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Solar energetic particle events observed by SOHO/CELIAS/STOF

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Abstract. Since the launch of the Solar and Heliosheric Observatory (SOHO) on Dec. 2, 1995, the Suprathermal Time-Of-Flight (STOF) energetic particle sensor of the Charge, Element and Isotope Analysis System (CELIAS) has observed gradual and impulsive solar particle events from solar activity cycle minimum to maximum. The instrument CELIAS/STOF has the capability of detecting energetic ions between 35 and 630 keV/q and determine the mass, energy and charge of each particle. We report on the measurements of the detected energetic particle events from 1996 to 2000, i.e. the daily averages of the He/Pr, the He charge state and the Fe/O ratios. For selected events we analyse the velocity dispersion of the suprathermal ions and estimate the onset of the solar event and set limits on the propagation length along the connecting magnetic field line.

1 Introduction

The gradual and impulsive solar energetic particle events can be studied presently by a fleet of spacecrafts carrying in-situ instrumentation, i.e. ULYSSES, WIND, SOHO or ACE. The instruments cover the energy regime from the solar wind, the suprathermal, energetic and high energy ions. The origin of impulsive solar energetic particle events is attributed to the acceleration in solar flares and they have charateristic abundancy enhancements such as high ^{3}He/^{4}He or Fe/O ratios of about 1 (Mason et al. 1986, Reames, Richardson and Wenzel 1992, Reames et al. 1997, Mason, Dwyer and Mazur 2000). The acceleration time is much shorter than the timescales for the propagation to the spacecraft, i.e. to 1 AU. The dispersion of the velocity distribution of the energetic ions is then dominated by propagation effects in the interplanetary medium (Mason et al. 1989, Mazur et al. 2000, Giacalone, Jokipii and Mazur 2000). The large gradual solar energetic particle events had also been attributed to originate from solar flares. However, in the recent years it became more and more obvious from observations that the large gradual events are accelerated in shock waves driven out of the corona by coronal mass ejections (CMEs) and not in solar flares (Lee and Ryan 1986, Gosling 1993, Reames, Kahler, & Ng1997).

In the following, we will report on the observations by CELIAS/STOF onboard SOHO, in the time interval from 1996 to 2000 or during the quiet and increasing part of the recent solar activity cycle. For selected events, we attempt to examine the connection of the particle event to solar X-ray events and set limits on the propagation length of the ions along the magnetic field lines.

2 Instrumental

CELIAS is onboard of SOHO, a 3 axis stabilized satellite, launched on Dec 2, 1995 and orbiting the sun in a Halo orbit near the Lagrange Point L1 at about 0.99 AU.

The CELIAS/STOF sensor consists of a curved energy/charge analyser to determine the energy per charge, a time-of-flight spectrometer to determine the velocity and a solid state detector to measure the residual energy of an incoming particle. The mass, charge and energy of the particle is then deduced from these three measurements. STOF measures suprathermal ions in the energy per charge range 35 to 630 keV/q (E/Q resolution: 0.11, 30 logarithmical spaced steps), the geometrical factor of STOF is 0.05 cm^2 sr and the STOF field of view (3° x 17°) points 7° west off the Sun. STOF is more sensitive to scattered ultraviolet light than expected and, therefore, exhibits a relatively high background due to accidental coincidence rates.

HSTOF is a section of the STOF instrument. HSTOF has its boresight set at 37° west of the Sun-SOHO line and a field of view (FOV) ±2° in and ±17° off the ecliptic. HSTOF identifies the mass and energy of each incident energetic particle by its speed measured by a time-of-flight (TOF) unit and the residual energy deposited in a pixellated solid-state detector. In front of the TOF unit is a flat-field electrostatic en-

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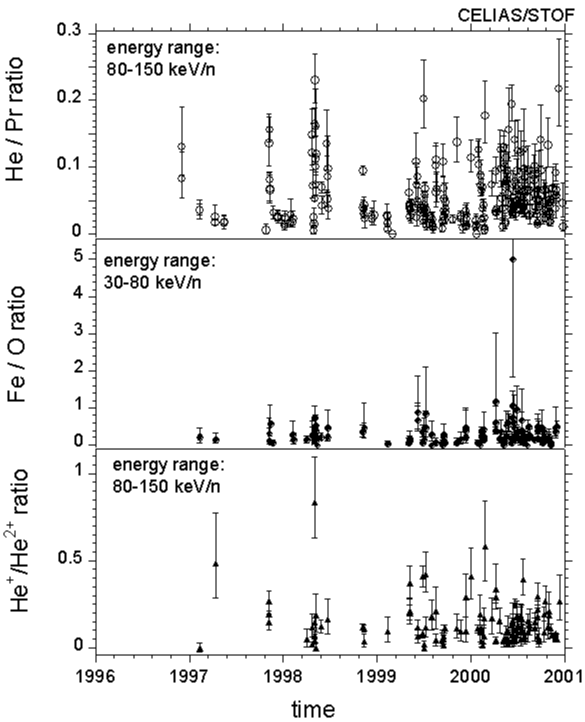

