Proceedings of ICRC 2001: 3439

ICRC 2001

Variable abundance of energetic He^+ in CME related SEP events

H. Kucharek[1], B. Klecker[2], E. Möbius[1], W. Li[1], A. Popecki[1], A. B. Galvin[1], M. Hilchenbach[3], and P. Bochsler[4]

[1]Dept. of Physics and Inst. for the Study of Earth, Oceans and Space,University of New Hampshire, Durham NH 03824
[2]Max-Planck-Institut für extraterrestrische Physik, Postfach 1312,85741 Garching
[3]Max-Planck-Institut für Aeronomie, 37819 Katlenburg-Lindau, Germany
[4]University of Bern, CH-3012 Bern, Switzerland

Abstract.
We have investigated several coronal mass ejections (CME) related solar energetic particle (SEP) events with unusually high abundance of He^+ in the energetic particle population. There were observed between 1998 and 1999 with SEPICA on ACE and CELIAS/STOF on board SOHO. Whereas usually the abundance of He^+ is below a few percent, at these times the He^+/He^{2+} ratio can be close to one. Possible sources for He^+ are interstellar pickup ions or cold solar ejecta in CMEs. The abundance of He^+ is expected to vary depending on where the major acceleration occurs, i.e. close to the sun or mainly locally close to the observer.

1 Introduction

According to a widely accepted view solar energetic particle (SEP) events are usually subdivided into two classes. Gradual solar events are characterized by high fluxes of energetic particles, generally with a low electron to ion ratio and a composition that reflects on average normal solar corona conditions (e.g. Reames et al., 1992). In contrast impulsive events generally show low fluxes of energetic particles in interplanetary space with a high electron to ion ratio, substantial enhancements in the abundance of ions heavier than O, and mostly also dramatic enhancements of 3He over 4He (e.g. Mason et al., 1986; Reames, 1990). While the former are usually accompanied by a coronal mass ejection (CME), the latter are thought to originate from acceleration in compact solar flares on the sun. In accordance with this picture, gradual events usually contain ionic charge states that are consistent with coronal values (Luhn et al., 1984; Klecker et al., 1999) and impulsive events typically feature very high charge states (Klecker et al., 1984; Luhn et al., 1987; Möbius et al., 2000). The situation was complicated by the finding of a substantial contribution of He^+ to energetic particle populations in interplanetary space by Hovestadt et al. (1984). As a possible source of these ions the admixture of cold solar material was suggested. Subsequently, the detection of interstellar pickup He^+ (Möbius et al.,1985) in the inner heliosphere has introduced another potential source for particle acceleration in interplanetary space. These ions had been suggested already earlier by Fisk at al. (1974) as the source for the anomalous component of cosmic rays.

The connection of pickup ions with energetic particles was first confirmed for a CIR at 5 AU by Gloeckler et al. (1994). They identified interstellar pickup He^+ as the major contributor of the suprathermal He in CIRs with Ulysses SWICS for energies up to 60 keV. More recently, He^+ was also found as part of the suprathermal CIR population at 1 AU up to 200 keV/Q with SOHO STOF (Hilchenbach et al., 1999) and with Wind STICS (Chotoo et al., 2000). These observations led to the suggestion that pickup ions may constitute a generally important source of suprathermal ions for further acceleration at interplanetary shocks (Gloeckler, 1999). For a recent series of unusual CIRs close to solar maximum in 1999 and 2000, Möbius et al. (2001a) have reported a substantial fraction (10 - 30%) of He^+ in the energy range 0.25 - 0.8 MeV/nucleon, which they attributed to interstellar pickup ions. For the same CIR events Morris et al., (2001) have shown that the He^+/He^{2+} ratio increases as time elapses from the beginning of the CIR. This increase was interpreted as the increase in the relative contribution of interstellar pickup ions over solar wind ions with distance from the sun in the CIR population. Transport effects do not seem to play a major role in producing the observed temporal variation of the ratio (Möbius et al., 2001b). In this paper we will study the charge distribution of He in several CME related SEP events with ACE SEPICA and SOHO STOF. The work is motivated by the statistical analysis of the He^+/He^{2+} ratio in the suprathermal (85 - 280 keV) ion population with SOHO STOF by Klecker et al. (2001). They find substantial variations of the He^+/He^{2+} ratio that show some correlation with the solar wind conditions. In the data set they find several time periods with high ratios that occur during CME related

Correspondence to: Harald Kucharek
(Harald.Kucharek@unh.edu)

events. For a sample of these events we will extend the energy range to 0.8 MeV/nucleon in order to study the energy dependence of the He^{+}/He^{2+} ratio. We will also take notice of the temporal variation in order to gather information on the potential source populations of the He^{+} ions and their relative contribution. At the time this paper is being written the analysis is not complete, and therefore only preliminary interpretations are given.

