

# Propagation upstream from the shock of the High Latitude, Ulysses, CIR associated particle increases

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## Abstract

The first high solar latitude pass of the Ulysses spacecraft revealed the presence of MeV particle increases up to latitudes above 60 degrees, well outside the CIR belt but associated in time with the regular passage of these plasma interfaces at more equatorial latitudes. The particle increases have been explained variously as due to diffusion from a field line connection with a CIR at a greater distance, perpendicular diffusion in latitude, propagation from the inner Corona or an acceleration process on a connecting field line. Numerical solutions to the 1-D propagation equation upstream of a CIR shock for reasonable diffusion mean free paths are shown here to limit the source of the increases to within about 2 AU of the CIR's, assuming the CIR's either trap or accelerate energetic particles.

### 1. Introduction:

Although Ulysses found that high speed solar wind streams driving CIR's were limited to solar latitudes between 13° and 40°, associated energetic particle increases appear up to 64° in the case of 0.5-1.0 MeV protons and to 75° in the case of 50 keV electrons. This observation constituted a major surprise to workers on interplanetary energetic particle transport and clearly potentially contains crucial information on the relative importance of various competing processes (Fisk, 1997). The particles may have originated in the CIR's due to interplanetary diffusive shock acceleration (Palmer and Gosling, 1978), or they may have been mainly accelerated close to the sun and carried out in a trapping region (Lim et al., 1996). In either case, cross-field diffusion from the CIR to Ulysses (Jokipii and Kota, 1996) or sunward diffusion along a field line connecting to an expanded CIR beyond the Ulysses orbit (Keppler et al., 1995, Lanzerotti et al., 1995) or sunward diffusion along a field line constrained to move in latitude under the combined influence of differential solar rotation and differing wind speeds which eventually meet the streamer belt (Fisk, 1996) are all possible modes of propagation for the high latitude energetic particles. A third alternative is that particles, originally accelerated at the sun, diffuse in the inner corona before they move out along connecting field lines to Ulysses (Quenby et al., 1996). In the following we describe data relevant to the high latitude increases and discuss possible models.

### 2. Data:

The data to be employed has already been presented by Keppler et al., 1995 and was obtained from the Ulysses EPAC experiment. 3 identical, three-element semiconductor telescopes mounted at different angles to the spin axis yielded 8 sector information over 80% of the solid angle. The geometry factor to measure 0.3 to 1.5 MeV protons and 0.4 to 6 MeV/N heavy ions was 0.08 cm<sup>2</sup>ster.

We confine ourselves to use of 0.4-1.0 MeV/N omnidirectional helium data obtained on the first Ulysses southern solar pass. A mean spectrum for energetic He ions within a CIR is established from data obtained close to the reverse shocks identified between latitudes -32° and -38°. We will also use data at higher latitudes, again coinciding with the regular particle increases which seem CIR-associated, at the distance (AU) and southern latitude (degrees) pairs; (4.2,41), (4.0,44), (3.8,47), (3.6,52), (3.4,56), (3.2,60).

### 3. Shock Expansion Model:

In order to determine the likely range of diffusion lengths, it is necessary to establish plausible estimates of the expansion history of a CIR as it moves beyond Ulysses. Following Quenby et al., 1995, we assume a radial speed of 500 km/s and an Alfvén speed in the latitude direction of 150 km/s. Starting from the observed extent of the streamer belt as reaching 36°S at 4.4 AU, the CIR is estimated to lie on the same radial vector as Ulysses at the following pairs of distances and latitudes; (5.8,41),(6.9,44),(8.2,47), (10.8,52),(13.6,56),(17.1,60). It is not easily known how the intensity increase inside the CIR varies with distance, so we assume it stays constant and take the mean intensity found previously as applying both as the source intensity for the (41,5.8) observation and to the subsequent points. All the intensities corresponding to the above pairs of positions are assumed to refer to observations upstream (or sunward) of the expanded reverse shock of the CIR. These intensities, normalised to the 'in the CIR' intensity (shock and observation at 5.8 AU) are plotted in figures 1 and 2, together with the estimated upstream distances on the Quenby et al., 1996 model.

