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Author(s):

M. I. Desai  
R. G. Marsden  
T. R. Sanderson  
R. J. Forsyth  
J. T. Gosling

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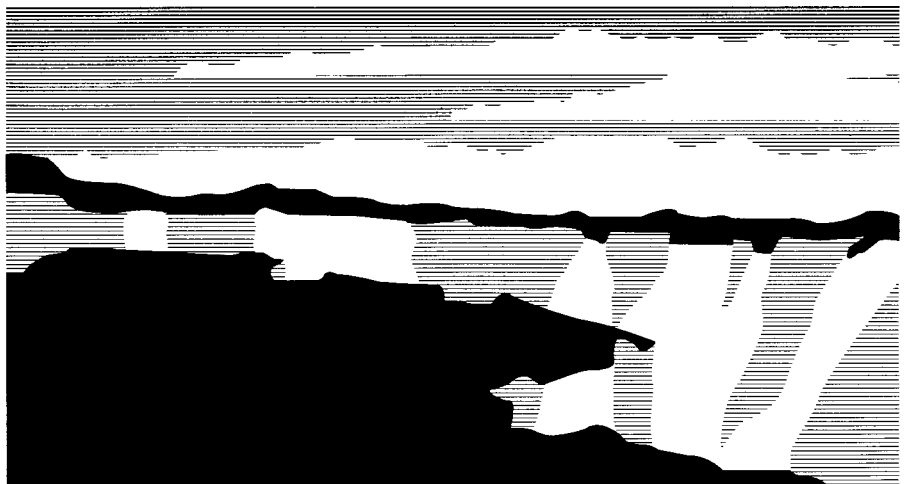
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## ENERGETIC PARTICLE ACCELERATION AT COROTATING INTERACTION REGIONS: ULYSSES RESULTS

M. I. Desai<sup>1</sup>, R. G. Marsden<sup>1</sup>, T. R. Sanderson<sup>1</sup>, A. Balogh<sup>2</sup>, R. J. Forsyth<sup>2</sup>, and J. T. Gosling<sup>3</sup>

<sup>1</sup>*Space Science Department, ESTEC/ESA, 2200 AG Noordwijk, Netherlands*

<sup>2</sup>*Blackett Laboratory, Imperial College, London, UK*

<sup>3</sup>*Los Alamos National Laboratory, NM 87545, New Mexico, USA*

### ABSTRACT

We present here statistical properties of energetic ions ( $\sim 1$  MeV) accelerated by corotating interaction regions observed at the Ulysses spacecraft. We have correlated the  $\sim 1$  MeV proton intensity measured near the trailing edges of the interaction regions with their compression ratio. We interpret our results in terms of the plasma conditions experienced at Ulysses and identify a likely source of the low-energy seed particles accelerated at the interaction regions.

### INTRODUCTION

The Ulysses mission has provided an opportunity to investigate latitudinal differences in the properties of  $\sim 26$  day recurrent energetic particle ( $\sim 1$  MeV) intensity increases associated with corotating interaction regions (CIRs) which are formed when fast solar wind streams originating from coronal holes overtake slow solar wind streams originating from coronal streamers (Gosling et al., 1981). At low latitudes such CIRs are usually bounded by forward and reverse waves on their leading and trailing edges, respectively. At large heliocentric distances these waves typically steepen into shocks which accelerate particles to  $\sim 1$  MeV energy. Ulysses observations at high heliographic latitudes have shown the presence of energetic ( $\sim 1$  MeV) ions accelerated at CIRs (Sanderson et al., 1994; Simnett et al., 1994). These ions are thought to be accelerated via the Fermi acceleration mechanism, according to which the particle intensity should increase with the compression ratio of the CIRs provided that the low-energy background intensity remains constant (Lee and Fisk, 1982). To test this prediction we have investigated the relationship between the  $\sim 1$  MeV proton intensity measured near the trailing edges of the CIRs and their compression ratio, here defined as the ratio of the magnetic field strengths downstream and upstream of the CIRs.

