Solar energetic electrons propagation in converging interplanetary magnetic structures by Ulysses (event of day 081, 1995)

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Abstract

Fine time resolution observations of energetic (40-112 KeV) electrons made by the HI-SCALE experiment onboard the Ulysses spacecraft, during the onset of a major solar electron event on day 81 of the year 1995 and the technique of mapping the solar wind at the solar corona, are used, in order to obtain the large-angle scattering distance of these particles in a converging structure of the large scale interplanetary magnetic field. Consequently, effective mean free paths are determined.

1. Introduction

The great variety of the large-scale magnetic structures of the interplanetary space cannot be explored by local plasma and field measurements alone. In this respect, the energetic particles provide an excellent means for remote diagnosis of such structures.

The acceleration of energetic electrons at the sun, the subsequent ejection and propagation in the interplanetary magnetic field and the generation of electromagnetic radiation through their interaction with the interplanetary plasma have been studied for years. First evidence for the existence of solar energetic electrons was provided from observations of solar radio waves (Boischot and Denisse, 1957). Solar energetic electrons were noticed at 1 AU for the first time by Van Allen and Krimigis (1965) while complete time history and energy spectra of energetic electrons following a solar flare were obtained by Cline and McDonald (1968a, b).

The study of nonrelativistic and relativistic electrons propagation in the interplanetary space has been of particular interest. Energetic electrons have smaller gyroradii compared to the scale size of the magnetic inhomogeneities being responsible for their scattering in the interplanetary space. Lanzerotti et al. (1973) and Jokipii (1971) have derived mean free paths for a diffusive propagation of energetic electrons from measured interplanetary magnetic field spectra. Allum et al. (1971) with anisotropy measurements underline the existence of a component diffusing back towards the Sun and they infer that scattering of electrons certainly occurs in the interplanetary medium although it may take place predominantly beyond 1 AU.

Roelof (1979) points out that the observed strong anisotropies during the onsets of solar electron events are consistent with the idealized depiction of a "scatter-free" propagation of electrons along the magnetic field lines and the presence of a reflecting boundary in the deep space. Sarris et al. (1983) and Sarris (1988) have found out the "effective" large-angle scattering distance for propagation of electrons beyond the Earth's orbit while Malandraki et al. (1997) determined the same parameter for propagation of electrons beyond Ulysses's position. Kunow et al. (1991) give a detailed review of recent theoretical and experimental advances on the parameters that determine particle propagation.

Through this article, a thorough examination of the anisotropy characteristics is attempted, during the onset of a major solar flare electron event on day 81 1995, by the usage of high time resolution measurements in relation to angular distributions of electron intensities being obtained by the HI-SCALE experiment onboard Ulysses, near the ecliptic plane (+5.5^{o}, ~157.56^{o}E) at a heliocentric distance of 1.34 AU. The Ulysses mission, having as its primary objective the study of the inner Heliosphere in three dimensions, provides an important step toward achieving this goal. A good estimation of the time delay between the detection of the first outgoing electrons and the first backstreaming is achieved from which the large-angle scattering distance beyond the spacecraft is evaluated. This evaluation is confirmed by the technique of mapping the solar wind and the frozen-in magnetic field lines back to the solar corona (Nolte and Roelof, 1973 a,b), fact, providing information about large solar wind and IMF structure in the interplanetary space.

2. ULYSSES mission and instrumentation

The Heliosphere Instrument for Spectra, Composition, and Anisotropy at Low Energies (HI-SCALE) onboard the ULYSSES spacecraft (Lanzerotti et al., 1992) is designed to obtain measurements of interplanetary ions and electrons. The ions (E_i>50 KeV) and electrons (E_e>30 KeV) are detected by five separate solid-state detector telescopes, oriented to give essentially complete pitch-angle coverage from the spinning spacecraft.

3. Observations

Figure 1 depicts the intensity profiles for 1-8A^o and 0.5-4A^o solar X-rays for the time period from 20th to 26th March 1995 (*ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/ SOLAR_FLARES/*) and shows that on March 22th (day 81), the GEOS-7 X-ray detector monitored three X-ray flares (A, B and C). The most important of them was the flare marked C that was started at 14:40 UT. This flare was associated with the active region S15^o W22^o.

