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On the variability of suprathermal He^{+} ions at 1 AU

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Abstract. Using data from the STOF sensor of the CELIAS experiment onboard SOHO we investigate the variation of suprathermal He^{+}/He^{2+} abundance ratios in the energy range 85-280 keV during the years 1997 to 1999. We observe a large variability of the He^{+} abundances in solar energetic particle events ranging from He^{+}/He^{2+} <5% to $He^{+}/He^{2+} > 1$. Large He^{+} abundances are closely related with the passage of interplanetary shocks, whereas abundance ratios of ~ 0.15 have been observed at 1 AU during CIR events. Combining the data from STICS/WIND and SOHO/CELIAS/STOF for one of the events with He^{+}/He^{2+} ~ 1, a pickup He^{+} distribution with the typical cutoff energy at twice the solar wind velocity and a suprathermal tail extending to ~ 150 keV/nuc is observed. We correlate 12 hour averages of the He^{+} abundances in the suprathermal tail for all days with significant He flux with solar wind parameters and find a general anti-correlation of He^{+} abundances with the solar wind velocity and the solar wind thermal velocity, with a large scatter superimposed on the general trend. We discuss possible causes of this variability, in particular variations of the solar wind and pickup ion source strength.

1 Introduction

Singly charged He ions in solar energetic particle events have first been observed by Hovestadt et al. (1981). They reported a large variability of the He^{+}/He^{2+}-ratio in the energy range 0.41–1.05 MeV/nuc with values ranging from < 0.1 to >1.0 (Hovestadt et al., 1984a). As a possible source of these ions, an admixture of cold matter to hot solar material was suggested. However, the mean ionic charge states of heavy ions as determined for events with particularly large He^{+} abundance showed values of 7.2±0.2 (O) and 14.0±0.8 (Fe), indicative of hot coronal material of ~$2.5 10^{6}$ K, and showed no traces of low charge states as expected for contributions of 'cold' solar material. (Hovestadt et al., 1984b). Thus, the hypothesis of a mixture of hot and cold material was unsatisfactory and the origin of He^{+} remained unexplained.

However, shortly after these early measurements the detection of interstellar pickup He^{+} in the inner heliosphere (Möbius et al., 1985) showed that there is an additional source of particles that could be accelerated in interplanetary space. Somewhat later, the acceleration of interstellar pickup H^{+} and He^{+} with suprathermal tails extending to ion speeds > 10 x V_{SW} has been observed in corotating interaction regions (CIR) at ~ 4.5 AU with the SWICS and HI-SCALE instruments onboard Ulysses, and interstellar He was suggested to be the source of the previously observed energetic He^{+} population (Gloeckler et al., 1994). These measurements also indicated that the injection efficiency for pickup ions is orders of magnitude larger than for the solar wind population, a fact which can be understood in terms of the significantly different velocity distribution of solar wind and pickup ions (Jokipii and Giacalone, 1996). A similar conclusion resulted from numerical hybrid simulations (Scholer and Kucharek, 1999). Pickup ions of interstellar origin have also been suggested as the source of the anomalous component of cosmic rays (ACR) (Fisk et al., 1974), which are accelerated to energies of ~ 240 MeV/e, presumably at the termination shock (Jokipii and Giacalone, 1996, s.a. Klecker et al., 1998, and references therein).

More recently, He^{+} was also found in the suprathermal particle population of CIRs at 1 AU with instruments onboard WIND, SOHO, and ACE, and typical values of He^{+}/He^{2+} ~ 0.15 (Chotoo et al., 2000) and 0.16 to 0.31 in the energy range 25 - 150 keV/nuc (Hilchenbach et al., 1999) have been found (s.a. Möbius et al., 2001). Helium ionic charge abundances in CMEs are also discussed by Kucharek et al., 2001, this conference.

In this paper we report the results of a statistical study of the variability of He^{+}/He^{2+} abundance ratios in the energy range 21 – 70 keV/nuc obtained with the CELIAS/STOF sensor onboard SOHO. This statistical study is comple-

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mented by one case study, where the energy range of the measurement could be extended to low energies by combining data from CELIAS/STOF and WIND/STICS. In this case study the suprathermal He^+ ions are identified as the high energy tail of pickup He of interstellar origin, accelerated at an interplanetary shock. In order to investigate the high variability of the He^+/He^{2+}-ratio we correlate in the statistical study 12 hour averages of the He^+/He^{2+}-ratio and He intensities with 12 hour averages of the solar wind parameters density, velocity, and thermal velocity.

