OBSERVATION OF PICK-UP IONS IN THE SOLAR WIND: EVIDENCE FOR THE SOURCE OF THE ANOMALOUS COSMIC RAY COMPONENT?

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ABSTRACT. Singly ionized energetic helium has been observed in the solar wind by using the time-of-flight spectrometer SULEICA on the AMPTE/IRM satellite between September and December, 1984. The energy-density spectrum shows a sharp cut-off which is strongly correlated with the four-fold solar wind bulk energy. The absolute flux of the He^+ ions of about 10^4 ions/cm^2·s is present independent of the IPL magnetic field orientation. The most likely source is the neutral helium of the interstellar wind which is ionized by solar UV-radiation. It is suggested that thes particles represent the source of the anomalous cosmic ray component.

1. Introduction. In 1972 anomalous features in the low energy quiet time cosmic ray energy spectrum have been detected for helium, oxygen, nitrogen, and neon by GARCIA-MUNOZ et al.(1972), HOVESTADT et al.(1973), and Mc DONALD et al.(1974). These four elements are known to have a high first ionization potential compared to other elements like carbon, magnesium, silicon and iron (e.g ALLEN (1973)). This fact lead FISK et al.(1974) to suggest that the source of the particles is the interstellar neutral wind which becomes ionized in the inner heliosphere by interaction of the atoms with solar ultra-violett radiation and/or solar wind ions. The newly created ions then are picked-up by the interplanetary magnetic field. With their gyro-motion in the solar wind frame they represent a distinguished population which is subsequently convected into the outer heliosphere while being accelerated within the turbulent magnetic fields of the heliosphere (e.g. FISK 1976a,b) or at the terminating shock (PESSES et al. (1981)). The resulting energy spectrum is then reshaped to the observed spectrum by modulation and propagation effects in interplanetary space.This paper presents first direct observations of the distribution function of freshly ionized helium in the solar wind which likely has its origin in the neutral interstellar wind and probably represent the source of the anomalous helium component in cosmic rays.

2. The Pick-Up Process. Freshly ionized helium atoms are locally subjected to the combined forces of the interplanetary $V_{SW} \times B$ field of the solar wind and the Lorentz-force in the magnetic field, B, where V_{SW} is the solar wind velocity; i.e. in the inertial-system (which nearly coincides with the spacecraft-system) the particles undergo initially a cycloidal motion in a plane perpendicular to the local magnetic field, B, with a minimum velocity which is equal to the velocity of the neutral wind(assumed to be < 20 km/s and therefore being neglected in the following).The maximum velocity which these ions can obtain in the pick-up process is determined by the solar wind velocity and the angle α between its flow direction and the direction of the local magnetic field:

$$v(max,loc) = 2 \cdot V_{SW} \cdot \sin\alpha \qquad (1)$$

This leads to an energy of

$$E(max,loc) = 4 \cdot M/2 \cdot V_{SW}^2 \cdot \sin^2\alpha \qquad (2)$$

In the solar wind frame the motion initially leads to a conical pitch-angle distribution with the pitch angle α. The velocities parallel and perpendicular to the local magnetic field are given by

$$v(par) = V_{SW} \cdot \cos\alpha \quad (3) \quad \text{and}$$
$$v(perp) = V_{SW} \cdot \sin\alpha \quad (4) .$$

Therefore the total ion velocity in the solar wind frame is given by

$$v = (v_{par}^2 + v_{perp}^2)^{1/2} = |V_{SW}| \qquad (5)$$

If the interplanetary medium were homogenious with parallel magnetic field lines and if there were no scattering imposed by intrinsic or self-generated waves, the distribution function would remain gyrotropic and ring-shaped in the three-dimensional velocity space.

In the real world ,however, the motion of the particles is subjected to effects generated by temporal and spatial magnetic irregularities in the expanding interplanetary medium. While energy-changing wave-particle interactions can be neglected, pitch-angle scattering and adiabatic deceleration can greatly influence the particle distribution. Within a scattering mean free path-length λ the initially ring-type velocity distribution is expected to be reshaped by pitch-angle diffusion into a spherical-shell type distribution which is fully convected with the solar wind . The orbital velocity $|v| = |V_{SW}|$ remains constant in the solar wind frame as long as adiabatic deceleration does not play a significant role. In the inertial system the expected velocities range from zero to $2 \cdot V_{SW}$ with corresponding observable energies between zero and four times the solar wind bulk energy ($0 < E_{pick-up} < 4 \cdot M/2 \cdot V_{SW}^2$).The energy spectrum should show a clean cut-off at that energy value . The spectrum below cut-off should reflect the effect of adiabatic deceleration in the expanding interplanetary medium upstream of the observer.