2 Spacecraft and Instrumentation

The Suprathermal Time Of Flight (STOF) sensor is part of the (Charge ELement and Isotopic Analyzing System) CELIAS instrument and is designed to study the composition of the solar wind and of solar and interplanetary energetic particles on the (SOlar and Heliospheric Observatory) SOHO spacecraft. It was launched in December 1995 and injected into a halo orbit around L1. The STOF sensor is an ion telescope with a relative large geometrical factor (0.05 cm**2 sr) for the measurement of the energy distribution of individual charge states of various elements of solar energetic particles. It covers the energy range from 35 to 630 keV/Q by employing an electrostatic deflection system.

The Advanced Composition Explorer ACE spacecraft was launched on August 1997, and it is also in a halo orbit around L1. The Solar Energetic Particle Ionic Charge Analyzer (SEPICA) is the main instrument on ACE to determine the ionic charge states of solar and interplanetary energetic particles in the energy range from 0.2 MeV/nuc to 5 MeV/charge. The charge resolution is achieved by focusing of the incoming ions through a multi-slit mechanical collimator, deflection in an electrostatic analyzer with a voltage up to 30 kV, and measurement of the impact position in the detector system. To determine the nuclear charge (element) and energy of the incoming ions the combination of thin-window flow-through proportional counters with isobutane as counter gas and ion implanted solid state detectors provide for 3 independent E (energy loss) versus E (residual energy) telescopes.

For this study several CME events in 1998 and 1999 have been selected for which we have determined the He^{+}/He^{2+} ratio. The statistical study by Klecker et al. (2001) is based on 12 hour averages of the ratio. Since the time periods were selected from this study, we have kept the same 12 hour cadence in our data. For SEPICA we have chosen an energy range from 0.25 MeV/nuc up the 0.8 MeV/nuc. Within this energy range the He track in the SEPICA measurements is well separated from heavier elements at the lower limit and high enough in detection efficiency at the higher end. Figure 1 shows the charge state distribution of Helium as observed by SEPICA on ACE for one CME event on Day Of Year (DOY) 120 in 1998.

The diamonds indicate observations whereas the full line represents a fit to the measurements. We have used a least square fit method, and as a fit function we used two Gaussians with variable peak position, height and width. As one can see from Figure 1 the two charge states are clearly separated in the chosen energy range, and the good counting statistics provides for an accurate determination of the He^{+}/He^{2+} ratio. The ratios are determined in a similar way from the SOHO/STOF data. In Table 1 we have summarized the He^{+}/He^{2+} ratio as observed by SEPICA on ACE and by STOF on SOHO. For the analysis we have used the same accumulation time of twelve hours for both data sets. The time periods over which the related SEP events extended, as seen at an energy of 0.5 MeV/nucleon, are listed at the bottom of Table 1. As can be seen from the times given the samples with the He^{+}/He^{2+} ratio represent only a fraction of the events in some cases. The selection was limited by time periods with high ratios (i.e. > 0.1) with the STOF sensor and enough counting statistics. It is apparent that often only part of the entire SEP event is He^{+}-rich. This is very prominent for events B, C and D. In general the ratio varies drastically during individual events, with the variation being substantially stronger at lower energies. For example, the ratio decreases by more than a factor of 30 within two consecutive days during event D in the suprathermal ion population, while the same ratio at 0.5 MeV/nucleon only varies by a factor of 2.5.