2 Spacecraft and Instrumentation

The observations presented here were carried out with the CELIAS and STICS experiments onboard the SOHO and WIND spacecraft, respectively. CELIAS is the Charge, Element and Ionic Charge Analysis System onboard SOHO. SOHO is orbiting the sun in a Halo orbit near the Lagrangian Point L1, about 1.510^6 km from the Earth. The CELIAS/STOF sensor consists of a curved plate energy/charge analyzer, a time-of-flight system and solid state detectors to determine the velocity, the mass, and the ionic charge of incoming ions. STOF measures suprathermal ions in the energy range 35 to 630 keV/e. The geometrical factor of STOF is 0.05 cm^2sr and the STOF field of view (3°x17°) points 7° west off the Sun. Solar wind data have been provided by the CELIAS/MTOF/PM Proton Monitor. The Proton Monitor measures the solar wind plasma parameters density, speed, and temperature (Ipavich et al., 1998). A detailed description of the CELIAS experiment is given in Hovestadt et al., 1995.

Data from the STICS experiment have been used in a case study to extend the energy range of the STOF experiment to lower energies. During the time of the STICS observations included here, the WIND spacecraft was also far upstream of the Earth's bow shock, at a distance of 215 R_E. The STICS (Suprathermal Ion Composition Spectrometer) sensor uses electrostatic deflection followed by a time-of-flight and residual energy measurement to determine the mass, ionic charge, and energy of all dominant ion species from H to Fe with energies between 6.2 – 200 keV/e (Gloeckler et al., 1995). This energy range is covered in 30 logarithmically spaced steps with a 2% (FWHM) passband. The arrival directions of the ions are binned into 3 polar sectors covering ± 79.5° relative to the ecliptic plane and 16 azimuthal sectors covering 360°.

3 Data Selection and Observations

For the investigation of the variability of He^+ and He^{2+} fluxes we computed 12 hour averages of He^+ and He^{2+} in the energy range 85 – 280 keV using data from the CELIAS / STOF experiment. Figure 1 shows as an example a compilation of the He flux and the He^+/He^{2+}-ratio for the years 1997 to 1999. In 1997 and 1998 only a few large solar energetic particle events related to CMEs and Interplanetary

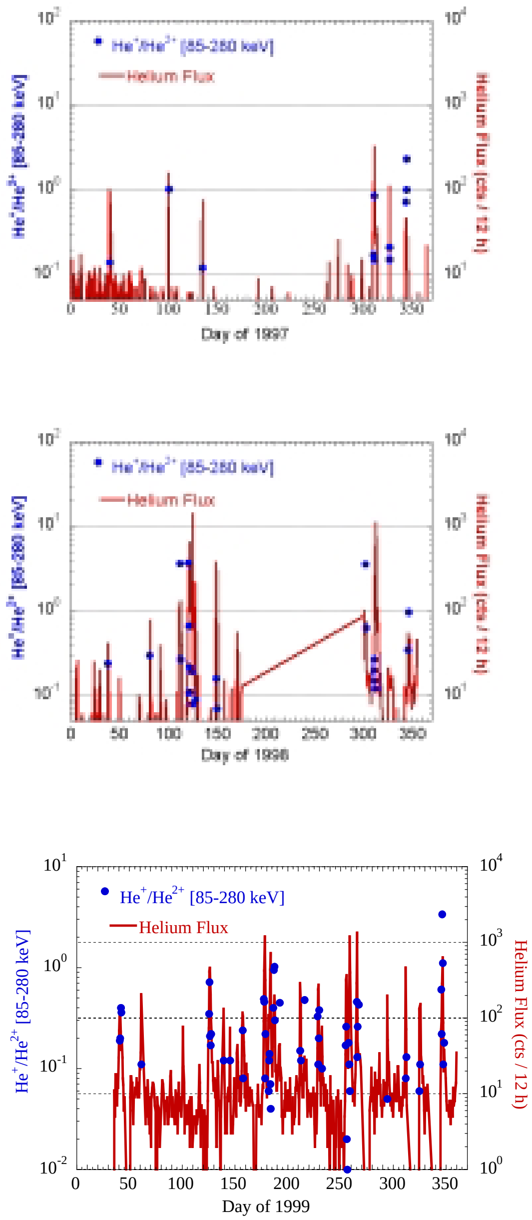

Fig. 1 Averages (12 hour) of the He flux and He^+/He^{2+}-ratio (filled circles) for the years 1997, 1998, and 1999.