3. INSTRUMENTATION and SATELLITE. The data presented here are obtained with the suprathermal particle spectrometer SULEICA of the Max-Planck-Institute/ University of Maryland onboard the IRM spacecraft of the Active-Magnetospheric-Particle-Tracer Explorer project (AMPTE), launched on 11. August 1984 into a highly elliptical orbit with an apogee of 18.9 earthradii. During the time period from launch until December 1984 the S/C spent a large fraction of each orbit in the solar wind upstream of the bow-shock of the earth. The SULEICA spectrometer is based on the techniques of electrostatic deflection followed by a time-of-flight and residual energy measurement(for details see MÖBIUS et al.1985). The electrostatic deflection analyser, represented by two concentric segments of a sphere, selects incoming ions according to their energy per charge in 24 logarithmically spaced voltage steps corresponding to an energy range from 5 to 226 keV/charge. After passing through the analyser the ions enter the time-of-flight section where the velocity of the ions is measured. The ions are stopped in a Silicon surface barrier detector where the residual energy is determined. The geometrical factor of the instrument is $4.3 \cdot 10^{-2}$ cm ^{2}sr and the energy resolution is $\Delta E/E \approx 0.097$.

For the investigation presented here the energy of the pick-up ions is too low to create a sufficiently high energy signal in the solid-state detectors. Therefore we identify the ion-species only by combining the electrostatic deflection (E/Q)and the time of flight signal (TOF). For a given E/Q step the TOF histogram as shown in figure 1 therefore represents a mass-per-charge histogram which is taken in the direction of the solar wind.

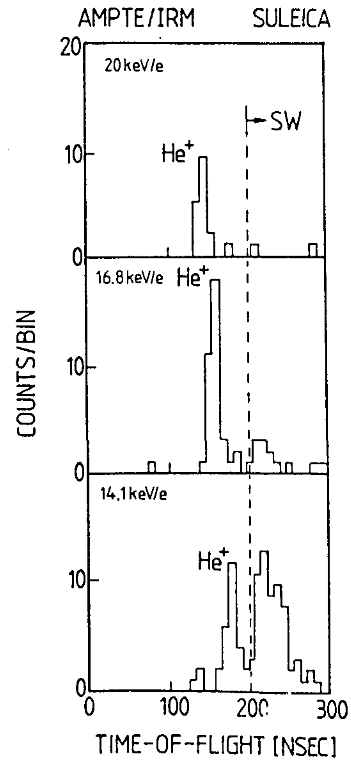

Figure 1: Typical TOF-histogram at three different energy steps, takenin the solar sector.Data are obtained on Nov.11,1984 at ≈18 R_E in front of the bow- shock

4. OBSERVATIONS. A limited number(ten) of observational periods were chosen in the solar wind between launch of the S/C and December,15, 1984. During all periods we observed a peak in the TOF-histograms at M/Q = 4 at E/Q steps which are significantly higher than we would expect for genuine solar wind particles. Depending on the E/Q step and the solar wind velocity, we also observe in addition a broad and variable peak at TOF values which correspond to the solar wind velocity. These ions with M/Q values above 5 correspond to solar wind heavy ions. Figure 1 shows a typical example of TOF histograms for three different E/Q steps obtained on November 11, 1984. It should be noted, that the He^+ peak is visible at all orientations of the interplanetary magnetic field no matter wether bow-shock accelerated ions are present or not.

Figure 2 shows the energy-density spectrum of the M/Q = 4 peak as measured during a sample period of 40 minute duration on Novenber 11,1984, when there are no bow-shock accelerated particles present. The spectra are taken from the directional sector which also contains the solar wind. Except the two neighbouring sectors all other sectors do not show any counts in the M/Q = 4 bin.There is a sharp cut-off at an energy of about 23 keV/e which corresponds to four time the bulk-energy of the solar wind. Below the cut-off energy we observe a more or less flat distribution which ends at a sharp rise of the spectrum at about 8 keV/e. We attribute the rise to solar wind particles of M/Q = 4 which will be not discussed in this paper.

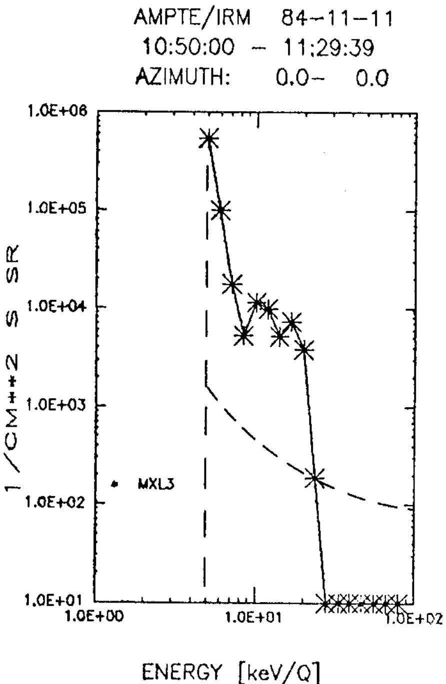

Figure 2:Example of an energy-density spectrum of the M/Q=4 ion channel accu- mulated over 40 minutes. Dashed curved line represents the 1 count/step level.

5. Discussion. Following the arguments in section 2 we tried to correlate the experimental cut-off energies, firstly (figure 3) with the full four-fold solar wind bulk-energy for mass M = 4 (Helium), and secondly (figure 4) with the four-fold component perpendicular to the local interplanetary magnetic field (eq. (2)).