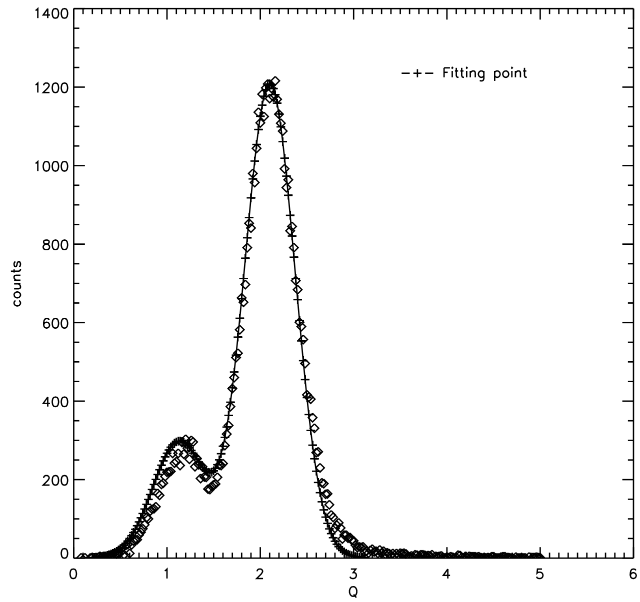

Fig. 1. Charge state distribution of Helium of a CME related SEP event observed with SEPICA on April 30 (DOY 120), 1998, 00:00 - 12:00 UT

3 Discussion

We have determined the He^{+}/He^{2+} ratio for several time periods during CME related SEP in the energy range 85 - 280 keV with SOHO STOF and 0.25 - 0.8 MeV/nucleon with ACE SEPICA. The selection of the time periods is based on a statistical study in the suprathermal energy range (85 - 280 keV) with SOHO STOF (Klecker et al., 2001). High He^{+}/He^{2+} ratios of up to about unity are found during frac-

Table 1. *He^{+}/He^{2+} abundance ratio for CME events in the years 1998 and 1999*

DOY	acc. time	He^{+}/He^{2+} SEPICA (0.25-0.8 MeV/n)	He^{+}/He^{2+} STOF (21-70 keV/n)
1998			
event A			
120	00:00 - 12:00	0.25	3.7
	12:00 - 24:00	0.16	0.67
event B			
301	12:00 - 24:00	0.20	3.54
302	00:00 - 12:00	0.12	0.63
event C			
345	12:00 - 24:00	0.11	0.35
346	00:00 - 12:00	0.12	0.97
1999			
event D			
346	00:00 - 12:00	0.08	3.38
	12:00 - 24:00	0.05	1.11
347	00:00 - 12:00	0.03	0.11

event	start – end [YY DOY hh:mm] UT
A	98 120 00:00 – 98 120 24:00
B	98 301 12:00 – 98 304 03:00
C	98 344 01:00 – 98 348 04:00
D	99 344 06:00 – 99 349 12:00

tions of events in the suprathermal range, whereas at the higher energies the ratios do not exceed 0.25 in the current sample. The He^{+}/He^{2+} ratio seems to increase towards the suprathermal energies. In addition, the ratio is highly variable over the course of individual events, with a stronger variation at the lower energies.

The key questions at this point are, what are the possible sources for He^{+} and what causes the observed the variation. The study of the energy dependence and the temporal evolution of the He^{+}/He^{2+} ratios may shed some light on these problems.

Two possible sources for He^{+} have been suggested: cold solar atmospheric material, which is occasionally found in the solar wind (Schwenn et al., 1987) and interstellar pickup ions (Möbius et al., 1985; Gloeckler, 1999). Cold solar material can be injected into further acceleration at any location from the Sun to the observer and may also predict an increase of the He^{+}/He^{2+} ratio with time as a CME evolves. Because the main acceleration is expected to occur at the CME shock, more interstellar material should be injected as the distance from the Sun increases. Then local acceleration at 1 AU should lead to a He^{+} anhancement over events that are accelerated mainly close to the Sun, if pickup ions are the main contributor. In addition, an enormous enhancement of the He^{+}/He^{2+} ratio can be attributed to an enhanced injection and acceleration efficiency for pick up ions over solar wind ions in a CME driven shock. Suprathermal ions can be more effectively injected into an acceleration as for example demonstrated by Scholer (1999) and Scholer and Kucharek (1999). Pickup ions are indeed essentially suprathermal ions in the frame of the solar wind, while the solar wind itself is rather cold. Therefore, interstellar pickup ions should have an advantage over solar wind to being accelerated.

The observed substantial increase of the He^{+}/He^{2+} ratio towards lower energies and the variability during individual events may hold a clue on the sources. It appears possible that injection of additional material at lower energies that is not so strongly visible anymore at higher energies may play a role in the observed evolution. This would be roughly consistent with the very strong variability of the ratio overall as observed by Klecker et al. (2001) in their statistical study. However, it is premature to draw any conclusions at this point. Temporal variations of the contributing sources, of the acceleration efficiencies and additional transport processes may play a role in the observed variations. As a next step, detailed case studies of the events identified in this work will be carried out that will include the exact time evolution of the solar wind and interplanetary parameters as well as the morphology of the CME related structures. This may provide a hint to any possible contribution from cold solar ejecta that may be embedded in these events.