Shocks have been observed. More events were observed in 1999 reflecting increasing solar activity. These large events show typically > 50 cts/12h in the selected STOF energy range and a high variability of the relative abundances of the He ionic charge states, ranging from ~ 0.01 to > 1.

We now investigate one of these events, where we were able to extend the energy range of the STOF measurements to low energies, using data from the STICS instrument onboard WIND, in greater detail. On April 10, 1997 a large increase of the low energy particle flux was observed, which was related to an IP shock at 12:58 UT as determined by the Proton Monitor. Figure 2 shows the composite energy spectra of He^+ and He^{2+} from ~2 to 150 keV/nuc, obtained for the time period April 10, 1997, 13:00-17:00

UT. For the STICS observations the azimuthal and polar sectors matching the view direction of STOF have been used. The data clearly show a cutoff in the energy spectrum of He^+ that agrees well with the cutoff for pickup ions determined from the local solar wind velocity (E_{cut} = 4 * E_{SW}), indicated in Fig. 2 by a vertical dashed line. At higher energies, both He^+ and He^{2+} exhibit high energy tails, extending up to ~150 keV/nuc, with comparable fluxes of He^+ and He^{2+}.

We next investigate possible correlations of the suprathermal tails of the He^+ and He^{2+} distributions as measured with STOF with solar wind parameters. In Fig. 3 we correlate the He^+/He^{2+}-ratio with the solar wind velocity (protons) as determined with the CELIAS/PM proton monitor. Figure 3 shows a general trend of He^+/He^{2+}-ratios decreasing with increasing solar wind velocity, with a large scatter of a factor of ~ 10 superimposed on this trend. The trend can be approximated by a power law, i.e. $He^+/He^{2+} \sim V_{SW}^{\gamma}$, with $\gamma \sim -2$ to -3. There is a similar anti-correlation of the He^+/He^{2+}-ratio with solar wind thermal velocity, but no correlations between the He^+/He^{2+}-ratio and solar wind density and He flux, and also no correlation of the He^+ and He^{2+} intensities with the solar wind velocity have been observed.

4 Discussion

Both, the general trend and the superimposed variability of the He^+/He^{2+}-ratios could be due to the variability of the solar wind and / or the pickup ion source, and / or due to the variability of the acceleration conditions. The influence of the variability of acceleration conditions will be investigated with numerical simulations in a paper by Kato et al. (2001) at this conference. Here, we will discuss the variability of the pickup ion and solar wind sources.

4.1 Variability of the Pickup Ion Source

The velocity distribution of pickup He^+ can be written as

$$f(v) = 3\,S(R)\,R_0 / (8\,\pi V_{SW}^4) * (v/V_{SW})^{-1.5} \qquad (1)$$

where S(R)= N(R) ν(R) depends on the local neutral gas density N(R) and ionization rate ν(R), and strong pitchangle scattering has been assumed (e.g. Vasyliunas and Siscoe, 1976; Möbius et al., 1988). We first investigate possible consequences of the dependence of f(v) on V_{SW} by integrating Eq. (1) in order to estimate the total density of pickup He^+ available for injection. We obtain

$$N(He^+) = 4\pi \int f(v) v^2 dv \sim 1/V_{SW} \qquad (2)$$

From equation (2) we could expect a systematic decrease of the He^+/He^{2+}-ratio with solar wind velocity, but somewhat less pronounced than the observed V_{SW}^{-2} to V_{SW}^{-3} dependence.

