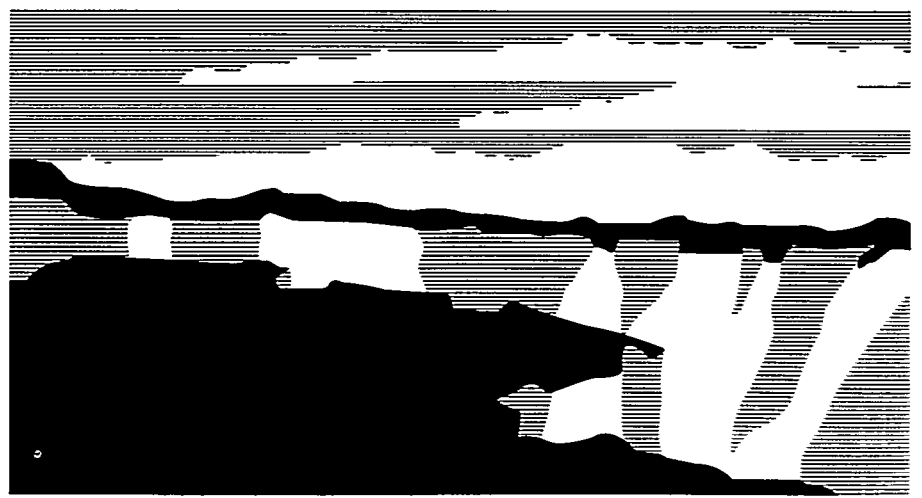


Title: EFFECTS OF COROTATING INTERACTION REGIONS ON ULYSSES HIGH ENERGY PARTICLES

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# Effects of Corotating Interaction Regions on ULYSSES High Energy Particles

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Short title:

**Abstract.** Since June 1992 the Kiel Electron Telescope on board Ulysses measures variations of more than 10% in the fluxes of high energy H and He showing a periodicity of about 26 days in coincidence with the passage of corotating interaction regions (CIR). At low energies MeV protons are accelerated at the shocks of the CIRs. These effects are observed up to high southern latitudes, where the signature of a CIR is no longer visible in plasma or magnetic field data. After passing over the south polar cap ULYSSES has now returned to the solar equator and climbs up to the north pole. In this paper we study the relative intensity variations with latitude and the latitude dependence at solar distances smaller than ever studied before.

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## Introduction

ULYSSES, launched October 6, 1990, has a trajectory passing Jupiter followed by a polar orbit around the Sun. We report observations from the Kiel Electron Telescope (COSPIN/KET) [Simpson et al., 1992] measuring nuclei between 5.4 MeV/N and  $> 2$  GeV/N and electrons between 2.7 MeV and  $> 5$  GeV from June 1992 until April 1995 covering the south polar pass, return to the solar equator and ascent to the north pole up to  $80^\circ$ .

## Observations

On its way to the southern solar polar region ULYSSES encountered a stable long-lasting corotating high-speed solar wind stream from June 1992 to March 1994. The underlying heliospheric current sheet is described in [Hoeksema, 1995], the development of the interplanetary structure in [Balogh et al., 1993; Balogh et al., 1995; Smith et al., 1993; Bame et al., 1993; Gosling et al., 1993]. Sanderson et al. [1994] discuss the corotating events in the  $\approx 1$  MeV-range. Fig. 1 shows daily averaged count rates observed in selected channels. Protons and alpha particles (250–2200 MeV/N) show a general increase due to the long-term recovery in the declining phase of solar cycle 22 as discussed in detail in [Heber et al., 1995]. High energy proton data corrected for the underlying long term trend exhibit a modulation by regular decreases with 26 day recurrence which remains constant within a factor of two and even persists through the polar cap passage with an amplitude reduction by less than a factor of 4.

5.4–23 MeV/N protons and alpha particles (top panel) show remarkable increases of up to 4 orders of magnitudes in coincidence with the modulation depressions observed at higher energies. The amplitudes are highest within region 2 where a well developed CIR is observed bounded by both a forward and a reverse shock [Phillips et al., 1994;

Balogh et al., 1995]. The highest increases, however, are associated with coronal mass ejections (CME). The CIR related increases are highest following CMEs and decrease in amplitude thereafter. Corotating increases (corotating events) diminish gradually in region 3 with no peak above 30% above the background value over the south polar cap.

