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CHARGE-EXCHANGE BORN He^+ IONS IN THE SOLAR WIND

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Abstract. The effect of charge transfer between solar wind alpha-particles and hydrogen atoms of interstellar origin is revisited. Singly-charged helium ions born in the charge transfer carry important information on processes in the solar wind and the heliosphere. The velocity distribution of such He^+ ions is substantially different from that of He^+ pick-up ions due to ionization of the interstellar helium atoms. Estimates of the expected abundances of the charge-exchange born He^+ in the solar wind are presented, and the possibility of measuring this plasma component on deep space missions is discussed.

Introduction

Singly-charged helium observed in the solar wind is usually assumed to be pick-up ions [Holzer and Axford, 1970]. Helium atoms of interstellar origin penetrate the solar system where they are ionized and picked up by the solar wind plasma bulk flow. These ions, studied in detail by Moebius et al [1985], Moebius [1990], are a distinct population in the solar wind, characterized by a spherical shell velocity distribution function superimposed on the solar wind bulk velocity. Occasionally observed high concentrations of He^+ ions following interplanetary shocks [Schwenn et al, 1980; Gosling et al, 1980] are related to transients in the sun's atmosphere and are not considered here. The study of singly-charged helium ions is important for understanding the formation of the anomalous cosmic rays (ACR), interstellar gas (ISG) flow, as well as properties of the expanding solar wind. The ACR's are believed to originate from interstellar neutral atoms that are ionized in the heliosphere, carried away by the solar wind, and accelerated to the high energies [Fisk et al, 1974]. Measurement of the pick-up ions in the solar wind gives a tool for a local study of the interstellar particles [Moebius, 1990]. The new generation of space instruments, such as SWICS [Gloeckler et al, 1992], are highly sensitive and should allow one to study characteristics of the He^+ plasma component in detail.

Two processes, other than photoionization of the ISG, contribute to the population of the He^+ ions in the solar wind. First, such ions are present originally in the solar wind, and the He^+:He^{++} abundance ratio is about 3×10^{-6} in the million-degree solar corona [e.g. Feldman et al, 1974]. This source of He^+ is negligible in the context of this letter. Another process is the "asymmetric resonant" charge exchange of He^{++} on hydrogen atoms

$$He^{++} + H \longrightarrow He^+ + H^+ \qquad (1)$$

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The velocity distribution of such He^+ ions is similar to that of alpha-particles in the solar wind and their temperature is much smaller than that of pick-up ions. Study of the characteristics of He^+ ions should allow one to sort out effects of various processes in the solar wind.

The charge-exchange process (1) was invoked by Hundhausen et al [1968] as an explanation of early measurements of He^+ performed by Vela's. However, an unrealistic population of hydrogen atoms was used and, to my knowledge, the contribution of the process (1) has never since been considered. As the He^+ pick-up ions can be used to study the helium component of the ISG, the He^+ ion flux from (1) can be used to study the ISG hydrogen which makes it similar to the neutral component of the solar wind [Gruntman et al, 1990].

The aim of this letter is to revisit the effect of the charge exchange between solar wind alpha-particles and interstellar hydrogen atoms. Estimates of the expected abundances of the He^+ ions are focused on the possibility of observing them by the deep space missions.

Model

It is assumed here that the only source of neutral atoms in interplanetary space is the ISG penetrating the solar system. The ISG consists mostly of hydrogen and helium atoms with number density distributions $n_{H,He}(R_o,\Theta_o) = n_{H,He}(\infty)\, f_{H,He}(R_o,\Theta_o)$, where $n_H(\infty)$ and $n_{He}(\infty)$ are the number densities in the unperturbed ISG. At any given point R_o,Θ_o (figure 1) there are two distinct populations of He^+, viz. pick-up ions and ions formed by (1). The latter are referred to further as charge-exchange ions. Functions $f_{H,He}(R_o,\Theta_o)$ were calculated by many authors, e.g. [Fahr, 1974; Meier, 1977; Wu and Judge, 1979]. The solar wind velocity, V_{SW}, is assumed to be constant and the alpha-particle flux in the solar wind is $\Phi_{He++}(R) = \Phi_E\,(R_E/R)^2$, where Φ_E is the flux at R_E = 1 AU from the sun. The rate of (photo)ionization of helium atoms is proportional to $1/R^2$ and is β_E^{He} at 1 AU from the sun. The flux of the pick-up ions, which are