Figure 2 displays energetic electron (a, b) and ion (c) flux-time profiles detected by the HI-SCALE instrumentation onboard the Ulysses spacecraft on days 81-82 and 81 of 1995 respectively. In particular, Figure 2 shows electron observations from the channels E'1 - E'4 of the LEFS60 telescope (a) and the electron channels DE1 - DE4 of the LEMS30 telescope (b) and energetic (56-1802 keV) ion observations from the P1, P3, P5, P7 channels of the LEMS30 telescope. The electron flux – time profiles of Figures 2a and 2b clearly shows the onset of an energetic (~40 – ~300 keV) electron event on March 22th at ~17:20 UT; a similar energetic electron burst was also detected by the telescope LEFS150 in the energy range 40-280 keV (data not shown in the figure). However, during the day 81 there seems to be no comparable effect in the ion flux-time profiles measured by LEMS30 telescope (Fig. 2c).

On March 22th, Ulysses traveled near the ecliptic plane (+5.5^o, ~157.56^{o}E) at a heliocentric distance of 1.34 AU and magnetic connection longitude (CL) of 180.44^o (Figure 3). We infer, therefore, that the electron event detected by Ulysses at ~17:20 UT was most probably triggered by the flare at 14:40 UT (Flare C);

In Figure 4a, we expose high time resolution counting rates of energetic (40-65 keV) electrons streaming away from the Sun as observed by the LEFS60 telescope (sector S7/ channel E'1) and in Figure 4b the counting rates of the sunward propagated electrons observed by the anti-sunward directed telescope LEFS150 (sector S3/channel E1), for the time interval 16:00-19:00, day 81, 1995; evidently, the sunward propagated electrons observed by LEFS150 corresponds to flare electrons reflected beyond the position of Ulysses (1.34 AU). Figures 4c and 4d depict electron counting rates in the energy range 60-107 keV detected by the oppositely directed sectors 2 and 4 of the LEFS60 telescope, which correspond to energetic electrons streaming away from and towards the Sun, respectively. The delay times between the first outgoing and the first backstreaming electrons of Figure 4 were found to be ~1500 sec for the 40-65 keV and the 65-112 keV electrons, corresponding to large angle scattering distances of ~0.756 and ~0.972 AU, respectively.

In Figure 5, we present 30 sec averaged pitch angle distributions (PADs) snapshots during the onset of the outgoing (LEFS60 telescope/E'1, E'2 channels) and the back scattered (LEFS150 telescope/ E1, E2 channels) electrons. The PADs in panel (a) indicate a strong anisotropy of the electron propagated away from the Sun in the antiparallel direction of the IMF. These peaked electron PADs argue for nearly scatter-free propagation of the concrete particles, during their outward transit from the corona to the position of Ulysses. A beam parallel to IMF (panel b) seems to correspond to backscattered electrons.

In Figure 6 the technique of mapping the solar wind at Carrington's connection longitude back to the solar corona (Nolte and Roelof, 1973a) is applied, in order to examine the configuration of the interplanetary space during the electron event. The relationship between Carrington's connection longitude L and distance R from the Sun is given by the equation: $L(t)=L_o(t)+\Omega R/V$ where $L_o(t)$ is the Carrington's longitude of Ulysses at the time of observation, Ω the solar sidereal rotation and V the solar wind velocity measured by the

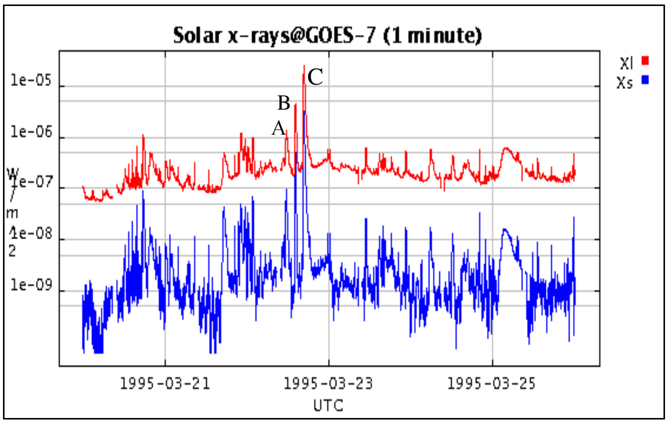

Figure 1. Intensity (W/m^2) - time profiles of solar X-rays observed by the GEOS-7 X-ray detector in the period 20-26 March 1995. The two curves correspond to wavelengths of 1-8 A^o (top) and 0.5-4 A^o (bottom). Three major bursts (A, B, C) were observed on day 81 (22 March) 1995, and the most important of them was burst-C with maximum intensity over C-43.

