IMPACT OF DENSE INTERSTELLAR GAS CLOUDS ON THE NEUTRAL GAS AND SECONDARY PARTICLE ENVIRONMENT IN THE INNER HELIOSPHERE

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ABSTRACT

We investigated the passage of the solar system through cold dense interstellar clouds with a variation in bulk flow velocity by using multi-fluid models of the global heliosphere and kinetic models of the He flow to derive the spatial distribution of interstellar neutral H and He in the inner heliosphere. We also estimated the corresponding populations of pickup ions and energetic particles. Under all circumstances interstellar He maintains its dominant role as neutral gas contributor in the inner heliosphere. For total interstellar densities up to 100 times the current value, a parameter range for which the heliosphere remains large compared to the Earth's orbit, the interstellar neutral gas generally does not yet affect the solar wind dynamically at 1 AU, except for the region of the He focusing cone on the downwind side of the interstellar flow. Because dense clouds usually are also cold a rather narrow cone with a drastically increased density develops, which acts like a huge and stationary comet. Thus in the cone the solar wind would be decelerated to approximately the interstellar flow speed at 1 AU. In cases when the flow vector is almost aligned with the ecliptic plane the Earth would regularly encounter a region dominated by the interstellar gas. Here neutral solar wind and neutrals generated from the He pickup ions by charge exchange would bombard the Earth's atmosphere, not being blocked by the magnetic field. Under such conditions energetic particles generated from interstellar pickup ions would also dominate the energetic particle population during solar minimum.

1. INTRODUCTION

Interstellar neutral gas flows through the inner heliosphere because of the Sun's relative motion with respect to the surrounding local interstellar medium. Even for the contemporary conditions of a warm and dilute interstellar medium with a neutral H density of about 0.18 cm^{-3} and a He density of 0.015 cm^{-3} interstellar He constitutes the largest neutral gas contributor in interplanetary space at Earth's orbit. This neutral gas is the source of a small, but noticeable population of pickup ions in the solar wind, which in turn is injected into ion acceleration processes much more efficiently than solar wind ions. In fact, He^{+} has been found to be the third most abundant energetic ion species at 1 AU after H^{+} and He^{2+}. During its lifetime the Sun has encountered a variety of different interstellar medium conditions. In fact, it has apparently entered the current local cloud only a few ten thousand years ago, coming from the even more dilute and hot environment of the so-called local bubble. It is expected that the solar system has encountered much denser clouds in the past and will again in the future (Yeghikian & Fahr 2004). We have modeled the neutral gas flow through the inner heliosphere together with the production of pickup ions and related neutral atom populations for the encounter with cold dense interstellar clouds with H densities up to 15 cm^{-3}. In such cases the focusing of the He in the downwind direction of the flow leads to a substantial slowdown of the solar wind in the focusing cone even inside 1 AU, reminiscent of a huge stationary comet. The effects of interstellar neutral gas in the inner heliosphere during encounters with interstellar clouds of varying parameters are discussed in more detail elsewhere (Möbius et al., 2005).

2. HELIOSPHERE MODELING

To study the influence of the interstellar neutral gas and its secondary products under varying interstellar cloud conditions we have concentrated on the current warm cloud and potential dense cold cloud environments. We have ignored the hot environment of the Local Bubble

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Table 1: Environmental conditions for the heliospheric models

Case	n_H (cm^{-3})	n_H^+/n_H	T (K)	v_{ISN} (km/s)	Species	Comments
1	0.26	0.18	6000	26	H, He	Contemporary heliosphere
2	0.28	0.14	6000	13	H, He	Warm cloud, different speed
3	0.24	0.42	6000	52	H, He	Warm cloud, different speed
4	0.28	0.14	10	52	H, He	Cold cloud, high speed
5	0.28	0.14	10	13	He	Cold cloud, different speed; for He cone
6	15	0.01	10	26	H, He	Cold and very dense cloud; He density scales

since it would not lead to interstellar neutrals inside the heliosphere. Finally, we have restricted ourselves to cases with the Earth still located in the inner heliosphere, i.e. with a termination shock distance of ≥ 8 AU. First the global geometry of the heliosphere was computed using a multi-fluid approach for the interaction with interstellar H (Zank et al. 1996; Zank et al. 2003), and then the He flow through the inner heliosphere was modeled separately, using Keplerian trajectories in a hot model of the interstellar gas flow (Rucinski & Bzowski 1995, Rucinski et al. 2003). Table 1 shows the parameters used for 6 cases of clouds. The density information is not needed for He because the absolute He flow scales linearly with the interstellar He density. The most interesting cases are the cold clouds (4-6) because of the strong He density concentration in the cone; for the corresponding hydrogen distributions see Müller et al. (2005).

