Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008

Vol. 1 (SH), pages 217–220

ID 357

30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07 Mérida, México

Observations of the December 2006 Particle Events at High Latitudes with the KET aboard *Ulysses*

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Abstract: An unexpected rise of solar activity close to its minimum in December 2006 resulted in four X-class flares and four energetic particle events. These events were observed close to Earth and above 70 degree South by the *Ulysses* spacecraft, which was at a heliocentric distance of 2.8 AU at that time. Three out of these four events produced significant intensity increases up to several hundred MeV/nucleon for protons and alpha-particles and several 10 MeV for electrons at high southern latitudes. They were associated with X9.0, X6.5 and X3.4 flares from the AR 10930, coronal type II bursts and strong microwave emission on 5, 6 and 13 December, respectively. The parent solar flares have similar X-ray and microwave time profiles. However, the event on December 13 is the weakest among the three at *Ulysses*, but it is the largest near Earth. It produced a ground level event leading to an intensity increase of about 34 % in the Kiel neutron monitor. In contrast the December 6 particle event was the largest at *Ulysses*. We discuss these events in context of previous *Ulysses* observations at high heliolatitudes in September 2000 (South) and in November 2001 and their consequences for our interpretation of particle propagation to solar polar regions.

Introduction

An unexpected rise of the solar activity close to its minimum in December 2006 was observed when the active Region 10930 became visible on the east limb of the Sun. It produced four X-class flares and four energetic particle events. All flares were associated with hard X-ray and gamma-ray emissions, type II and III radio bursts. Details of the non-thermal solar emission have been described in Struminsky and Zimovets [1]. These observations provide evidence of a complex behavior of the solar chromosphere and corona after the initial energy release of the flare, the Coronal Mass Ejections (CME's) and associated shocks.

The particle signature of these events were observed close to Earth and above 70 degree South by the *Ulysses* spacecraft, which was at a heliocentric distance of 2.8 AU at that time.

During the solar maximum Solar Energetic Particles (SEP) have been observed at all latitudes [2]. Eight large proton events of 2000-2001 have been investigated in [3], where it is shown that the maximum intensities and total fluences of 38-125 MeV protons at *Ulysses* vary by a factor 2-3 only. In contrast to the *Ulysses* observations the maximum intensities and fluences measured at Earth during these events vary by orders of magnitudes. It is important to note, that the observed limits at

Ulysses are well below the maximum intensities related to the streaming limit [4].

Within this context the observations of protons from 5 to 2000 MeV by the Kiel Electron Telescope (KET) aboard *Ulysses* in December 2006 during the declining phase of solar cycle 23 will be discussed and compared to previous observations at high latitudes in September 2000 (South) and November 2001(North). Observations of low energy protons and electrons are presented in [5].

Instruments and Data

Ulysses launched on October 6, 1990 effectively operates in solar orbit inclined by 80^o with respect to the ecliptic plane. The Kiel Electron Telescope (KET) aboard *Ulysses* measures protons and helium in the energy range 6 MeV/n to above 2 GeV/n and electrons in the energy range from 3 MeV to a few GeV [6]. They are compared to the Energetic Particle Sensor (EPS) on board the *GOES* satellite (http://rsd.gsfc.nasa.gov/goes/text/goes.databook.html). The count rate of the 250-2000 MeV *Ulysses* channel was normalized to the 165-500 MeV *GOES* intensity in May-June 2001, when both spacecraft were at heliocentric distances of ~1 AU in the ecliptic [7]:

$$U_{norm} = (59 \cdot U + 5) \cdot 10^{-4} \left(cm^2 s \cdot ster\ MeV\right)^{-1}$$

Observations

In Figure 1 *Ulysses* observations for the December 2006 activity period are summarized. In the upper panel the count rates of 5-25 MeV, 38-125 MeV, 125-250 MeV and 250-2000 MeV are displayed by the black, red, blue and cyan curve respectively. A simple inspection of Figure 1 shows that three proton intensity increases related to the solar events on December 5, 6 and 13 are observed in the 38-250 MeV range. The enhancements the 250-2000 MeV channel are barely visible due to the logarithmic scale of Figure 1. But two of the three intensity increases are clearly measured, as can be seen when plotting the data on a linear scale (Figure 2). The SEP event of December 14 was observed by *GOES* (Figure 2 and 3). However, the maximum intensities were relatively small although GOES was magnetically well connected with the source. Thus we can not exclude that a corresponding increase is hidden by the high background due to the previous events at *Ulysses*.