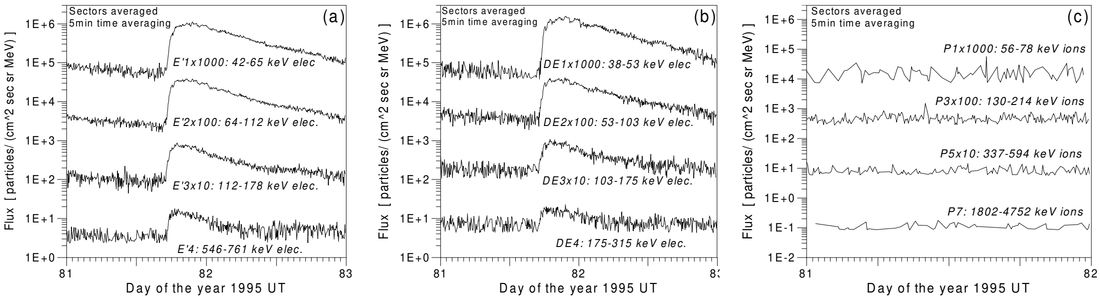

Figure 2. The onset of the highly anisotropic solar flare electron event observed by the HI-SCALE instrumentation onboard the Ulysses s/c on 22 March (day 81) 1995: (a) Electron Observations from the sunward looking telescope LEFS60 (channels E'1, …, E'4). (b) Electron observations from the LEMS30 telescope (chan. DE1, DE2, DE3). (c) Intensity-time profiles of energetic ions measured by the LEMS30 telescope (channels P1, P3, P5, P7) in the same time period; contrary to electrons, there is no comparable effect in the ion fluxes.

Solar Wind Plasma Experiment onboard Ulysses. In this depiction the time marked on the horizontal line at 1.34 AU, runs from the right to the left as Ulysses crosses the streamlines which are fixed to the Sun. The streamline carrying the frozen magnetic field from the solar corona which passes by the spacecraft at the time of the onset is distinctly marked. This flux tube is intersected beyond 1.34 AU by a faster solar wind stream. The distance along the flux tube from the spacecraft to the point of intersection is estimated to be ~1.5 AU which is close to the large-angle scattering distances computed from the delay times.

4. Conclusions

The large-angle scattering distance of the flare electrons observed by Ulysses on March 22th 1995 in a converging structure of the IMF was estimated by the measured delay time between electrons streaming away from and towards the Sun and was found to be ~1.5 AU. We infer that on March 22th 1995 the mean free-path for large-angle scattering should exceed ~1.5 AU for these particles.

References

Allum, F.R., R.A. Palmeira, U.R. Rao, K.G. McCracken, J.H. Harries, and I. Palmer, 1971, Solar Phys. 17, 241.

Boischot, A., and J.F. Denisse, 1957, Compt. Rend. Acad. Sci. Paris, 245, 2194.

Burlaga, L.F., L. Klein, 1980, NASA, TM-80668.
Cline, T.L. and F.B. McDonald, 1968a, Solar Phys. 5, 507.
Cline, T.L., and F.B. McDonald, J. Can., 1968b, Phys. 46, S527.
Jokipii, J.R., 1971, Rev. Geophys. Space Sci., 9, 27.
Kunow, H., G. Wibberenz, G. Green, et al., 1991, in Physics of the Inner Heliosphere, ed. By R. Schwenn and E. Marsch, Springer-Verlag, Vol. II, 243.
Lanzerotti, L.J., D. Venkatesan, and G. Wibberenz, 1973, J. Geophys. Res. 78, 7986.
Lanzerotti, L.J., R.E. Gold, K.A. Anderson, T.P. Armstrong, R.P. Lin, S.M. Krimigis, M. Pick, E.C. Roelof, E.T. Sarris, G.M. Simnettt, and W.E. Frain, 1992, Astron. Astrophys. Suppl. Ser. 92, 349-363.

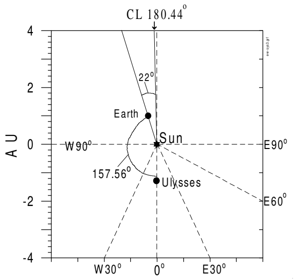

Figure 3. The relative positions of Sun, Earth and Ulysses spacecraft on the ecliptic plane.