We are using a stationary model for the He distribution here, although it is known that the temporal variation of the ionization rate influences the spatial He distribution inside the heliosphere. However, this simplified approach is justified because for the discussions in this paper we are interested in the average and extreme values of the neutral gas densities in the inner heliosphere and not so much their temporal evolution and their detailed spatial pattern. To illustrate the differences between the contemporary warm interstellar gas environment and a typical cold gas cloud, Fig. 1 shows longitudinal density profiles of the neutral interstellar He density at 1 AU normalized to the He density at infinity for the current conditions (case 1) along with cases 2 and 3 in the upper panel and for a cold interstellar cloud at T_∞ = 10 K with three different relative velocities (cases 4 – 6) in the lower panel. For the cold cloud conditions with an average ionization rate for He of 10^{-7} s^{-1} at 1 AU the density enhancement in the peak of the cone exceeds a factor of 80. Taking the low ionization rate of $6 \cdot 10^{-8}$ s^{-1} at solar minimum or the high rate of $2 \cdot 10^{-7}$ s^{-1} at solar maximum the cone is higher by a factor of ≈1.5 or lower by a factor of ≈3, respectively. In addition, the cones are very concentrated. In order to make the central cone visible for the cold clouds the angle range is stretched by a factor of 6 in the inset. For the fastest velocity chosen (52 km/s) the cone is extremely narrow, but for 13 km/s the half width of the cone at 1 AU reaches 5°, which is equivalent to almost 0.1 AU, still a substantial width. It should be noted that even for the highest density in the cone the mean free path for collisions is ≈ 0.25 AU and thus noticeably larger than the cone width. Therefore,

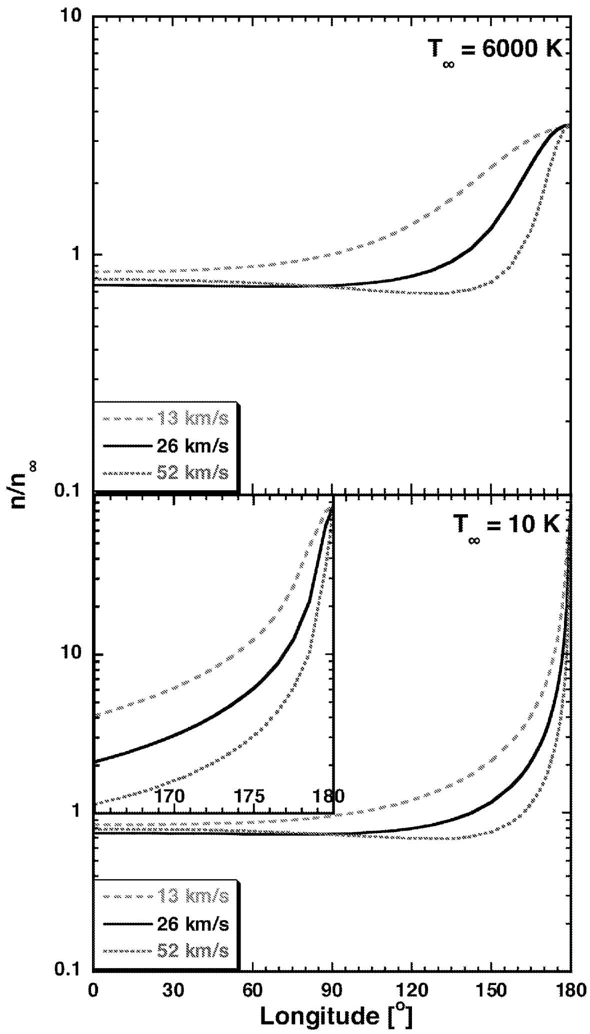

Figure 1. Longitudinal density profile of interstellar He at 1 AU exactly across the gravitational focusing cone for ISN gas with T_∞ = 6000 K and 13, 26, and 52 km/s flow speed, including the contemporary heliosphere (Cases 1-3, upper panel). Same set of velocities for the cold gas with T_∞ = 10 K (Cases 4-6, lower panel). Inset: Tailward (longitude = 180°) detail of the cold cones