If the connection between the CIR from beyond Ulysses to the spacecraft is via a field line moving in latitude according to the Fisk, 1996 model, the radial distance to be moved is typically 10 AU for a line seen at 70° in the inner heliosphere.

### 4. Semi-quantitative consideration of the possible propagation:

The limitations on the ability of MeV particles to propagate  $\sim 10$  AU and be seen with the observed intensity and be reasonably in phase with the established low latitude solar rotation periodicity are critically dependent on the radial or perpendicular diffusion mean free path adopted. It is difficult to better the 'Palmer Consensus' value of 0.1 AU as applying in a wide rigidity and distance range for  $\lambda_{rr}$ . This is in accord with recent realistic, magnetometer based computations of the parallel mean free path (Drolias et al., 1997) over the Ulysses orbit which yield  $\sim 0.1$  AU provided we are  $\sim 1$  AU but is already puzzling at  $\sim 5$  AU where  $\lambda_{rr} = \lambda_{\parallel} \cos^2 \chi$  where  $\chi \sim 70^\circ$  or  $\lambda_{rr} \sim 0.1$  AU, unless  $\lambda_{\perp} \sim \lambda_{\parallel}$ .

Using the expression for the diffusion time,  $\tau$ , to reach peak flux over distance,  $L$ , with velocity,  $v$ ,  $\tau \sim (3/4)L^2/\lambda_{rr}v$ , we find it takes 94 days to diffuse 10 AU, 23 days to diffuse 5 AU and 90 hours to diffuse 2 AU. These numbers suggest that unless the 'source' of the high latitude increases is within a few AU of Ulysses, the 27-day periodicity in the enhancements will be difficult to explain.

### 5. Quantitative radial back diffusion model:

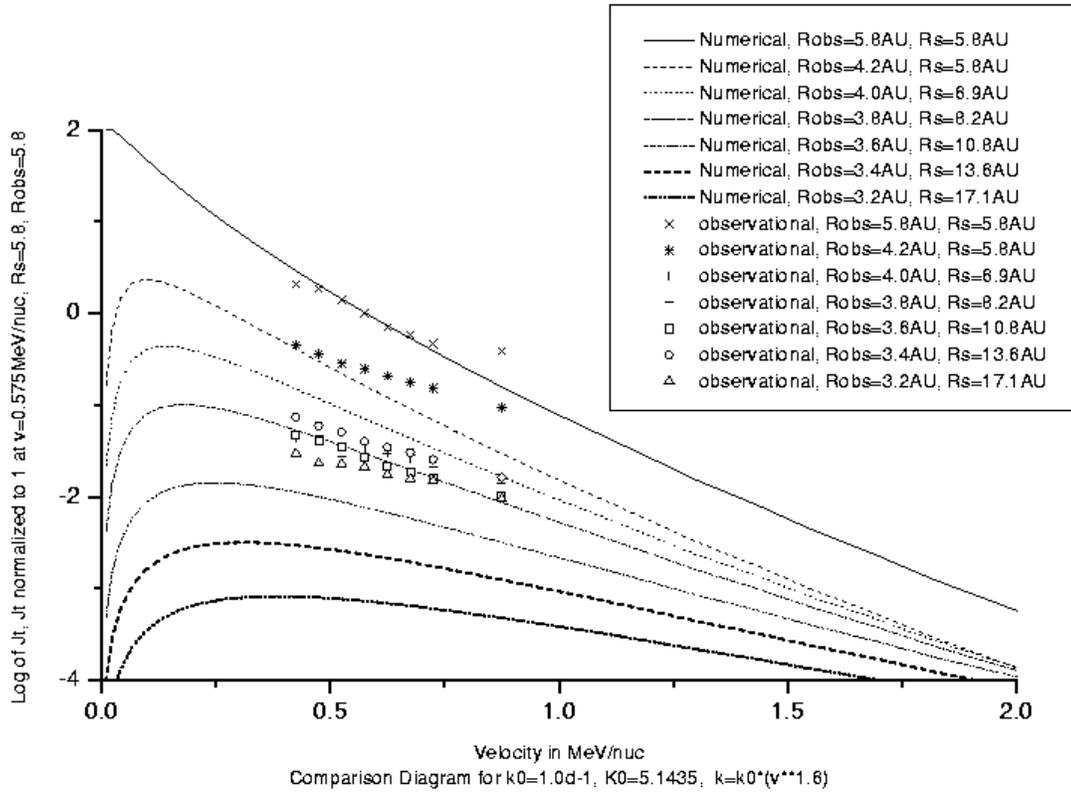
In this section, we numerically solve the Fokker-Planck transport equation for the case of spherically symmetric propagation back towards the sun from the reverse shock of a CIR. The Fokker-Planck with only radial coordinate dependence and assuming a steady state is