There is an excellent correlation with the full energy (correlation coefficient = 0.98) while the correlation with the perpendicular component is rather poor (correlation coefficient = 0.26). This result suggests that the originally injected ions have lost their directional information in the solar wind frame due to pitch angle scattering, while maintaining their injection energy. The poor correlation with the perpendicular component shows that the ions have lost their directional information and therefore suggests that the source region of the ions extends beyond one mean free scattering length upstream of the observer. The magnetic rigidity of suprathermal singly ionized helium of a few keV/nucleon is in the order of 5 to 10 MV. The mean free path is known to be of the order of 0.05 AU during quiet interplanetary conditions (e.g.compilation in MASON et al.(1983)). The apparently large extent of the source region excludes a terrestrial origin of the ions.

The effect of adiabatic deceleration is expected to be high due to strong coupling of the particles to the solar wind. This sets an upper limit for the distance between point of origin and observer. Ions originating too far upstream (or too close to the sun) loose so much energy that they become indistinguishable from the solar wind itself.

To get a rough estimate of the source strength of the pick-up ions we use the energy spectrum (figure 2) and argue that the energy channels below the cutoff energy are populated via adiabatic deceleration , the rate of which is assumed to vary as 1/r with heliocentric distance. The measured quantity $E \cdot dj/dE \cdot d\Omega$ in each energy channel in figure 3 is related to the relevant source- quantities as: $E \cdot dj/dE\, d\Omega \approx E \cdot S(r) \cdot \Delta r \cdot 4 \cdot \Delta\Omega_{SULEICA}/(4\pi \cdot \Delta E \cdot \Delta\Omega) = S(R) \cdot \Delta r/\pi \cdot (E/\Delta E)$

where $S(r) = N_{He} \cdot \nu_{ion}$ is the source strength of singly ionized helium. For a relative energy width of the instrument of $\Delta E/E = 0.1$ the length of the source column upstream of the S/C translates into Δr = 0.2 AU = $3 \cdot 10^{12}$cm. Using an average value of $7 \cdot 10^3$ for the energy density of the pick-up ions(from figure **2**) we obtain a source strength $S(r=1\ AU) \approx 8 \cdot 10^{-10}$ /cm^{3}s. For an ionization rate of $8 \cdot 10^{-8}$/s (e.g.Holzer 1977) we arrive at a neutral interstellar helium density $N_0 = 10^{-2}$ /cm^3, a value which is fully compatible with results from optical EUV measurements of He II resonantly scattered EUV-lines (WELLER and MEIER 1974; DALAUDIER et al.1984) in the heliosphere. These measurements represent the first direct observation of energetic helium ions picked-up by the solar wind from the interstellar neutral wind thereby filling one more gap in the hypotheses to explain the anomalous cosmic ray component.

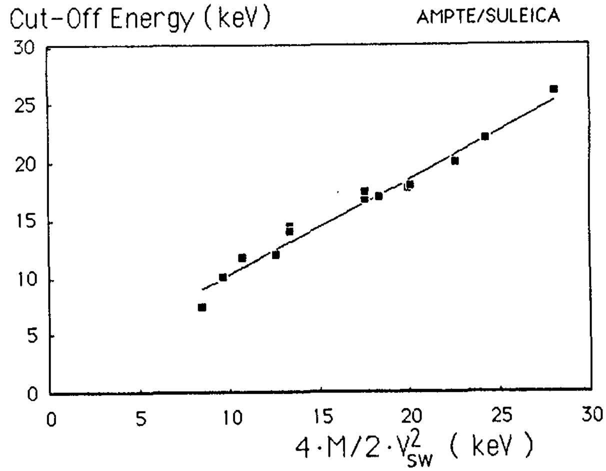

Figure 3: Correlation between experimenmtal cut-off energies and the four-fold solar wind bulk-energy (Correlation coefficient = 0.98).

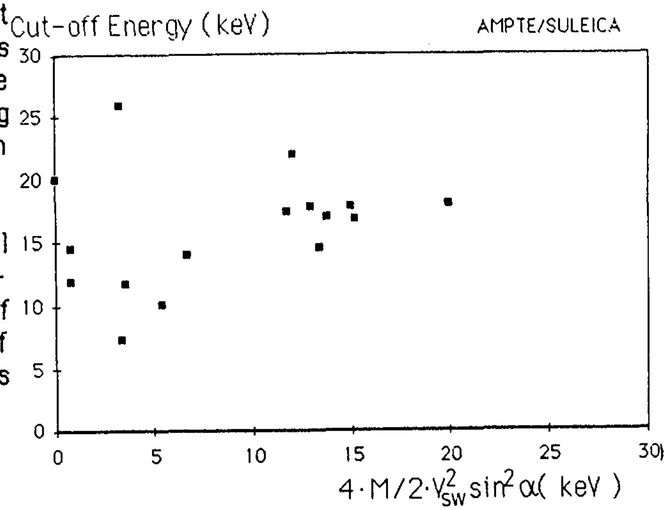

Figure 4: Same as figure 3, but abscissa is vertical-to-B component of the SW bulk-energy(Corr.coeff.=0.26).

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