the collisionless approximation used in the simulations is still valid. For interstellar neutral gas (ISN) speeds of 13 and 26 km/s the density enhancement is equal or stronger over the entire angle range as compared with contemporary conditions. Taking into account the increased overall density in a cold dense cloud, i.e. $n_{He\infty} = 1.5\ cm^{-3}$, the He density will be substantially higher at all locations.

The present interstellar flow vector is inclined about 6^o relative to the ecliptic plane (Witte, 2004; Möbius et al., 2004), and the bulk of a narrow cone would mostly miss the Earth's orbit. Therefore, the cone center may not directly influence the Earth's environment for the majority of interstellar clouds. If the orientation of the velocity vector were completely at random, the probability for the Earth's orbit to cut through the half-width of the cone at 13 km/s is still ≈5%.

3. SECONDARY PARTICLES AND SOLAR WIND SLOWDOWN IN THE CONE

Neutral He is the dominant interstellar species in the inner heliosphere under all interstellar conditions, and it features the well-known gravitational focusing cone with enhanced density on the downwind side of the interstellar flow. The importance of the cone for the neutral solar wind (NSW) and the pickup ions is reflected in their high densities along the cone axis in Fig. 2, which shows the radial variation of the neutral interstellar He, NSW He, and pickup ion He^+ density as well as the density of neutrals that stem from charge exchange of pickup ions with the ISN gas. The 13 km/s ISM flow (case 5) has been chosen because it produces the widest cone structure. To compute the secondary products charge exchange cross sections for a 400 km/s solar wind and an average ionization rate of $10^{-7}\ s^{-1}$ for He were used. The secondary particles are accumulated starting at 0.03 AU, leaving out the innermost portion of the region where the solar wind is still accelerating and where the neutral densities are negligible. As far as secondary products are concerned He^+ pickup ions are most important under all circumstances. They exceed the neutral He in the solar wind, typically by a factor of 30, because photo-ionization is the prevalent production process for He^+ ions (McMullin et al., 2004). NSW hydrogen (not shown here), produced by the interaction with interstellar He, is even rarer because of the extremely low charge exchange cross section between protons and He, which is lower by about two orders of magnitude compared with double charge exchange between He^{2+} and He.

Surprisingly, a tertiary neutral particle product becomes very important on the downwind axis. Through charge exchange with the interstellar He neutrals that are strongly enhanced in the cone, He^+ pickup ions, which are also strongly enhanced here, are turned into neutral He with the velocity distribution of the pickup ions. Because the enhancement in the cone translates quadratically into the density of this product, its density is enhanced by about four orders of magnitude compared with the upwind direction. To compute the radial profile of these pickup-ion-generated neutrals we accumulated their production along the downwind axis, since they also follow the solar wind on average. However, these neutrals will disperse from the cone according to their pickup ion inherited velocity distribution. This effect is modeled through a free expansion of the cone structure of these neutrals in two dimensions, using an equivalent thermal speed of the generating pickup ions according to Burlaga et al. (1996). For simplicity the density profile across the cone is assumed to be Gaussian.

On the cone axis pickup He^+ reaches the average solar wind density at 1 AU, with obvious impact on the solar wind dynamics. In addition, pickup ions that turned neutral, carry away momentum from the solar wind, because they were originally accelerated on average to the solar wind speed and thus contributed to its mass-loading. To demonstrate the order of magnitude of the solar wind slowdown due to the interaction with interstellar He in the density enhancement of the cone, Fig. 3 shows the radial evolution of the mass-loading ratio (M_{PUIHe^+}/M_{SW}) and the effective solar wind speed (v_{sw}), assuming a homogenous interstellar density. The mass-loading ratio has reached almost 10, and the solar wind has slowed down dramatically at 1 AU. Beyond 1 AU the solar wind blends smoothly into the interstellar gas flow, approaching its speed of 13 km/s. To compute this estimate the loss of momentum to neutral solar wind and neutrals, which originate from He^+ pickup ions, was included, since it becomes important already at ≈ 0.3 AU. It should be noted that the overall solar