$$\frac{1}{r^2} \frac{\partial}{\partial r} (r^2 k \frac{\partial f}{\partial r}) - (V - V_s) \frac{\partial f}{\partial r} + \frac{2}{3} \frac{V v}{r} \frac{\partial f}{\partial v} = 0 \quad (1)$$

Here  $k$  is the radial diffusion coefficient,  $f$  the distribution function,  $V$  the wind speed,  $V_s$  the shock speed,  $r$  the solar radial distance and all quantities measured in a solar reference frame. The equation expresses the facts that while the diffusive and adiabatic deceleration divergence terms depend on distance from the Sun, the convective motion must be considered relative to the shock. The boundary condition derived from continuity of streaming at the CIR reverse shock is

$$-k \left( \frac{\partial f}{\partial r} \right)_1 + \frac{v}{3} \left( \frac{\partial f}{\partial v} \right)_1 (V_s - V_1) = \frac{v}{3} \left( \frac{\partial f}{\partial v} \right)_2 (V_s - V_2) \quad (2)$$

where 1 and 2 refer to upstream and downstream conditions. Using the inverse compression ratio  $\beta$ ,  $V_s - V_2 = \beta(V_s - V_1)$ . The boundary condition equates upstream diffusive and convective flows with downstream convection with negligible diffusion. Following Savopulos et al., 1995, equations 1 and 2 are combined