The descent from the south pole to the equator is characterized by a high perihelion space probe velocity resulting in a fast scan of  $19^\circ$  per solar rotation and small radial distance changes (only 0.2 AU from  $45^\circ\text{S}$  to the equator). The current sheet tilt angle remains low and constant at about  $13^\circ\text{S}$  and the high speed solar wind stream structure changes from one to two streams. The first CIR related increase after the South Solar Pol Passage (S.P.P.) is observed at  $45^\circ\text{S}$  on January 16, 1995. From there it takes only 2.5 solar rotations until ULYSSES reaches the solar equator. Detailed CIR studies are therefore difficult due to lack of events, but observed peaks are comparable to those observed during the ascent phase. Accelerated particle peaks and the minima of the recurrent decreases increase with decreasing latitude.

## Analysis

Following a suggestion by Sanderson et al. [1994] the ULYSSES passage through different latitudes can be divided into three distinct regions 1–3, see also Fig. 1, with marked differences in the relation between plasma structures and particle properties. Region 1 is streamer belt dominated ( $< 13^\circ\text{S}$ ), region 2 is current sheet dominated ( $13\text{--}29^\circ\text{S}$  ascent,  $22\text{--}10^\circ\text{S}$  descent), and region 3 is coronal hole dominated ( $> 29^\circ\text{S}$  ascent,  $> 22^\circ\text{S}$  descent). CIR effects in region 2 are similar to observations near the ecliptic. Fig. 2 shows an example from the KET data on an expanded timescale. The interplanetary structure is governed by the forward (F) and the reverse (R) shocks of the CIR, generally a few days apart. Acceleration of protons and alpha particles with energies up to a few 10 MeV/N is observed. The highest peak occurs at the R-shock with a second maximum at the F-shock. Peaks of accelerated particles are generally

broader and higher at lower energies. Acceleration is most efficient at about 5 AU from the Sun. The interplanetary structure is governed by one corotating stream, increases are generally larger than during periods with two corotating streams per rotation. For protons and heavier nuclei with energies above 100 MeV/N the intensity decreases in the vicinity of corotating interaction regions (recurrent decreases, RD). Minima are correlated with the R-shock, the onset with the F-shock. The amplitude of the depression remains at about 6% up to latitudes of 70°S when it is reduced to about 3% throughout the polar cap.

With the disappearance of the F-shocks we observe a dramatic decrease in the accelerated particle amplitude (cf., Fig. 3). However, the RDs still persist with about the same amplitude.

The disappearance of the reverse shocks cause the amplitude of accelerated particles to decrease even further. The modulation of the high energy particles, however, persists undiminished, even when at latitudes beyond 70°S statistically significant peaks of accelerated particles are no longer observed (see Fig. 4). The relatively rigid time relation between accelerated particle maxima, as long as they are visible, and modulated particle minima, however, does no longer exist. In many cases the increases are delayed by days with respect to the minimum of the modulation decrease which seems to occur at the time of the extrapolated reverse shock.

## Discussion and Summary

The observations described above can be extended to other particle species and energy intervals with similar acceleration increases (see e.g. Sanderson et al., [1994]) The rigidity dependence of the recurrent modulation has been discussed in Kunow et al., [1995] showing a small decrease of the modulation effect with increasing rigidity above 1 GV.

An enhancement of the CIR acceleration is observed after passage of CME disturbances with a decay constant of about one month. We cannot give a clear answer yet whether this is due to the availability of higher energy seed particles for subsequent acceleration in the vicinity of the CIR or whether the turbulence associated with the CME and the associated shock allow much more efficient acceleration at the CIR associated shocks.

The most striking feature is: Although the slow solar wind which is overtaken by the fast solar wind streams thus establishing CIRs is restricted to latitudes below 29°S and although CIR related shocks are restricted to 58°S the recurrent modulation still persists with nearly the same temporal relation and with only slightly reduced amplitude up to latitudes above 70°S.

Two additional observations contribute to the explanation of this behaviour:

1. With increasing solar distance the reverse shock of a corotating interaction region is displaced continuously poleward and eastward [Gosling et al., 1993].
2. Magnetic field observations over the south polar cap show a relatively homogenic distribution of magnetic field lines in contrast to the expected dipolar magnetic field. In addition large amplitude very low frequency waves are observed.