### OBSERVATIONS

We use data from the 1.2-3.0 MeV proton ( $\sim 1$  MeV) and 8-19 MeV/n ( $\sim 10$  MeV/n) helium channels of the Low Energy Telescope (LET) of the cosmic ray and solar particle investigation (COSPIN) on board Ulysses. The LET measures protons, alpha particles, and heavy ions in the  $\sim 1$ -50 MeV/n energy range (Simpson et al., 1992). In the interplanetary medium, the  $\sim 1$  MeV proton channel detects particles associated with CIRs and transients. In contrast, the  $\sim 10$  MeV/n helium channel responds mainly to helium ions from transients during periods of high activity on the Sun, thereby providing a crude measure of the level of solar activity. The term transient refers to events associated either with solar flares or with interplanetary shocks driven by coronal mass ejections (CMEs). We also use measurements from the Ulysses solar wind plasma experiment (Bame et al., 1992) and the magnetometer (Balogh et al., 1992).

Figure 1 (top panel) provides an overview of the  $\sim 1$  MeV proton (upper trace) and the  $\sim 10$  MeV/n helium (lower trace) intensities, from day 296, 1990 to day 36, 1997. Solid vertical lines show key events during the mission. Dashed vertical lines identify periods (I-VI) during which CIRs were detected at Ulysses. These periods are selected on the basis of distinct

plasma conditions experienced at Ulysses (Gosling et al., 1993, 1997). An overview of recurrent energetic particle observations at Ulysses may be found in Sanderson et al. (1995).

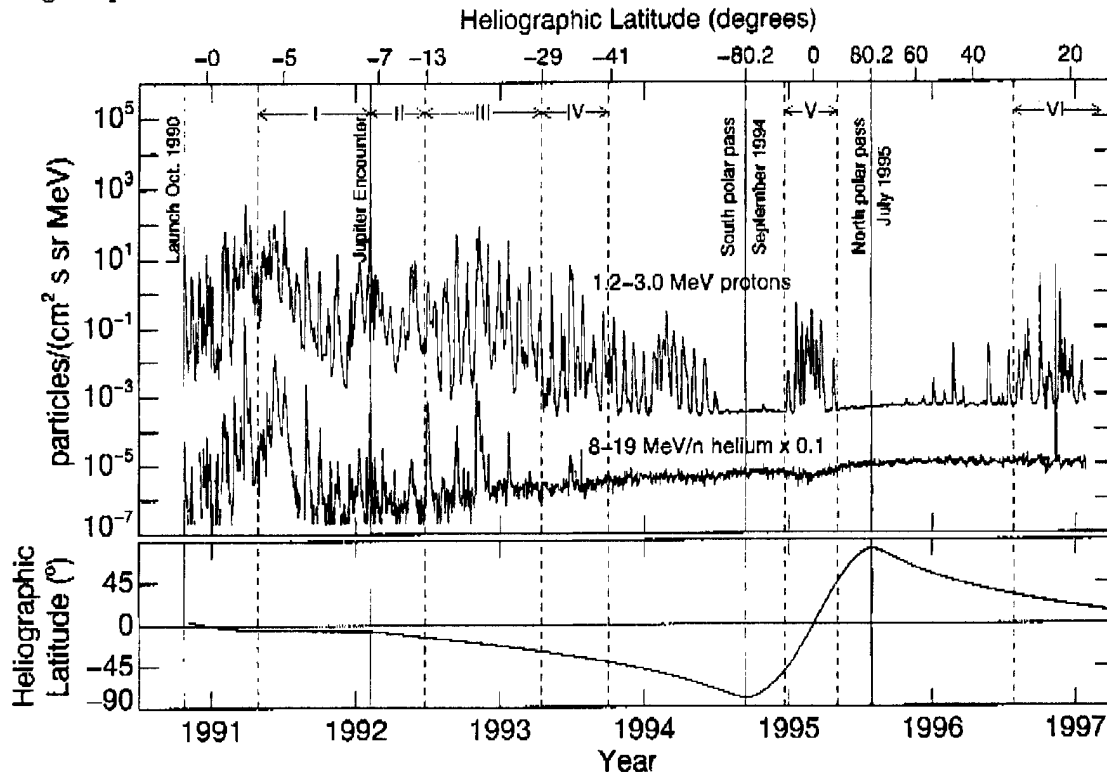


Fig. 1. Top panel: Overview of the Ulysses mission, showing the daily averaged  $\sim 1$  MeV proton (upper trace) and  $\sim 10$  MeV/n (lower trace) helium intensities measured by the COSPIN/LET from day 296, 1990 to day 36, 1997. The tick marks are shown at the start of each year. The helium intensity has been multiplied by  $10^{-1}$ . Bottom panel: The heliographic latitude of Ulysses as a function of time.