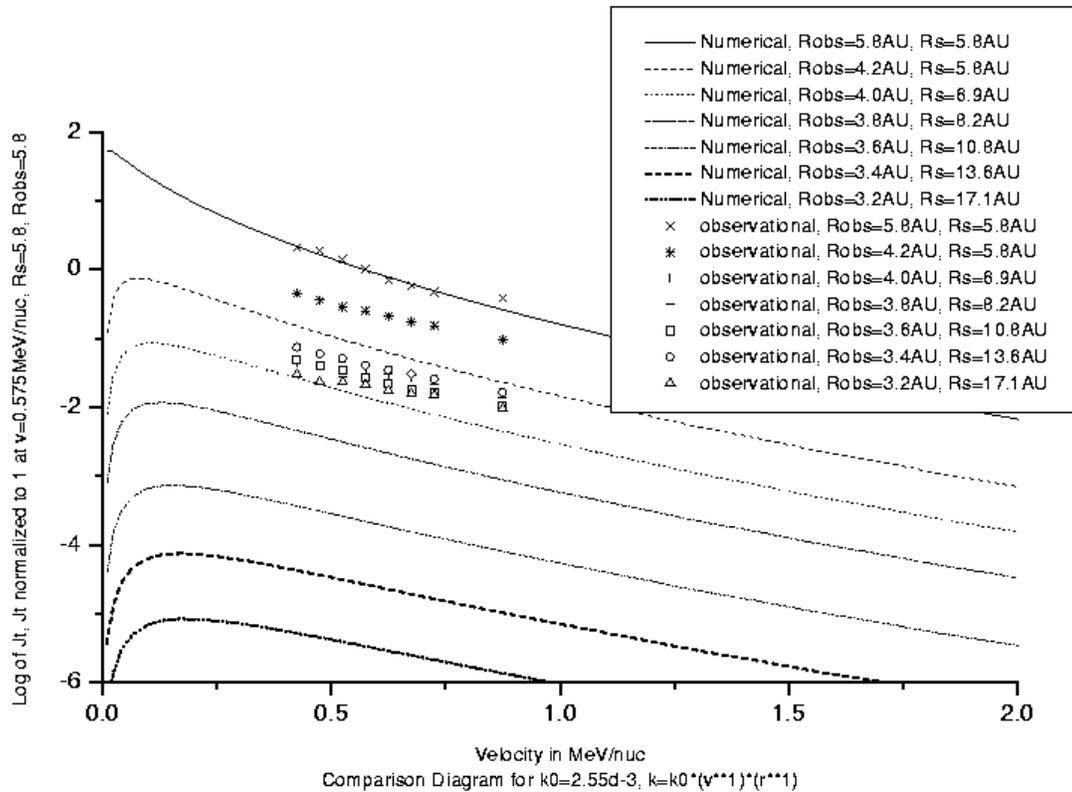


and numerically solved by inverting a quindagonal matrix allowing  $k = k_0 v^\alpha r^\epsilon$ .  $k_0$  will be quoted with  $v$  measured in units of  $10^8 \text{ m s}^{-1}$  and  $r$  in units of  $10^{11} \text{ m}$ .

We show in figures 1 and 2 as continuous lines solutions to equations 1 and 2 for two relations for  $k$ . In figure 1,  $\alpha = \epsilon = 1$  and  $\lambda_{rr}=0.008\text{AU}$  at 1 MeV/N and 1AU. In figure 2,  $\alpha = 1.6, \epsilon = 0.0$  and the  $k_0$  value of 5.1435 in the above units corresponds to  $\lambda_{rr} = 0.44 \text{ AU}$  at 1MeV/N independent of distance. The top curve is the fit to the He spectrum inside the CIR while the others correspond to the computed upstream spectra for the assumed shock-Ulysses distances on the model of section 3 for the latitudinal spread of a CIR. These distances can similarly be employed in the model of the latitudinal wandering of an interplanetary field line. The figures show that a variety of mean free path models can fit the data (as demonstrated by Savopulos and Quenby, 1998) although independent propagation evidence clearly favours an intermediate mean free path value. However, both figures confirm that there is little prospect of fitting the intensity fall-off apparently observed upstream of the reverse shock except within about 1 or 2 AU of the CIR, if either back diffusion model is adopted. The predicted fall-off is much too large.

## 6. Conclusions:

With accepted values of the radial mean free path in the few AU, few MeV/N region, the models for high solar latitude CIR associated particle increases which involve diffusion over 5-10 AU, either from behind Ulysses or directly from the Sun, have difficulty in fitting the relatively high intensities seen up to  $60^\circ$  when spherically symmetric solutions of the Fokker-Planck equation are employed. There is an additional problem in the long time required for such diffusion to take place. An alternative is to consider a perpendicular diffusion mean free path not much smaller than the parallel  $\lambda$ , allowing the CIR associated fluxes to propagate only 1-2 AU



to locations directly above the shock in latitude.

The relatively large value of the perpendicular diffusion coefficient required in the above analysis fits with the relatively small latitudinal gradients in low energy cosmic ray intensity seen by Ulysses which appear significantly less than expected on full drift models with  $K_{\perp} = 0.05 K_{\parallel}$  (see Drolias et al., 1997 and references therein).

## References

- Drolias,B., Garaud,P., Quenby,J.J., Smith,E.J.,1997,Proc.25th. ICRC,1,229.  
 Fisk,L.A., 1996, JGR, 101, A7, 15, 547.  
 Fisk,L.A., 1997, Proc. 25th. ICRC, 8, 27.  
 Jokipii,J.R., Kota,J., 1995, Eos Trans. AGU, 76(46), Fall Meet. Supl.F458.  
 Keppler,E., Franz,M., Korth,A., et al.1995, Science, 268, 1013.  
 Lanzerotti,L.J., Armstrong,T.P., Gold,R.E.,et al.1995, Science, 268, 1010.  
 Lim,T.L, Quenby,J.J., Reuss,M.K.,et al.1996, Ann. Geophysicae 14, 400.  
 Palmer,I.D., Gosling,J.T.,1978, JGR, 83, 2037.  
 Quenby,J.J., Drolias,B., Keppler,E.,et al.,1995, Geophys. Res. Lett., 22, 3345.  
 Quenby,J.J., Witcombe,A., Drolias,B.,et al.,1996, A & A, 316, 506.  
 Savopulos,M., Quenby,J.J., Bell,A.R.,1995, Solar Phys., 157, 349.  
 Savopulos,M., Quenby,J.J., 1998, Solar Phys., 180, 479.