edge of the streamer belt and for Fig. 3, above the regular, well-defined, fast stream latitude region, flow in equilibrium in the the plasma or solar wind rest frame is evident (The plots are Compton-Getting corrected). Statistical error estimates for the 6 hour anisotropy components are indicated in the figures to confirm the significance of the result. The persistence in outward flow across the streamer belt boundary, taken in conjunction with the continuing regularity of the 26-day period associated energetic particle flux increases, suggests no discontinuity in origin of the particle populations either side of the boundary. We proceed in the next sub-sections to discuss the various possibilities for the cause of the near polar latitude flux enhancements.

3. Models for the high latitude recurrent enhancements

3.1. Continued direct CIR activity effect

It is unlikely that vestiges of CIR activity are directly responsible for the high latitude increases since even for a very prominent, streamer belt event, Lim et al. 1995 found a predicted diffusive shock acceleration time constant five times larger than the sun-spacecraft travel time. This prediction was based on an upstream radial diffusion mean free path of about 0.1 AU, obtained by two, independent particle propagation methods. Direct magnetometer based upstream parallel mean free path estimates in a comparable situation yield about 0.3 AU (Quenby et al., 1993, Drolias, 1994). Because the root mean square fluctuation in the Parker spiral angle is about 23°, this translates into a mean radial m.f.p. of about 0.05 AU , using $\lambda_r = \lambda_{\parallel} cos^2\psi$ where ψ is the field-radial angle and hence the shock acceleration time cannot be much faster in any particular case. Moreover, since the acceleration time constant is inversely proportional to the difference in wind speed across the discontinuity, the significantly reduced

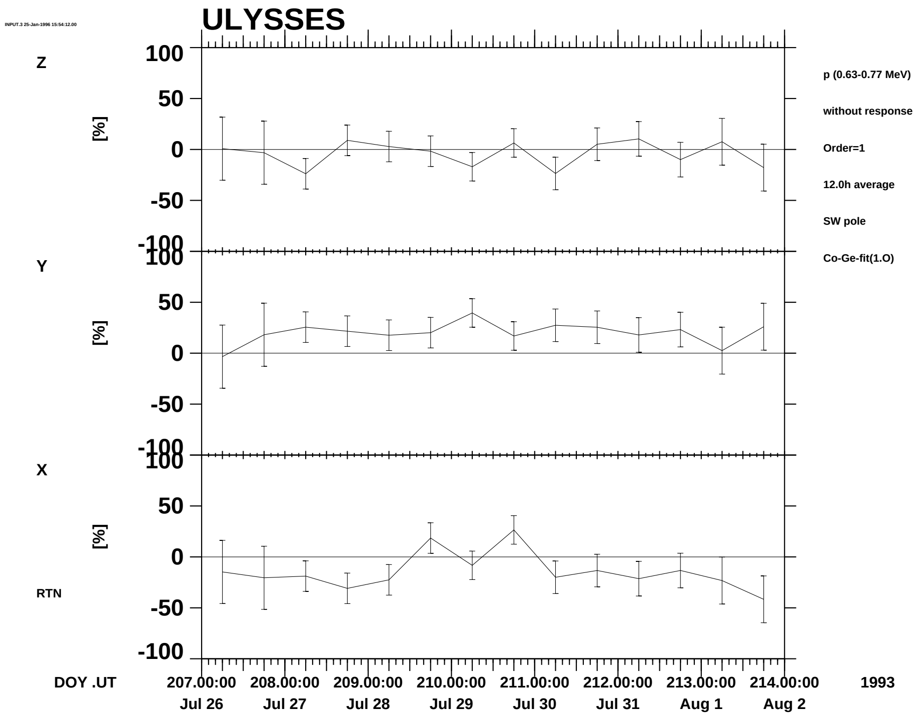

Fig. 2. First order, Compton-Getting corrected anisotropy for 0.5-1 MeV protons plotted at 12-hour intervals for the fast stream centred on 35° south.

magnitude of the velocity fluctuations above the streamer belt renders the expected time constant even larger. It is just possible that shock drift acceleration acting on lower energy, diffusive shock accelerated population causes the increases, at least where there are reverse shocks. However, there is now evidence that in general, quiet time interplanetary conditions, the m.f.p. in the 10's of keV region is very large (Gloeckler et al., 1995).

3.2. Particle escape from low latitude CIR's

Another possible origin of the high latitude enhancements lies in escape via interplanetary trajectories from the low latitude fast streams. Consider first cross field diffusion. Field line wandering and randomised intermediate scale gradient and curvature drift yield a perpendicular to parallel diffusion coefficient ratio, $K_\perp/K_\parallel \leq 0.1$. With $\lambda_\parallel \leq 0.3$ applying at 1 MeV where $\lambda_\parallel$ is the parallel m.f.p., $\lambda_\perp \leq 0.03$. The time to diffuse 20° in latitude at about 4 AU is then $\sim 3 \times 10^7$s. Hence interplanetary cross-field diffusion is too slow to explain the high latitude increases.

Both the EPAC (Keppler et al. 1995) and HISCALE groups (Lanzerotti et al., 1995) have speculated that the poleward spreading of fast stream associated reverse shocks eventually allows field lines going past the spacecraft to intersect with a region of enhanced particle flux when the CIR rotates underneath Ulysses, thus causing a particle increase at Ulysses. Even if the CIR associated increase within the beam is just trapped solar accelerated particles, an escape time constant of about a day is possible according to estimates of Lim et al. 1995, based on scaling of the m.f.p. discussed above. However, although the particles may escape, they will typically only spend 5×10^5s upstream of the shock, so it is not obvious that they will be seen when the stream is up to 5 AU beyond Ulysses, which is where Quenby et al., 1995 require it to be to effectively shield the spacecraft from galactic flux input with radial diffusion. The results of Figs. 2 and 3 on the other hand seem to strongly argue against this inward or return flux hypothesis for the high latitude enhancements.