Fig. 1. The elemental He/Pr and Fe/O ratios and the He charge state ratio as observed by CELIAS / STOF (daily averages)

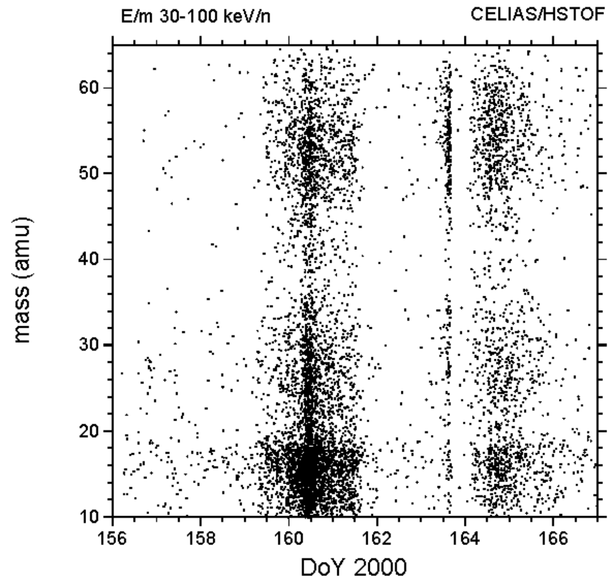

Fig. 2. The mass of heavy ions and the arrival time as observed by CELIAS/HSTOF in the time interval June 4 to 15, 2000.

ergy/charge (E/Q) filter, that cuts off ions of E/Q $<$ 80 keV/e. The geometrical factor of HSTOF is 0.22 cm^2 sr. Due to the E/Q stepping and the smaller geometrical factor, the sensitivity of STOF is about 0.008 that of HSTOF for energetic protons. A detailed description of the instrument is given by Hovestadt et al. 1995.

The SOHO spacecraft was not nominal operational for the second half of 1998 and the first month of 1999 and therefore the data contains notable gaps. The data was analysed on a daily average basis. High flux events such as the "Bastille Day" flare on July 14, 2000 were excluded from the survey as the instrument counters almost saturated. For the summary analysis we focused on events above a threshold of 29 proton counts/day for the He/Pr ratio, 13 O and Fe counts/day for the Fe/O ratio and 39 He counts for the He charge state ratio in the respective energy/nucleon intervals.

3 Observations

We observed ions in the suprathermal energy regime. For statistical reasons we limited the analysis to daily averages. The observations of CELIAS/STOF are shown in Fig. 1 for the time interval of solar cycle activity minimum in 1996 towards solar cycle activity maximum. As it is well established, the number frequency and the intensity of solar energetic particle events grow with the rising of the solar activity. The elemental ratios He/Pr and Fe/O as well as the He charge state ratios show no indication of a solar cycle relationship. The plotted data is biased due to the above described threshold criteria and therefore the large gradual solar events are more pronounced and the impulsive solar energetic particle events, which on average have lower particle flux intensities, are subpressed. Events with high He^{+}/He^{2+} ratio are often accompanied by interplanetary shock acceleration, i.e. CIRs or Halo-CMEs, and their composition is not necessarily associated with the solar corona. The energetic particle events at the beginning of May 1998, giving raise to high He/Pr and He^{+}/He^{2+} ratios are described and analysed by Bamert et al. 2001.

We picked a time interval in June 2000 which included a large gradual solar energetic particle event and an impulsive event. In Fig.2 the ion arrival time and mass is plotted. An interplanetary shock was observed on June 8, 2000, 8:40 UT by the CELIAS solar wind monitor (Ipavich 2000) and energetic ions were observed preceeding, at and after the shock passed the SOHO satellite. The energetic particle event on DoY 163 or June 11, 2000 was the solar impulsive event, identified by its very high Fe/O ratio of about 5, shown in Fig. 1. No transversing interplanetary shock was identified by the CELIAS solar wind monitor.