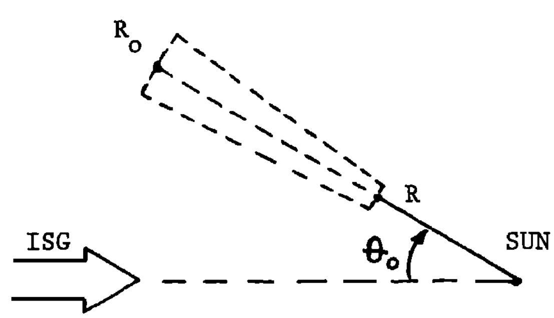

Fig.1. Flow of the ISG relative to the sun.

assumed to be picked-up immediately after their "birth", F_{pi}, at a given point is an integral over contributions along the solar wind flow from the sun to this point (figure 1). Then the flux F_{pi} and the flux of He^+ born via charge exchange, F_{cx}, are

$$F_{pi}(R_o,\theta_o) = \beta_E^{He} (R_E/R_o)^2\, n_{He}(\infty)\, I_{He}$$

$$F_{cx}(R_o,\theta_o) = \Phi_E (R_E/R_o)^2\, q(V_{SW})\, n_H(\infty)\, I_H$$

where $q(V_{SW})$ is the charge exchange cross-section,

$$I_{H,He}(R_o,\theta_o) = \int_{R_S}^{R_o} f_{H,He}(R,\theta_o)\, dR$$

and R_S is the solar radius. It will be convenient to use further the ratio, ξ, of fluxes

$$\xi (R_o,\theta_o) = \frac{F_{cx}}{F_{pi}} = \frac{\Phi_E\, q(V_{SW})}{\beta_E^{He}} \frac{n_H(\infty)}{n_{He}(\infty)} \frac{I_H}{I_{He}}$$

The charge-exchange process (1) may result in the production of the He^+ ions in various states (mostly electronically excited), the most probable (> 80%) being 2P. Its cross section is considered here as the total cross-section for the process (1) which is equal to 1.4, 2.8, and 4.3 $Å^2$ for V_{SW} = 400, 500, and 600 km/s respectively [Barnett et al, 1990]. Calculations of $f_{H,He}$ are performed within the framework of the "hot" model of the ISG [e.g. Meier, 1977; Wu and Judge, 1979]; the computer code was developed by D.Hall (private communication, 1992).

Results and discussion

The difference in the properties of the F_{pi} and F_{cx} fluxes is determined to a large extent by the difference between f_H and f_{He}. Interstellar helium atoms approach the sun closely and are gravitationally focussed in the wake region while the hydrogen atoms are largely extinct at 4 AU from the sun. Hence, the maximum of the F_{pi} flux is observed in the wake region [Moebius, 1990] and the maximum of the F_{cx} flux is expected in the upwind region. At very large distances from the sun, where the solar effects on neutral atoms can be neglected, the fluxes ratio is

$$\xi_\infty \approx \frac{\Phi_E\, q(V_{SW})}{\beta_E^{He}} \frac{n_H(\infty)}{n_{He}(\infty)}$$

For the values $\beta_E^{He} = 0.8\times10^{-7}$ s^{-1}; $\Phi_E = 1.5\times10^7$ cm^{-2} s^{-1}; $q = 2$ $Å^2$; $n_H(\infty) = 0.1$ cm^{-3}; and $n_{He}(\infty) = 0.01$ cm^{-3} used here, one obtains $\xi_\infty \approx 0.4$. The flux F_{pi} is larger than F_{cx} and an important implication for the ACR studies is that up to one third He^+ ions reaching the heliospheric interface region could be of charge-exchange origin.

How fast pick-up ions are assimilated by the solar wind plasma remains an open question. The pick-up ions, though moving approximately with the solar wind bulk velocity, may remain as a distinct population with a very high temperature for a long time [e.g. Isenberg, 1986]. For an observer at a spacecraft the pick-up He^+ would be coming from a hemisphere. Since process (1) occurs at a relatively large impact parameter collision, scattering during a charge exchange is small. The charge-exchange He^+ would be characterized by a temperature of solar wind alpha-particles and F_{cx} would be consequently confined to a rather narrow solid angle. At large distances from the sun the flux of charge-exchange ions, in the units of the flux per unit solid angle, would be much higher than that of the pick-up ions.