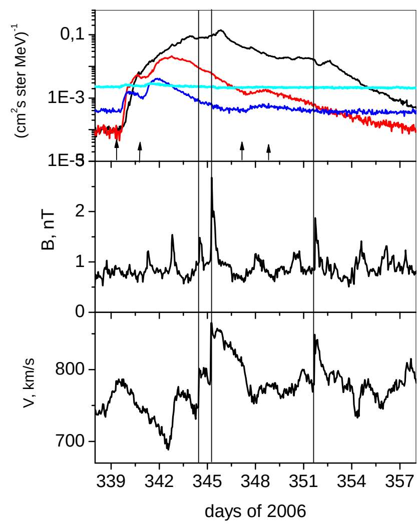


Figure 1: From top to bottom are presented KET/*Ulysses* proton intensities within energy bands 5 – 25 MeV (black), 38-125 MeV (red), 125-250 MeV (blue) and 250-2000 MeV (cyan); magnetic field strength (VHM/FGM) and solar wind velocity (SWOOPS). Black arrows mark X-class solar flares on days 339, 340, 347 and 348 (2006 December 5, 6, 13 and 14) [1]; vertical lines indicate the shock arrivals on days 344, 345 and 351, respectively [4].

The vertical lines in Figure 1 show the times when interplanetary shocks passed *Ulysses* [5]. When the shocks on day 345 and 351 passed *Ulysses* an intensity increase has been measured only by the lowest energy channel. No noticeable increases were observed at higher energies. At Earth four particle intensity increases have been observed by the GOES satellite and will be discussed in the following section.

Discussion

As shown in Figures 2 and 3 four well-separated proton intensity enhancements were observed in the energy range from 10 to 500 MeV.

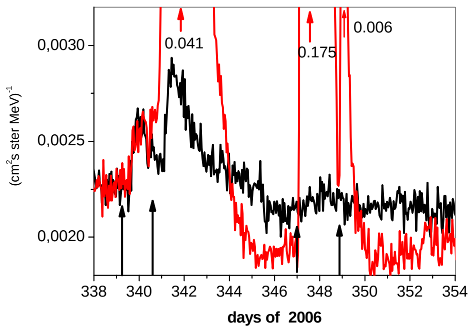


Figure 2: Comparison of 250-2000 MeV protons measured by KET on *Ulysses* with 165-500 MeV protons as measured close to Earth. Both instruments are normalized to the 165-500 MeV GOES intensity as described in Struminsky [6].

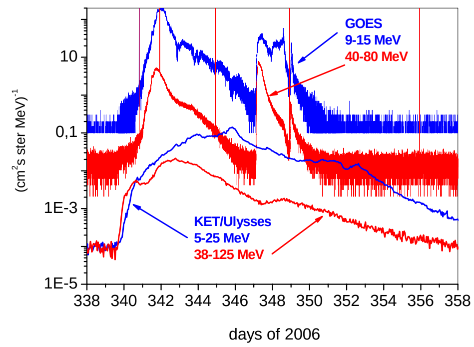


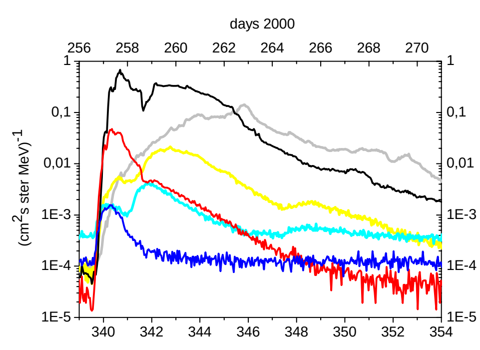
Figure 3: Comparison of ~10 MeV and ~ 50 MeV proton intensities measured by KET/*Ulysses* (hourly average) and *GOES* EPS (5-min average) in December 2006.