Velocity dispersion results because faster ions travelling along the connecting interplanetary field line are detected earlier than slow ions, all accelerated in the same solar event. The velocity of the ions is proportional to the root of energy/nucleon. The time t required for ions with the velocity v to propagate along a magnetic field line of length L is given by $t = L/(\mu.v)$, where μ is the cosine of the particle's pitch angle with respect to the magnetic field line (Reames et al. 1997). The time t is plainly the difference between the time of arrival at the detector and the time of the solar event onset

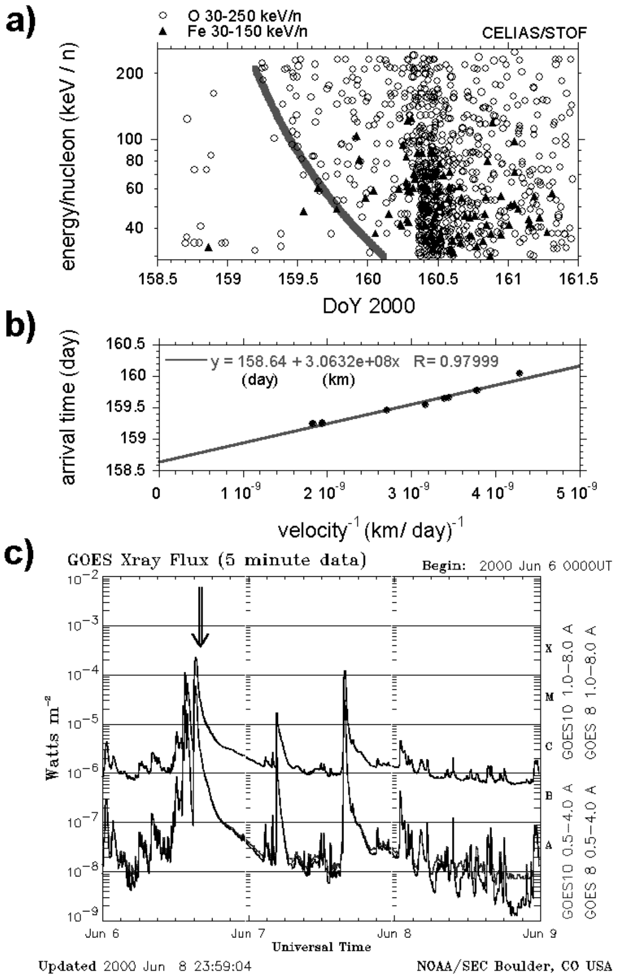

Fig. 3. a) Velocity dispersion of O and Fe ions on June 8, 2000 as observed by CELIAS/STOF. The broad line indicates the events selected to calculate the time of the solar event time. b)Linear fit for ion $velocity^{-1}$ and $arrival$ or detection time for the selected events. The calculated onset of the preceeding solar event is DoY 158.64. The ion path along the interplanetary magnetic field L is $\leq$ 2 AU. c) Solar X-ray data from GEOS Satellite Data (NOAA 2000) for the period June 6-8, 2000. The arrow indicates the calculated event onset (June 6, 2000, 15:30 UT).