Since interstellar hydrogen atoms are efficiently ionized, the F_{cx} at the Earth's orbit is much smaller than F_{pi}. However, for an observer moving away from the sun, the relative contribution of process (1) in the He^+ component of the solar wind would increase. Figure 2 shows the expected normalized flux, F_{cx}/Φ_E, and the ratio, ξ, in the solar wind plasma as a function of R in the upwind direction. The dependence of F_{cx}/Φ_{He++} on angle θ is shown in figure 3 for various distances from the sun. It is assumed that the ionization rate of hydrogen atoms is 7×10^{-7} s^{-1} at 1 AU from the sun, the ISG temperature is 10000 K, the ISG bulk velocity is 20 km/s, and the ratio of the sun's radiation to gravitational forces is 1 and 0 for H and He atoms respectively. The ratio ξ increases with R and approaches ξ_∞ at infinity, while the absolute value of F_{cx} decreases. The F_{cx} flux at 1 AU from the sun is smaller than the He^+ flux expected from the initial charge distribution in the million degree corona. Hence, for measurement of the F_{cx} flux an observer has to be situated at larger distances from the sun.

Deep space missions present a convenient platform to perform measurements of He^+ ions. Ulysses and Cassini reach distance of 5.2 AU and 9.5 AU from the sun

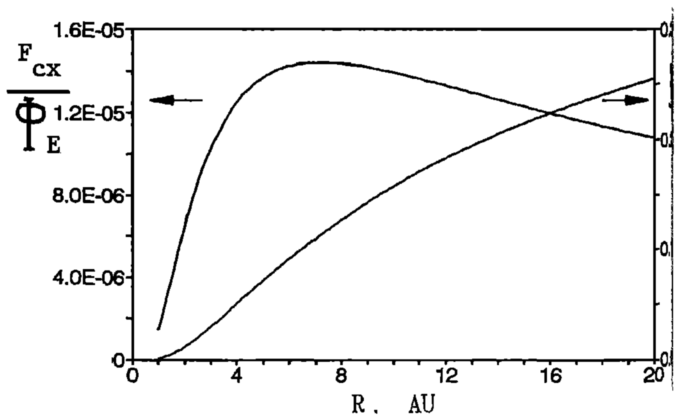

Fig.2. Dependence of the normalized flux of charge-exchange He^+ ions, F_{cx}/Φ_E, and ratio of fluxes of charge-exchange ions to pick-up ions, ξ, in the solar wind plasma as a function of a distance, R, from the sun in the upwind direction; $\theta = 0$; V_{SW} = 500 km/s.

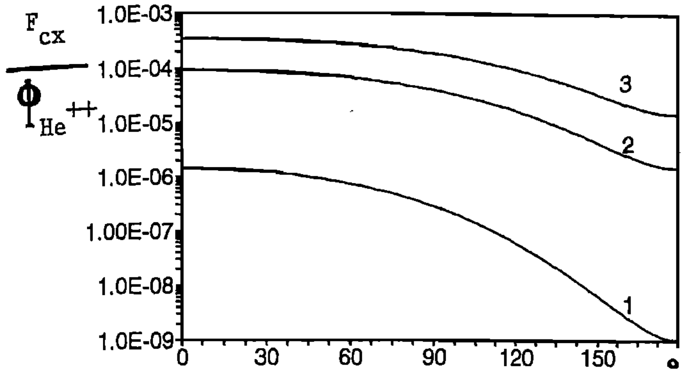

Fig.3. Dependence of the normalized flux of charge-exchange He^+ ions, F_α/Φ_{He++}, in the solar wind on the angle θ; V_{SW} = 500 km/s.
Distance from the sun: 1) 1 AU; 2) 3 AU; 3) 5 AU.

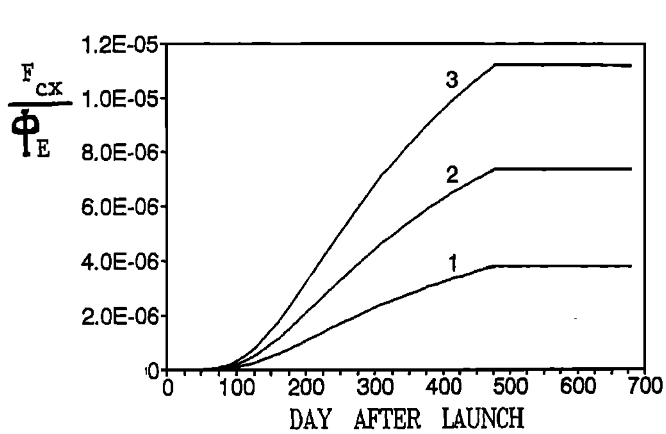

Fig.4. The expected normalized flux, F_α/Φ_E, of He^+ ions in the solar wind plasma along the Ulysses trajectory; day #1 is October 19, 1990; day #650 is 29 July 1992. The velocity V_{SW} is 1) 400 km/s; 2) 500 km/s; 3) 600 km/s.