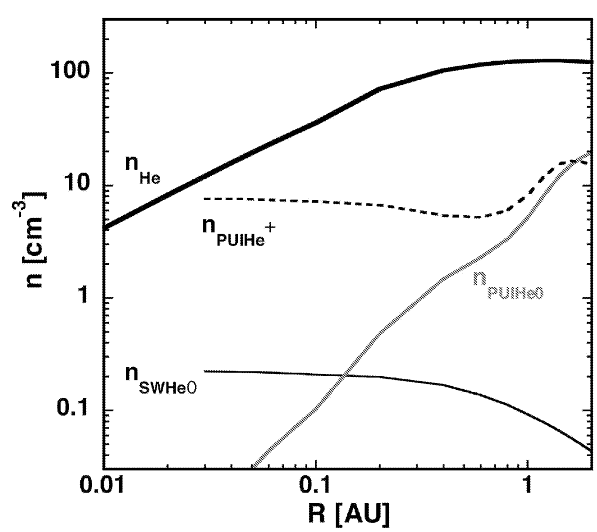

Figure 2. Densities of neutral interstellar He (n_{He}), neutral solar wind He (n_{SWHe0}), He^+ pickup ions (n_{PUIHe^+}), and pickup ions turned neutrals (n_{PUIHe0}) as a function of distance from the Sun for case 5.

wind slowdown is overestimated because the density enhancement in the cone is limited to a region that ranges from less than 1° to approximately 5° in both directions, depending on the interstellar gas flow speed. Through magnetic tension the solar wind in the cone is dynamically coupled to the region outside the cone, where mass-loading is substantially weaker. As long as the solar wind speed outside the cone still exceeds the Alfvén velocity, the coupling to the surrounding medium is weak though, because the information of the slowdown can only travel at the Alfvén velocity. Because this is mostly fulfilled at 1 AU, the estimate given here for the solar wind slowdown in the cone is roughly representative. For a detailed evaluation the cone needs to be treated like a comet (e.g. Schmidt and Wegmann, 1980; Schmidt et al., 1993).

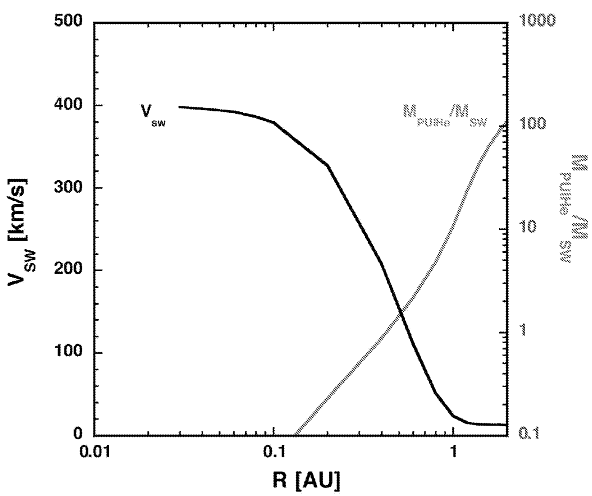

Figure 3. Radial evolution of the effective solar wind speed and the mass-loading by He^+ pickup ions on the downwind cone axis, assuming a homogeneous interaction between neutral He and the solar wind.

4. CONCLUSIONS

When the solar system passes through a cold dense interstellar cloud, even for parameters, which leave the Earth in the inner heliosphere, there is still the possibility that its environment is changed substantially. If the interstellar flow direction is within a few degrees of the ecliptic, the Earth will pass through a very dense focusing cone region where the solar wind is slowed down to the interstellar flow speed, filled with an abundance of neutrals with the velocity distribution of pickup ions. This will expose the Earth's atmosphere to a high flux of impinging neutrals with energies typical of the solar wind, which can alter the chemistry in the upper atmosphere (*Yeghikhyan & Fahr*, 2004). In addition, it should be pointed out that the presence of a massive amount of pickup ions in the inner heliosphere will boost substantially the inventory of energetic particles, in particular, during solar minimum, when acceleration in interplanetary space provides the dominant energetic particle population.

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