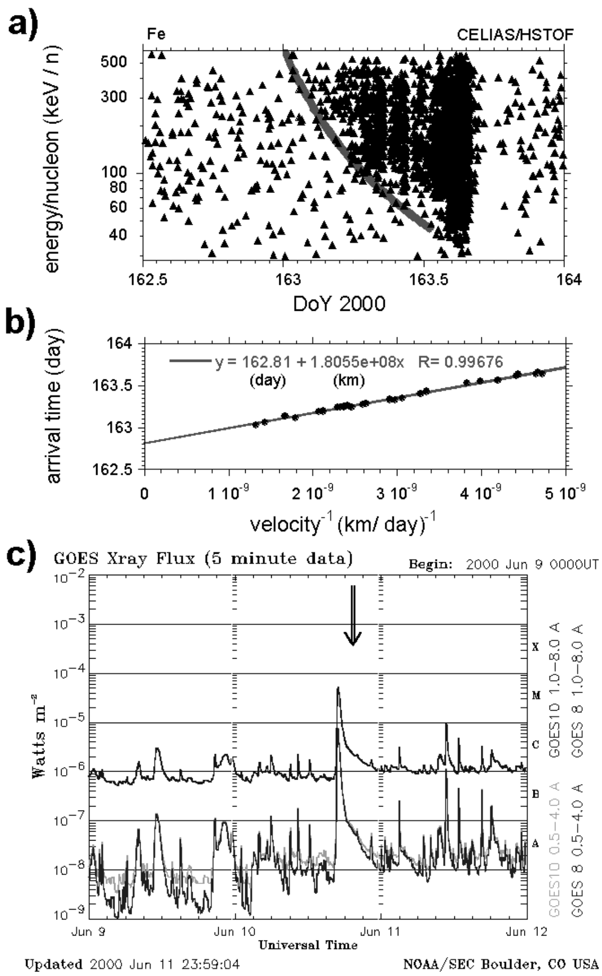

Fig. 4. a) Velocity dispersion of Fe ions on June 11, 2000 as observed by CELIAS/HSTOF. The broad line indicates the events selected to calculate the time of the solar event. b) Linear fit for ion $velocity^{-1}$ and $arrival$ or detection time for the selected events. The calculated onset of the preceeding solar event is DoY 162.82. The ion path along the interplanetary magnetic field L is $\leq$ 1.2 AU. c) Solar X-ray data from GEOS Satellite Data (NOAA 2000) for the period June 9-11, 2000. The arrow indicates the calculated event onset (June 10, 2000, 19:40 UT).

and therefore

$$arrival\ time = solar\ event\ onset\ -\ (L/\mu)\ .\ v^{-1} \qquad (1)$$

Plotting the foremost arrival or detection time of the energetic ions versus the reciprocal velocity allows the calculation of the time of the solar event onset (intercept) and L/μ (slope) from a linear fit. L/μ is the maximum travel distance or length of the magnetic field line as μ is always $\leq$ 1. The minimum value of L/μ is the radial distance between the solar event site and the detector, i.e. 1 AU for CELAIS/STOF on SOHO.

In Fig. 3 the velocity dispersion of the O and Fe ions detected by CELIAS/STOF is shown for the gradual solar event. The solar event accelerated ions arriving foremost and before the interplanetary shock were selceted manually. We compared the result of the fit with X-ray flare data observed by the GEOS satellites (NOAA 2000) and found a reasonable agreement with the X-ray flux observed and the calculated event onset within less than one hour. The ions travelled along an interplanetary magnetic field line $L \leq$2AU. Recently some low energy neutral particles (below and at solar wind energy) have been reported during this event on June 8, 2000 (Collier et al. 2001). We screened the data of the HSTOF section in the energy regime between 60 and 90 keV, where HSTOF is capable to detect suprathermal neutral atoms. We could not identify neutral atoms in this energy regime on a statistical significant level. However, HSTOF's field of view is directed 37° west of the Sun-SOHO line and one would expect the neutrals to arrive from the direction of the sun. In Fig.4 the velocity dispersion during the solar impulsive event on DoY 163 or June 11, 2000 is plotted. The onset time derived from the velocity distribution was about 3 hours later than the X-ray flare observed by GEOS satellites. A conceivable explanation is that the selected events are not the most foremost and therefore a later event onset was derived. The plot of the velocity dispersion shows the interplanetary field line mixing recently reported and discussed by Mazur et al. 2000, i.e. the ion flux shows a fine-scale temporal variation. Some magnetic flux tubes passing over the detector are filled with flare ions, others are not. The ion path along the interplanetary magnetic field is $L \leq 1.2$AU. For the energetic particle event on DoY 164 or June 12, 2000, we determined an event onset time on June 11, 2000, 10:30 UT and $L \leq 1.5$AU.

4 Discussion

The observations of suprathermal ions by CELIAS/ STOF from 1996 to 2000 could not reveal a notable alteration in the He/Pr and Fe/O ratios with the increasing solar activity. Since we limited the analysis to daily averages, the short-term variations in elemental abundancies from the onset of an energetic event towards its decay have not been followed up (Reames, Ng, & Tylka(2000)). The analysis is biased since large gradual solar events are favoured and small impulsive solar events are suppressed by the application of thresholds and the limited detection efficiency. The velocity dispersion of ions accelerated near the sun was used to determine the event onset and the maximum length of the magnetic field lines connecting the detector and the solar event site. The approach seems promissing and the search for an algorithm to trace the ”foremost” ions in a solar particle event is an ongoing task.

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