3.3. Coronal diffusion

Fisk and Schatten (1972) considered two models of coronal diffusion to explain MeV particle propagation in solar longitude which in extreme circumstances enables events on the invisible solar hemisphere to produce detectable increases. In the first, it is noted that coronal magnetic field models based on coronograph observations yield a large scale loop structure, extending typically up to 30° between footpoints. Particle diffusion over greater distances, or indeed to intermediate locations not directly connected by field lines, would require repeated particle mirroring and scattering low down in the corona. This process is considered to be unlikely because of ionization loss and inefficiency of cross-field scattering.

In the second suggestion, a network of neutral sheets separated by filaments associated with the granulation of the photosphere provides the diffusion paths. Drift speeds between $0.3 \times v$ and $0.46 \times v$ are possible, depending on whether the particle sees the field transition as gradual or discontinuous. While the observational evidence for the existence of many such neutral sheets is perhaps unclear, there is definite indication that many sheets of large field gradient do occur(e.g., Habbal, 1994). The drift velocity under a field gradient is

$$v_d = \frac{\rho v_\perp}{2} \frac{\nabla_\perp B}{B} \qquad (1)$$

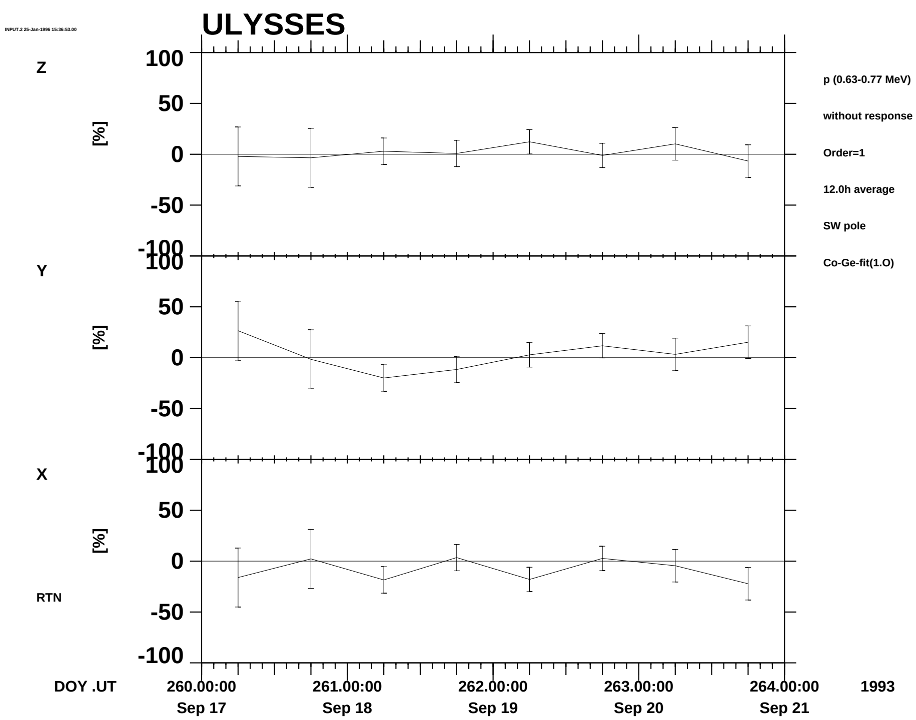

Fig. 3. First order, Compton-Getting corrected anisotropy for 0.5-1 MeV protons plotted at 12-hour intervals for the fast stream centred on 42° south.

where $v_\perp$ is the component of velocity perpendicular to the field $\underline{B}$ and ρ is gyroradius. If the scale size of the gradient, L, where $(\nabla_\perp B)/B \sim 1/L$ is such that $\rho \geq L$,

$$\frac{\nabla_\perp B}{B} \sim \frac{1}{2\rho}, v_d \sim \frac{v_\perp}{4} \tag{2}$$

Now ρ for 1 Mev protons in a 1 gauss field is 10 km and to obtain rapid diffusion at a reasonable fraction of the particle velocity, we require the filaments of field to be bounded by large transitions of this order of size. 10 km is significantly below the current satellite telescope resolution of 700 km at the photosphere. Thus direct solar observation is unlikely to confirm or repudiate the proposed gradient drift diffusion mechanism at the moment. On the other hand, this reinforcement from Ulysses data on particle latitude spread for the need for rapid coronal diffusion, first suggested by ecliptic plane data taken at different solar longitudes, is perhaps our best evidence for the existence of fine granulation in the magnitude of the coronal magnetic field.

3.4. Microflares as the coronal source

If we accept both the need for the bulk of the energetic particle acceleration to take place in the corona and also the existence of fast diffusion paths within the corona, we now must identify a suitable location for this acceleration. Yokoyama and Shibata, 1995, relate the observations of solar X-ray jets to microflares associated with compact loops. They show by MHD simulation that buoyant magnetic loops can give rise to reconnection at the interface with the coronal field, thus producing the jets seen in soft X-rays. We suppose that some fraction of plasma is accelerated into the 100's of keV region by the reconnection electric field. Schimizu et al. 1992 observe an energy content $\sim 5 \times 10^{28}$erg in microflares, which occur about once every 3 minutes. This is more than adequate to account for the $\sim 3 \times 10^{30}$ erg seen throughout a particular energetic particle stream at 5 AU. We would both expect microflaring to be concentrated in the region of the origin of fast streams and also particle escape to be favoured in these open field line regions, thus qualitatively explaining the 26-day recurrence in the energetic particle observations.

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