The source distribution S(R) varies strongly with time, due to systematic variations of the neutral He density and

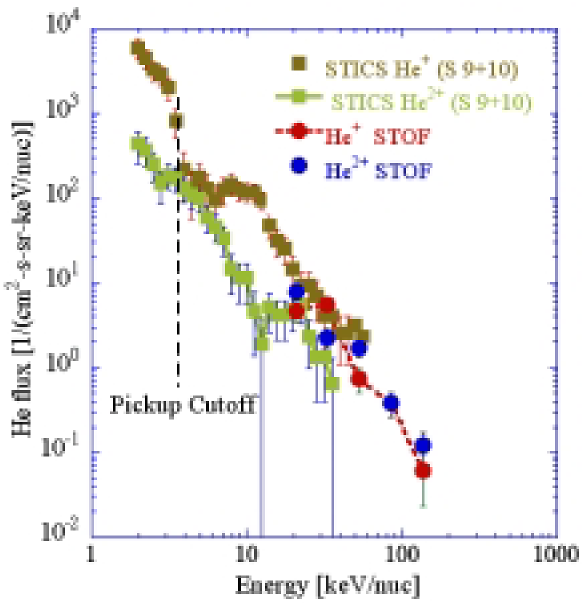

Fig. 2 Composite spectra of He^+ and He^{2+} from 2 to 100 keV/nuc as obtained with the experiments STICS and STOF onboard WIND and SOHO, respectively. The data clearly show the energy cutoff of the pickup He^+ distribution at E_{cutoff} = 4* E_{SW}, and a suprathermal tail extending to ~150 keV/nuc. At energies above ~ 30 keV/nuc the He^+/He^{2+}-ratio is ~1.

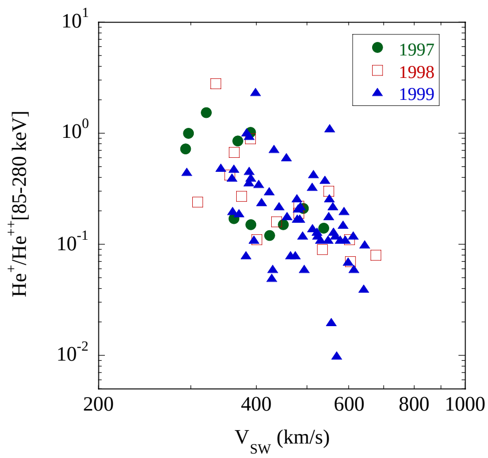

Fig. 3 Correlation of 12 hour averages of the He^+/He^{2+}-ratio with solar wind velocity.

variations of solar UV, the primary source for the ionization of neutral He (e.g. Rucinski et al., 1996). Solar cycle variations are not important for our study of only 3 years. Annual variations and variations on shorter time scales, however, could play a role. The neutral He density shows an annual variation due to the focusing effect of the gravitational field of the Sun and an increase of pickup He^+ by a factor of ~7 in the gravitational cone has been observed at 1 AU (Möbius et al., 1986). However, a close inspection of the variability of the He^+/He^{2+}-ratio at suprathermal energies (Fig. 1) shows that the variations are not correlated with the annual variation of the pickup He source.

Short term variations of the ionization rate of interstellar He by electron impact ionization, directly related to the passage of interplanetary traveling shocks, have been investigated by Isenberg and Feldman (1995). Using measured electron distributions near four interplanetary shocks at 1 AU they find electron impact ionization rates of He comparable to (upstream region) or exceeding (downstream region) the nominal values expected from solar UV. In order to investigate the importance of this process more case studies of this kind, including direct observations of pickup and suprathermal He will be needed.

4.2 Variability of Solar Wind Source

Because solar wind He measurements are not possible with SOHO for the 3 year time period under investigation, solar wind proton parameters have been used as a proxy. Large variations of the solar wind He^{2+} source could, in principle, also cause large variations of the flux of accelerated suprathermal He^{2+} ions. However, in view of the fact that no correlation of the He^+/He^{2+}-ratio with the solar wind proton density has been observed, this seems not to be likely. However, for part of the periods studied, solar wind He parameters are available from ACE and will be investigated in future work.

5 Summary

We find with CELIAS/STOF that at suprathermal energies (~ 85 – 280 keV)

(1) The He^+/He^{2+}-ratio is anti-correlated with the solar wind (proton) velocity.
(2) The He^+/He^{2+}-ratio is anti-correlated with the solar wind (proton) thermal velocity. In view of (1) this is not surprising, because solar wind speed and thermal velocity are strongly correlated (e.g. Burlaga and Ogilvie, 1970).
(3) The He^+/He^{2+}-ratio is not correlated with the Solar Wind (proton) density.
(4) The variability of suprathermal He^+/He^{2+} abundances is not primarily caused by the annual variation of the He^+ pickup ion source.