Acknowledgements. The work on the SEPICA instruments was supported by NASA under Contract NAS5-32626 and the data analysis under Grant NAG 5-6912 where as the work on STOF/CELIAS was supported under DLR contracts 50OC89056 and 50OC96059, NASA Grant NAG 5-2754.

References

Chotoo, K., et al., The suprathermal seed population for corotating interaction region ions at 1 AU deduced from composition and spectra of H+, He++, and He+ observed on Wind, J. Geophys. Res., 105, 23107 - 32122, 2000.

Fisk, L.A., B. Kozlowsky, and R. Ramaty, An interpretation of the observed oxygen and nitrogen enhancements in low-energy cosmic rays, Astrophys. J., 190, L35 - L38, 1974

Gloeckler, G., Observation of injection and pre-acceleration processes in the slow solar wind, Space Sci. Rev., 89, 91 - 104, 1999.

Hilchenbach, M., et al., Observation of suprathermal helium at 1 AU: charge states in CIRs, in: Solar Wind Nine, S.R. Habbal, R. Esser, J.V. Hollweg and P.A. Isenberg, Editor, 1999, American Inst. Physics: New York. p. 605.

Hovestadt, D., B. Klecker, G. Gloeckler, F. M. Ipavich, and M. Scholer, Survay of He^{+}/He^{2+} abundance ratios in energetic particle events, Astrophys. J., 282, L39 - L42, 1984.

Klecker, B., et al., Direct determination of the ionic charge distribution of helium and iron in 3He-rich solar energetic particle events, Ap. J., 281, 458, 1984.

Klecker, B., et al., The ionic charge composition of CME related solar energetic particle events as observed with SEPICA onboard ACE, Proc. of the 26th Internat. Cosmic Ray Conf., Salt Lake City, Utah, eds. D. Kieda, M. Salamon and B. Dingus, 6, 83, 1999.

Klecker, B., et al., On the variability of suprathermal He^{+} at 1 AU., Proc. of the 27th. Internatinal cosmic ray conference, Hamburg, 2001.

Luhn, A., et al., Ionic charge states of N, Ne, Mg, Si, and S in solar energetic particle events, Adv. Space Res., 4, 161, 1984.

Luhn, A., B. Klecker, D. Hovestadt, and E. Möbius, The mean ionic charge of silicon in 3He-rich solar flares, Ap. J., 317, 951, 1987.

Mason, G.M., et al., The heavy-ion compositional signature in He-3-rich solar particle events, Ap. J., 303, 849, 1986.

Möbius, E., et al., Survey of Ionic Charge States of Solar Energetic Particle Events During the First Year of ACE, in: Acceleration and Transport of Energetic Particles Observed in the Heliosphere, R. A. Mewaldt et al. ed., AIP Conf. Proc., 528, 131 - 134, 2000.

Möbius, E., et al., Direct observation of He+ pick-up ions of interstellar origin in the solar wind, Nature, 318, 426 - 429, 1995.

Möbius, E., et al., Charge states of energetic ions obtained from a series of CIRs in 1999 & 2000 and implications on source populations, Geophys. Res. Lett., subm., 2001a.

Möbius, E., et al., Variation of Energetic He+, He2+ and Heavy Ions Across Co-Rotating Interaction Regions, Proc. of the xx ICRC, this volume, 2001b.

Morris, D., et al. , Implications for source populations of energetic ions in co-rotating interaction regions from ionic charge states, in: ACE-SOHO Workshop on Solar and Galactic Composition, ed. R. Wimmer-Schweingruber et al., AIP Conf. Proc., subm., 2001.

Reames, D.V., Energetic particles from impulsive solar flares, Ap. J. Suppl., 73, 235, 1990.

Reames, D.V., Particle acceleration in solar flares - Observations AIP Conf. Proc. 264, 213, 1992.

Scholer, M., Injection and acceleration processes in corotating interaction regions: theoretical concepts, Space, Sci. Rev., 89, 105, 1999.

Scholer, M., and H. Kucharek, Interaction of pickup ions with quasi-parallel shocks, Geophys. Res. Let., 26, 29, 1999.

Schwenn, R., The solar wind, In ESA Space Astronomie sna Solar System Exploration, p. 131 - 141, 1987.