These increases were caused by the solar flares from December 5, 6, 13 and 14. In Figure 2 the intensity time profile of 165-500 MeV protons measured by EPS and of 250-2000 MeV measured by KET are shown. At Earth the highest maximum intensities were measured on December 13. This event has also been measured by ground based neutron monitors and was one of the few Ground Level Enhancements (GLEs) occurring during the course of the solar cycle. The largest solar particle event at *Ulysses* was the event on December 6. This SEP event was accompanied by outstanding characteristics of non-thermal emission [1]. In comparison with *Ulysses* the energy spectrum was much softer near Earth resulting in higher maximum intensities at lower particle energies.

Of special interest with respect to energetic particle propagation is the SEP on December 5. From Figure 2 it is obvious that the onset and time profiles of high energy protons observed by *Ulysses* and *GOES* are identical during this event. Under the assumption that both spacecraft observe the same particle population the transport in latitude and longitude must result in the same intensity profiles. This makes the model of particle acceleration or transport within the vicinity of the shock front to a proper field line unlikely for this event.

Fig. 3 displays the GOES and KET observations of ~10 to ~100 MeV protons. Due to the high background at GOES we can't analyse the onset times for these low energy channels. However, from the sudden intensity increases observed at 20:30 UT on December 6 (day 340) by GOES we conclude that the magnetic connection from AR 10930 to the Earth becomes better. A reason for that is most probably a reconfiguration of the interplanetary magnetic field due to a shock wave generated by the previous event.

In Figure 4 we compare the Ulysses measurements of 5-250 MeV protons on December 2006 at ~70 degrees South with the one on September 12, 2000 and on November 4, 2001 [2] in the upper and lower panel, respectively. The latter events were observed at similar latitudes during the solar maximum phase of solar cycle 23.



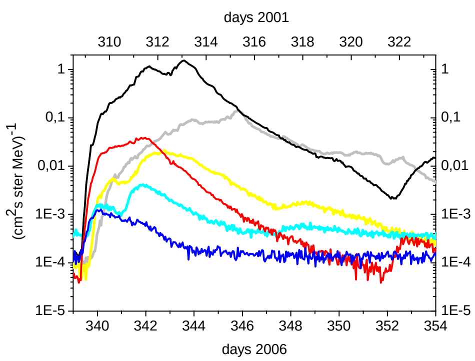


Figure 4: Comparison of KET time profiles (grey – 5-25 MeV; yellow – 38-80 MeV; cyan 80-125 MeV) measured in December 2006 with those in September 2000 and November 2001 (black, red and blue curves).

The time profiles in Fig. 4 are shifted to get the same onset time of the 80-125 MeV channel during the compared events. As a result we see similar time profiles in this energy band till onset of the December 6 event. Contrary, lower energies on December 5 show a time delay in comparison with 2000 and 2001 events indicating more complicated propagation of protons to high latitudes for energies lower than 80 MeV, which also leads to slower increase of proton intensity to maximum in December 2006.

Conclusions

We analyzed Ulysses COSPIN/KET and GOES EPS measurements during the December 2006 period and found that high energy protons (> 100 MeV) could propagate to high latitudes around solar minimum (Dec. 2006 event) in a similar way as during solar maximum (Sep. 2000 event and Nov. 2001 event). In contrast, at lower energies (< 100 MeV) the propagation was found to be different.

Acknowledgements

The Ulysses/KET project is supported under grant No. 50OC0105 by the German Bundesminister für Wirtschaft through the Deutsches Zentrum für Luft- und Raumfahrt (DLR). This work is partially supported by RFBR (grants 05-02-17105, 05-02-17251). AS thank the LOC for their hospitality.

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