Both observations allow field line connections at larger solar distances to much lower latitudes and therefore connections to regions which show at least higher turbulence or even connections to the reverse shock.

## Acknowledgements

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## Figure Captions

Fig. 1. Overview of the CIR effects on 5.4–23 MeV/N and 250–2200 MeV/N protons and alpha particles (first panel). Second panel shows the high energy protons corrected for underlying long term trend. Also shown are solar wind velocity (third panel), and radial distance and heliographic latitude of ULYSSES (fourth panel).

Fig. 2. CIR effects on 5 – 23 MeV/N protons and alpha particles (upper panel) and 250 – 2200 MeV protons (middle panel) for two events during December 1992 - January 1993 when ULYSSES was in region 2. F- and R-shocks are marked. Lower panel shows solar wind velocity.

Fig. 3. CIR effects on energetic particles for two events when ULYSSES was in region 3 where forward shocks had already disappeared.

Fig. 4. CIR effects on energetic particles during the south polar passage. Although shocks and peaks at lower energies are no longer observed the modulation of high energy protons persists.

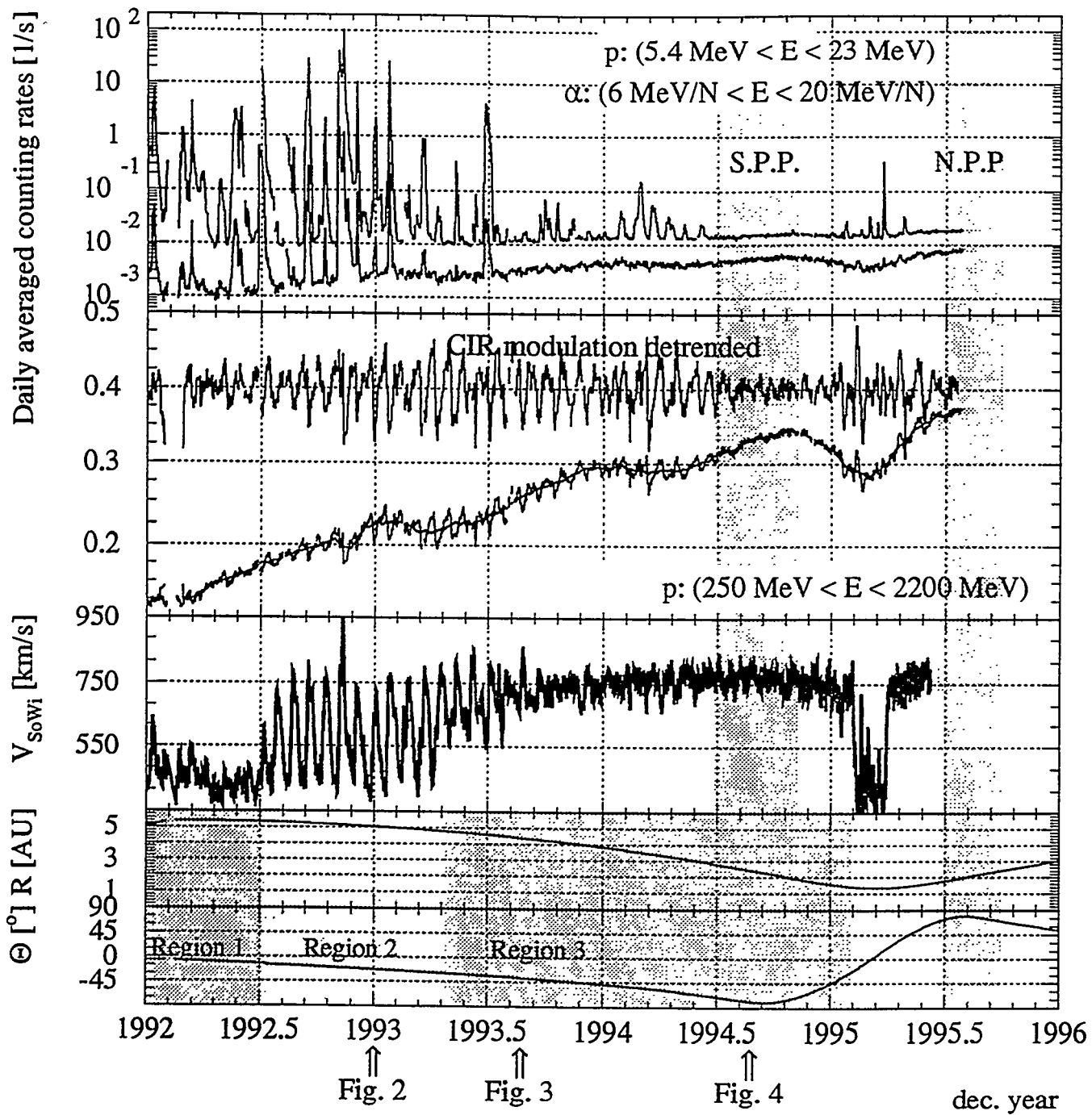


Figure 1

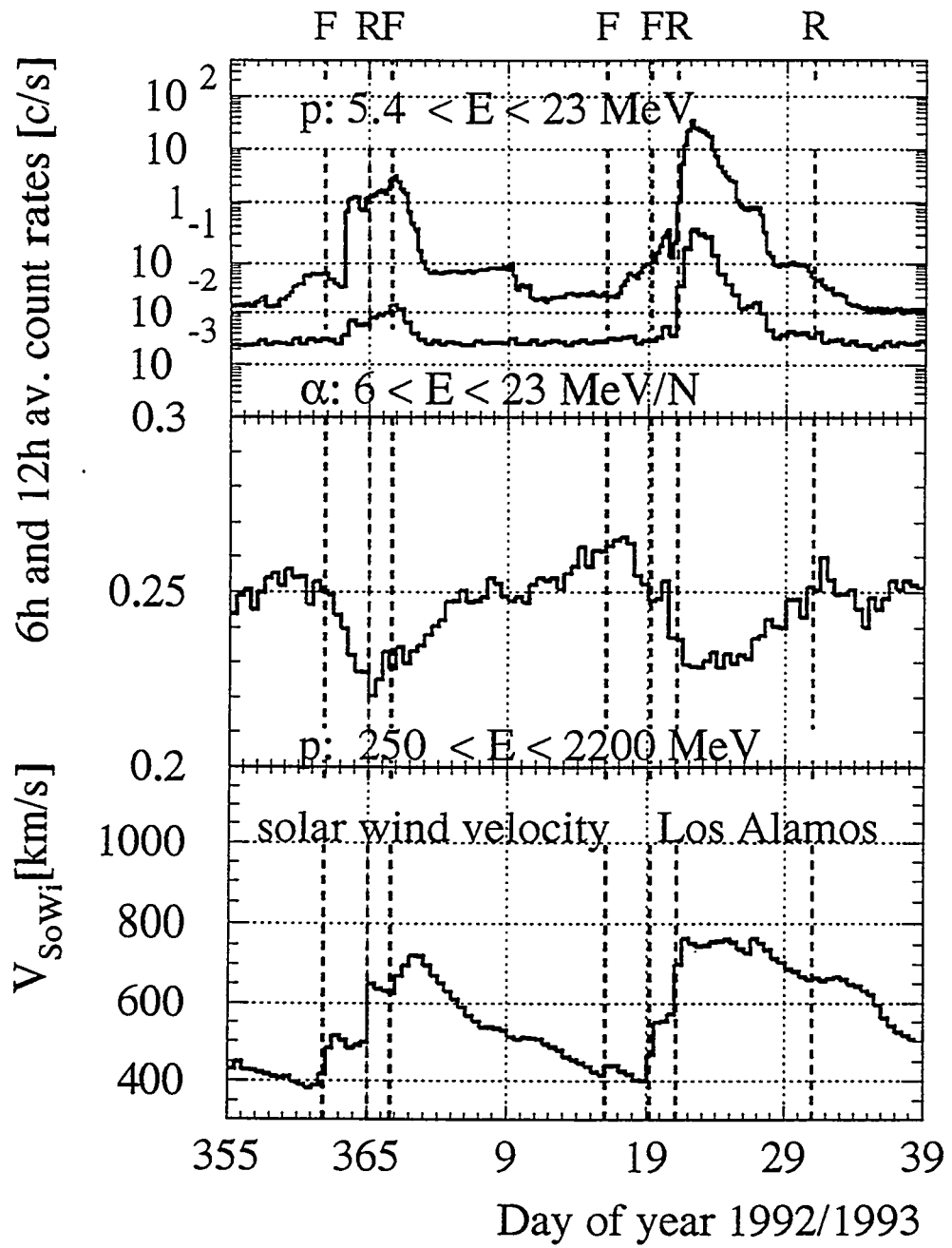


Figure 2

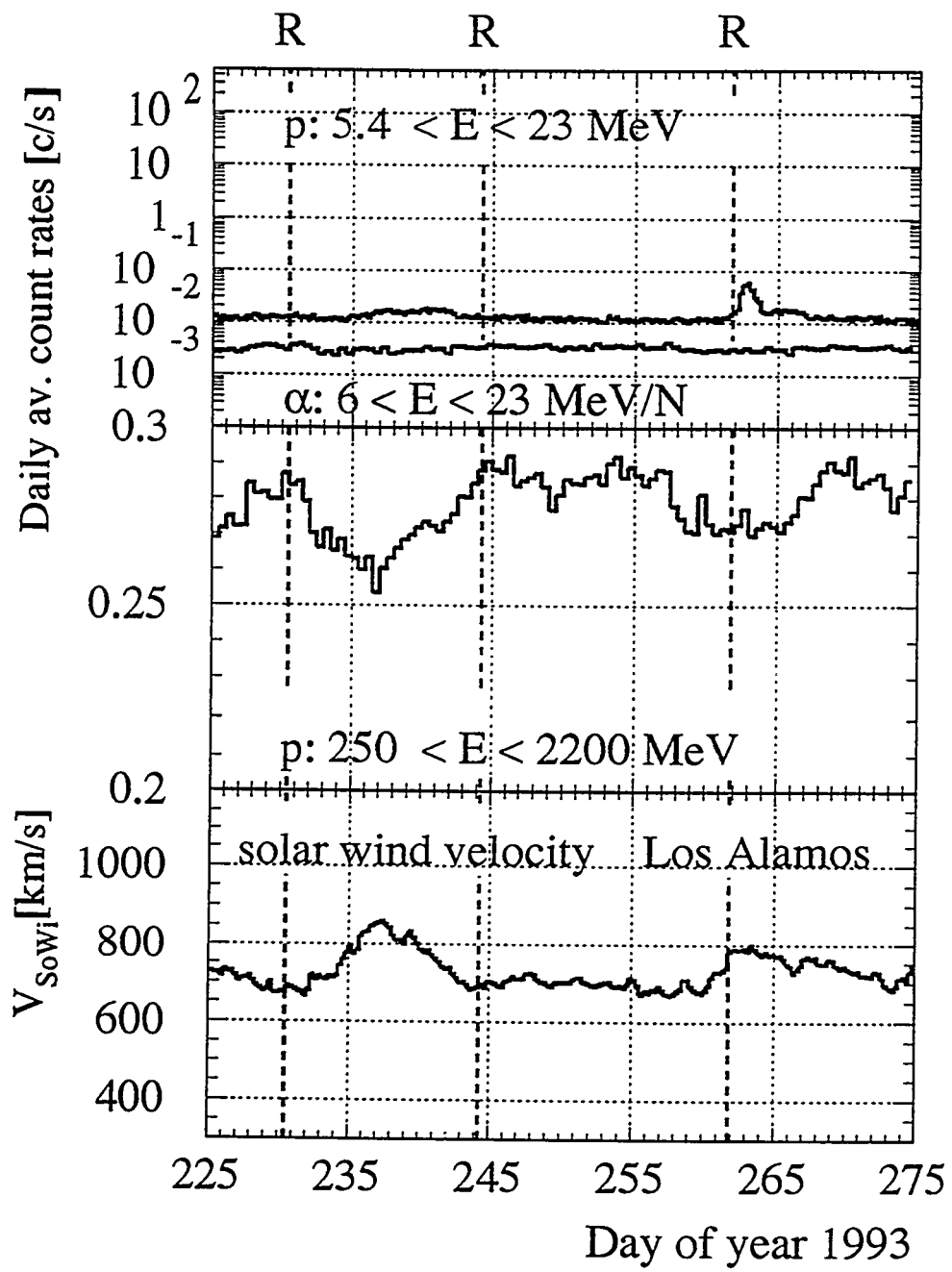


Figure 3

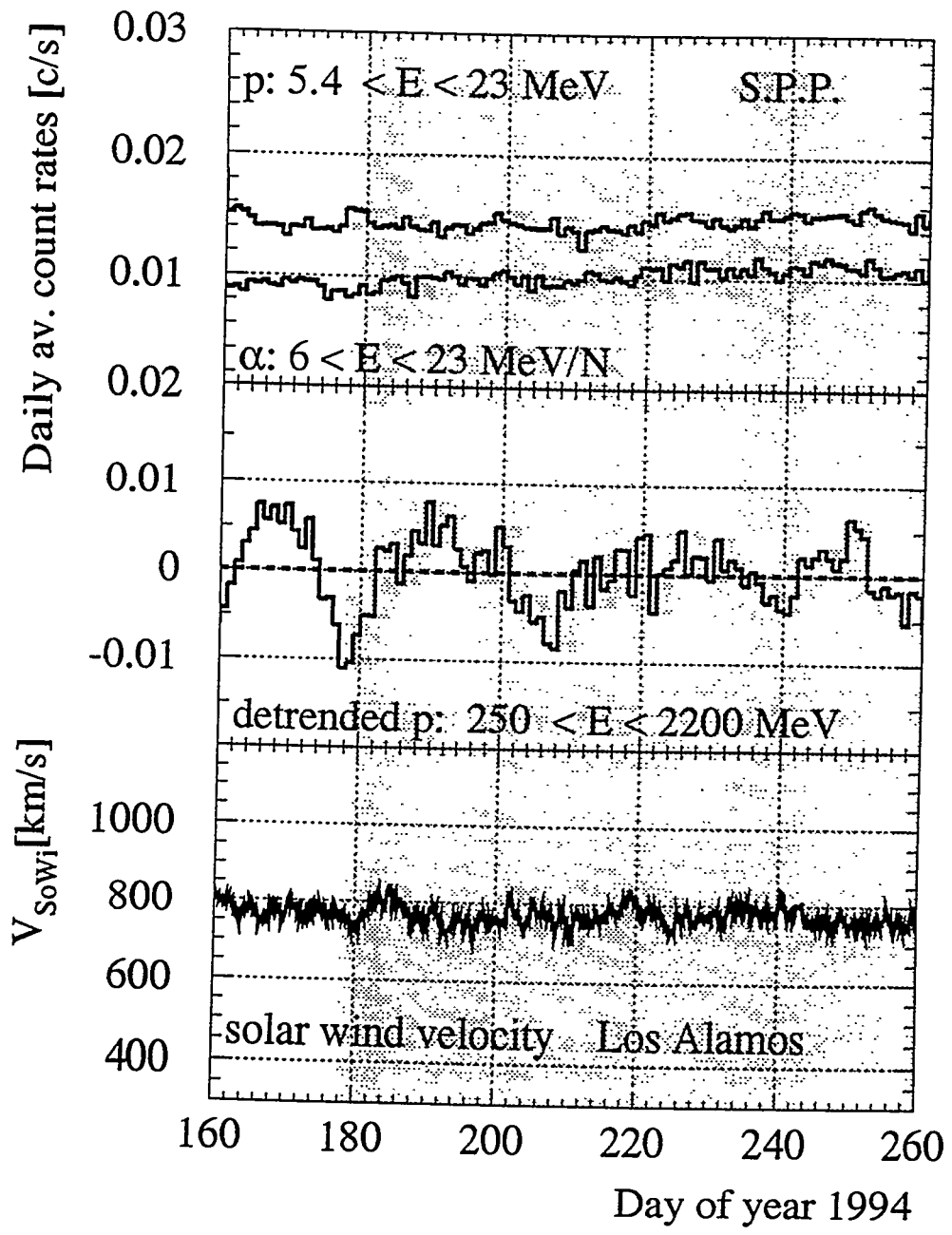


Figure 4