## RESULTS AND DISCUSSION

Figure 2 shows the correlation between the hourly averaged  $\sim 1$  MeV proton intensity ( $J$ ) and the compression ratio ( $C$ ) for the CIRs observed during Periods I-VI. The value of  $C$  for two CIRs during Period III was  $\geq 4$  because the interaction between the fast ( $\sim 750$  km  $s^{-1}$ ) and slow ( $\sim 450$  km  $s^{-1}$ ) streams originating from the southern polar coronal hole and the heliomagnetic streamer belt, respectively, was strongest between  $13^\circ S$  and  $29^\circ S$  (Pizzo and Gosling, 1994). We have excluded the data for these CIRs (CIRs 4 and 9, from Bame et al. (1993)) from the fit in order to compare the results for Period III with the results for other periods over the same range ( $1 \lesssim C \lesssim 4$ ) of compression ratios.

The uncertainties (not shown) in  $J$  are sufficiently small enough to be neglected. The uncertainties in  $C$  are generally less than  $\sim 0.6$ , and typically  $\sim 0.4$ . The slopes ( $m$ ), the correlation coefficients ( $r$ ), and the degree of scatter of the data indicate that (1)  $J$  is essentially independent of  $C$  during Period I (the in-ecliptic cruise), and (2)  $J$  is well correlated with  $C$  during Periods IV and VI, and to a lesser extent during Period III. Because of limited statistics the relationship between  $J$  and  $C$  during Periods II and V is not well determined.

An obvious question is what causes the differences in the results for Period I when compared with the results for Periods III, IV, and VI. Based on predictions of the Fermi model we suggest that the correlation between  $J$  and  $C$  was destroyed during the in-ecliptic cruise probably because the CIRs accelerated low-energy particles out of seed populations with significantly different intensities. In contrast, the strong correlation between  $J$  and  $C$  during the remaining

periods implies that the CIRs probably accelerated particles out of a background intensity that remained at a relatively constant level.

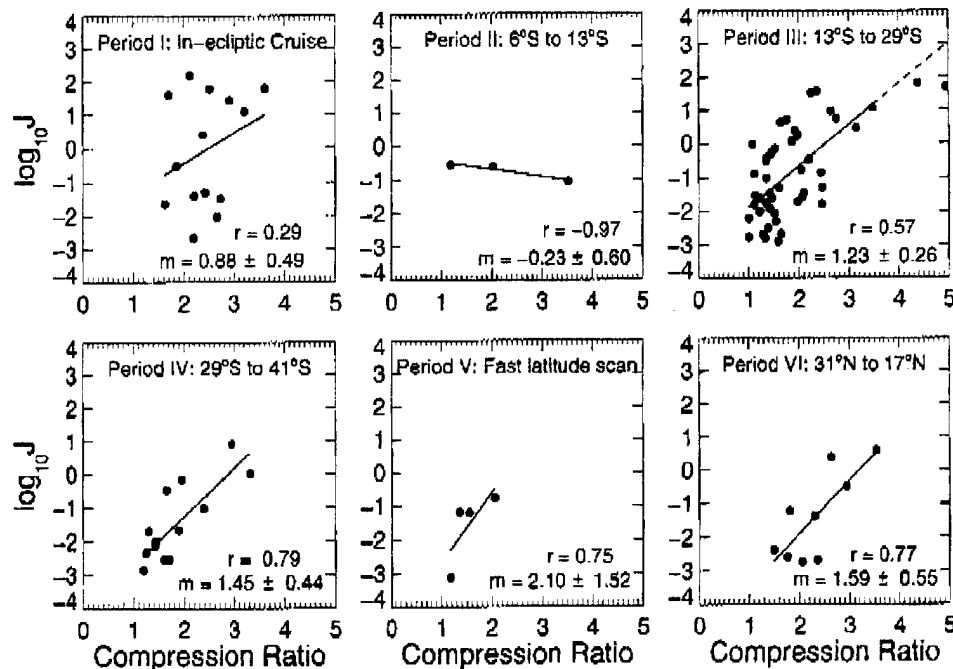


Fig. 2. Correlation between the  $\sim 1$  MeV proton intensity ( $J$ ) and the compression ratio ( $C$ ) for the CIRs observed during Periods I-VI (see text). The slopes of the fits (solid lines) and the correlation coefficients are given by  $m$  and  $r$ , respectively.