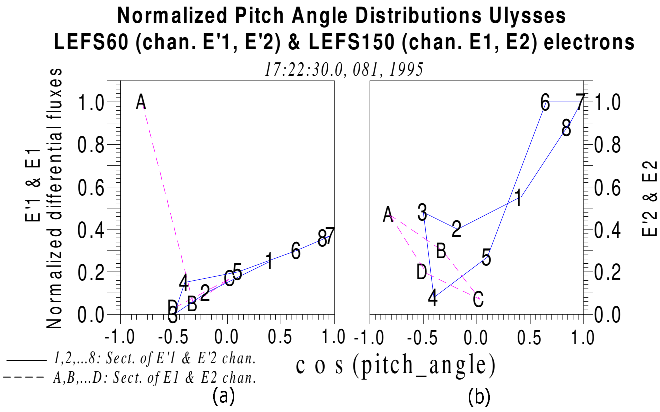

Figure 5. Pitch angle distributions (PADs) snapshots during the onset time of outgoing and backscattered electrons (40-112 keV) detected by the LEFS60 and LEFS150 telescopes of the HI-SCALE instrumentation onboard Ulysses on day 81, 1995: (a) PADs from E1, E′1 electron channels (b) PADs from E2 and E′2 channels. Energetic electron beams in the directions parallel and anti-parallel to the magnetic field were present at that time.

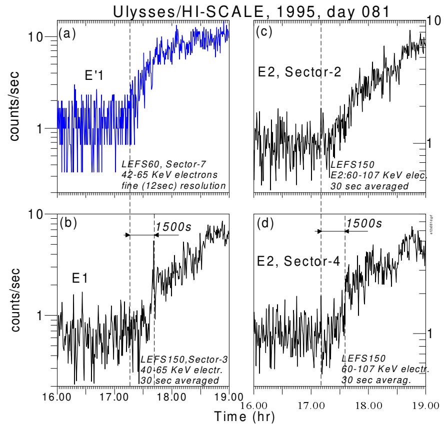

Figure 4. Observations of energetic electrons streaming away (back) from (towards) the Sun, during the onset of the solar flare event of March 22 (day 81), 1995 as observed by Ulysses/HI-SCALE.

Malandraki, O., G. Kasotakis, E.T. Sarris, P.C. Trochoutsos, D. Dialetis and G. Tsiropoula, 1997, Proceedings, 25th International Cosmic Ray Conference, 385-388.
Nolte, J.T., and E.C. Roelof, 1973a, Solar Physics, 33, 241.
Nolte, J.T., and E.C. Roelof, 1973b, Solar Physics, 33, 483.
Roelof, E.C., 1979, Geophys. Monogr. Ser. AGU Vol. 21, 220.
Sarris, E.T., P.C. Trochoutsos and G.C. Anagnostopoulos, 1983, Solar Physics, 83, 51.
Sarris, E.T., 1988, "In memorian D. Kotsakis", G.Contopoulos, B. Barbanis, and P.G. Laskaridis (eds.), Athens.
Van Allen, J.A. and S.M. Krimigis, 1965, J. Geophys. Res. 70, 5737.

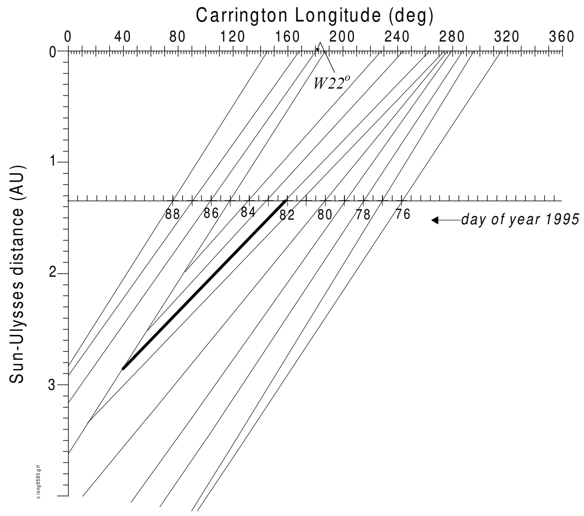

Figure 6. Mapping of the observed solar wind to the Carrington connection longitude at the solar corona during the solar electron event of March 22 (day 81), 1995.