respectively, and the Interstellar Probe will move in the upwind direction out of the solar system into interstellar space. On board Ulysses, one of the instruments, SWICS, is capable of measuring the ion flux in the solar wind down to 1-20 $cm^{-2}\ s^{-1}$ [Gloeckler et al, 1992]. Figure 4 shows the expected normalized flux, F_α/Φ_E, in the solar wind plasma along the Ulysses trajectory. It is assumed that the interstellar wind comes from the direction with ecliptic longitude 252° and latitude +7° [Lallement et al, 1990]. The expected F_α flux is larger than the SWICS sensitivity threshold for a large portion of the trajectory. The charge-exchange ions constitute only 3% of the total flux of He^+ ions. However, for an observer at the spacecraft pick-up ions are expected from a 2π solid angle while charge-exchange ions are confined within a 10°x10° solid angle. Therefore, the flux of charge-exchange He^+ ions per unit solid angle would be at least one order of magnitude larger than that of the pick-up ions.

Study of the He^+ ions may give a new insight into the models of the heliosphere and ACR's. Flux of He^+ ions would constitute about 10 % of alpha-particle flux in the solar wind at 100 AU. The ratio of He^+:He^{++} in the ACR could provide information on the size of the heliosphere (though non-trivial deconvolution is required) and impose limits on the theory of ACR acceleration. An interesting effect may be due to alpha-particles of higher, than typical solar wind, energies. The cross-section (1) peaks at about 40 keV energy (10 Å^2). Alpha-particles emitted from the sun with such energy would reach the termination shock as He^+ ions with a 40% probability. If such "high" energy ions are accelerated to ACR energies much more efficiently than ions from the bulk of the solar wind plasma, than high-energy alpha-particle emission from the sun may play important role in the formation of the ACR He^+ component. Incidentally, these high-energy He^+ ions may charge exchange and contribute to the population of the energetic neutral atoms (ENA) in the interplanetary space.

As was first pointed out by Paresce et al [1983], the charge-exchange process (1) would result in an emission of 304 Å photons since He^+ ions are born mostly in the 2P state. The expected photon flux (per unit solid angle) coming from the upwind direction to the observer at 1 AU from the sun would be 6.2×10^{-4}, 1.2×10^{-3}, and 1.9×10^{-3} R (1R = 1 Rayleigh = $10^6/4\pi\ cm^{-2}\ s^{-1}\ sr^{-1}$) for V_{SW} = 400, 500, and 600 km/s respectively. Excitation to 3P state of He^+ ions (cross-section 0.09 Å^2 for V_{SW} = 600 km/s [Barnett et al, 1990]) would result in a photon flux of 4.1×10^{-5} R at wavelength λ = 256 Å. The two-photon decay of the metastable 2S He^+ state (cross-section 0.3 Å^2 for V_{SW} = 500 km/s [Barnett et al, 1990]) would result in a diffuse EUV background with a relative intensity distribution similar to that produced by the decay of metastable hydrogen atoms [Gruntman, 1990]. This contribution to the EUV background would depend on wavelength, and constitute, as seen from 1 AU from the sun, 10^{-4} R/Å for λ > 304 Å, i.e. at least one order of magnitude smaller than the expected EUV background from other sources [Paresce and Jakobsen, 1980].

Conclusion

Charge-exchange of solar wind alpha-particles with ISG hydrogen atoms results in a distinct population of He^+ ions in the solar wind. These ions could provide a substantial part of the ACR helium component. Estimates show that state of the art of the instrumentation is adequate to detect on deep space missions He^+ ions produced by charge exchange. The measurements would allow one to impose restrictions on the combination of the parameters characterizing the ISG and the solar wind. It may also provide information on the large scale evolution of the solar wind parameters along the path from place of its origin to the observer.

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