The next question is whether the background fluctuations during the in-ecliptic cruise (Period I) are caused by spatial or temporal effects. We rule out changes in the heliocentric distance of Ulysses as a probable cause because during Period I Ulysses moved from 2.9 to 5.4 AU, i.e., a range of radial distance over which the general properties of CIRs are not expected to vary significantly. In addition, we believe that the radial gradient alone (which is probably  $\lesssim$  a few percent per AU) of the low-energy background intensity from 3 to 6 AU could not have been sufficient to cause the large variations in seed intensity that destroyed the correlation between  $J$  and  $C$ . Fluctuations in the background intensity due to changes in heliographic latitude are also negligible since Ulysses remained close to  $\sim 5^\circ$ S during Period I.

The results shown in Figure 2 can be attributed primarily to temporal changes in solar activity. To show that this is plausible we plot, in Figure 3, the correlation coefficients ( $r$ ) for Periods I, III, IV, and VI versus the mean sunspot number (obtained from Solar Geophysical Data) observed during the corresponding period. We note that  $r$  decreases substantially as the sunspot number increases (i.e., during Period I), which clearly indicates that the correlation between  $J$  and  $C$  tends to be suppressed during periods of high solar activity, and vice-versa.

Perhaps the most important question relates to the nature of the low-energy particle source which produced significant variations in the seed intensity during the in-ecliptic cruise but not during the other periods. To understand the physical meaning of our results and to identify the origin of the low-energy particles we appeal to the results obtained for transient interplanetary shocks observed at ISEE 3. Tsurutani and Lin (1985) showed evidence that suggests that interplanetary shocks accelerate a seed population of sub-MeV/n ions that is present essentially at all times in the heliosphere. Sanderson et al. (1985) and Tan et al. (1986) showed that ions accelerated at interplanetary shocks to above  $\sim 0.2$  MeV/n could originate from a source which provides particles that are more energetic than those present in the ambient

solar wind. Furthermore, they proposed that the energetic seed particles could originate from flare activity at the Sun.

We now apply these ideas to the CIRs observed at Ulysses. From the middle of 1991 to early 1992 (during the in-ecliptic cruise) the Sun was more active than from the middle of 1992 to late 1993 (from 13°S to 41°S) and during the latter part of 1996 (31°N to 17°N). As a result, Ulysses detected more transients during Period I than during Periods III, IV, and VI, as may be seen from the relative magnitude and number of ~10 MeV/n helium intensity increases in Figure 1. In analysing the transient events that occurred during March-April 1991, Roelof et al. (1992) showed that the heliosphere acts as a reservoir for low-energy particles that are produced during the events. Adapting this notion, we propose that the transients that occurred during Period I

fill the heliosphere with low-energy particles which constitute a significant proportion of the overall seed population available for acceleration at the CIRs. The transients provide low-energy particles to the reservoir in a sporadic fashion and thereby cause large and abrupt variations in the seed intensity, which consequently destroyed the correlation between  $J$  and  $C$  during the in-ecliptic cruise. In contrast, we observed a better correlation between  $J$  and  $C$  from 13°S to 41°S, and from 31°N to 17°N, probably because the sampled particles were accelerated out of a slowly decaying background which remained relatively unperturbed, a result of the drop in solar activity.

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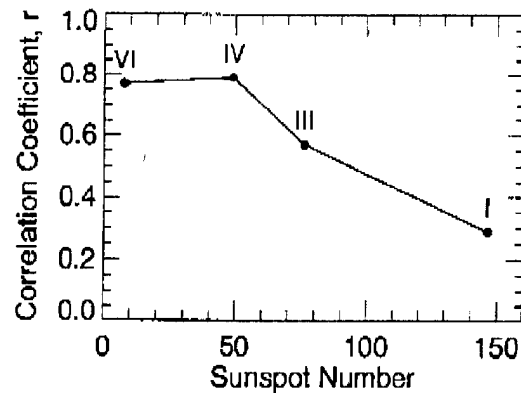


Fig. 3. A plot of the correlation coefficients,  $r$ , obtained from Figure 2, versus the mean sunspot number (from *Solar Geophysical Data*) measured during Periods I, III, IV, and VI.

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