At the present stage of the investigation the primary cause of the anti-correlation of He^+/He^{2+} abundances with solar wind velocity is not clear and needs further investigation. It could be due to an (unexpected) strong variation of pickup He^+ densities with solar wind speed, or also due to the variability of the thermal distribution of solar wind He^{2+} injected into the acceleration process.

The large variability of He^+/He^{2+} abundances, in addition to the general anti-correlation with SW speed, could also be due to varying acceleration conditions at the IP-shock and needs to be studied on an event-by-event basis.

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References

Burlaga, L.F. and Ogilvie, K.W., Heating of the solar wind, *Astrophys. J., 159*, 659-670, 1970.
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., Kozlowsky, B., and Ramaty, R., An interpretation of the observed oxygen and nitrogen enhancements in low-energy cosmic rays, *Astrophys. J., 190*, L35 - L38, 1974.
Gloeckler, G., et al., Acceleration of interstellar pickup ions in the disturbed solar wind observed on Ulysses, *J. Geophys. Res., 99*, 17637, 1994.
Gloeckler, G., et al., The solar wind and suprathermal ion composition investigation on the WIND spacecraft, *Space Sci. Rev., 71*, 79, 1995.
Hilchenbach, M., et al., Observation of suprathermal helium at 1 AU: charge states and abundances in CIRs, *Solar Wind 9, AIP Conference Proceedings 471*, New York, (Editors: S. R. Habbal, R. Esser, J. Hollweg, and P. Isenberg), 605-608, 1999.
Hovestadt, D., et al., Singly charged energetic helium emitted in solar flares, *Ap. J., 246*, L81, 1981.
Hovestadt, D., et al., Survey of He^+/He^{2+} abundance ratios in energetic particle events, *Ap. J. (Lett.), 282*, L39, 1984a.
Hovestadt, D., et al., Ionic charge state measurements during He^+ - rich solar particle events, *Ap. J., 281*, 463, 1984b.
Hovestadt, D., et al., CELIAS - Charge, Element and Isotope Analysis System for SOHO, *Solar Physics, 162*, 441, 1995.
Ipavich, F.M. et al., Solar Wind measurements with SOHO: the CELIAS / MTOF Proton Monitor. *J. Geophys. Res., 103, A8*, 17.205-17.213, 1998.
Isenberg, P.A. and Feldman, W.C., Electron-impact ionization of interstellar hydrogen and helium at interplanetary shocks, *Geoph. Res. Lett., 22*, 873-875, 1995.
Jokipii, J. R. and Giacalone, J., The acceleration of pickup ions, *Space Sci. Rev., 78*, 137-148, 1996.
Kato, C., et al., Simulation of He^+ and He^{2+} injection and acceleration at interplanetary shocks, this conference.
Klecker, B. et al., Anomalous Cosmic Rays, *Space Sci. Rev., 83*, 259-308, 1998.
Kucharek, H., et al., Variable abundance of energetic He^+ in CME related SEP events, this conference.
Möbius, E., et al., Direct observation of He^+ pick-up ions of interstellar origin in the solar wind, *Nature, 318*, 426 - 429, 1985.
Möbius, E., et al., Pick-up of interstellar neutrals by the solar wind, *Adv. Space Res., 6, No 1*, 199 - 208, 1986.
Möbius, E., et al., Interaction of interstellar pick-up ions with the solar wind, *Astrophys. Space Sci., 144*, 487-505, 1988.
Möbius et al., Variations of Energetic He^+, He^{2+} and heavy Ions across co-rotating Interaction Regions, this conference.
Rucinski, D., et al., Ionization processes in the Heliosphere - rates and methods ot their determination, *Space Sci. Rev., 78*, 73-84, 1996.
Scholer, M. and Kucharek, H., Interaction of pickup ions with quasi-parallel shocks, *Geoph. Res. Lett., 26*, 29-32, 1999.
Vasyliunas, V.M. and Siscoe, G.L., On the flux and the energy spectrum of interstellar ions in the solar system, *Journ. Geophys. Res., 81*, 1247-1252, 1976.