HOT NEUTRAL H IN THE HELIOSPHERE: ELASTIC H-H, H-P COLLISIONS

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Abstract. Williams *et al.* (1997) have suggested that a population of hot hydrogen atoms is created in the heliosphere through elastic H-H collisions between energetic 'solar' atoms (neutralized solar wind) and interstellar atoms. They used a BGK-like approximation (Bhatnagar *et al.*, 1954) for the Boltzmann collision term and the collision cross sections suggested by Dalgarno (1960). We show that both assumptions result in a significant overestimation of the the H-H collision effect. On the basis of calculated momentum transfer cross-sections for elastic H-H collisions, we argue that elastic H-H and H-p collisions cannot produce hot H atoms in the heliosphere.

1. Introduction

Williams *et al.* (1997) numerically simulated the effect of elastic H-H collisions on the heliospheric interface. They argued that collisions between energetic solar H atoms (formed inside the heliosphere by charge exchange) with interstellar atoms would produce hot H atoms in the heliosphere. Williams *et al.* (1997) used the H-H collision momentum transfer cross section suggested by Dalgarno (1960) and the Bhatnagar-Gross-Krook (BGK)-like approximation (Bhatnagar *et al.*, 1954) for the Boltzman's equation collision term. We show in this paper that these two assumptions lead to overestimation of the elastic collision effect.

We also consider are closely related to elastic H-H collisions elastic H-P collisions (without charge exchange).

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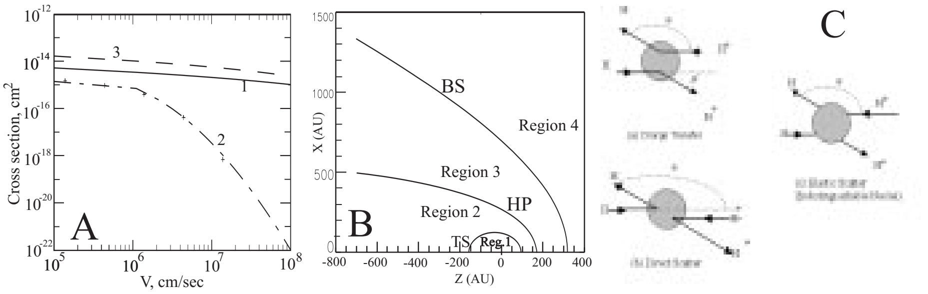

Figure 1. A. Momentum transfer cross sections (in cm^2) as functions of relative velocity (in cm sec^{-1}). (1) Dalgarno, 1960; (2) cross section presented in this paper; (3) charge exchange cross section; B. Structure of the heliospheric interface. Positions of the ternimation shock (TS), the heliopause (HP) and the bow shock (BS) are shown. The heliospheric interface is separated (by shocks) on 4 regions. C. Dynamically identical encounters for (a) charge transfer ($\theta' = \pi - \theta$); (b) direct scatter; and (c) quantum elastic scattering of indistinguishable nuclei. The shared area in each diagram represents the interaction region.

2. Cross Section of H-H Elastic Collisions

First, let us consider validity of using the Dalgarno cross section in the heliospheric interface problem. Treating the colliding particles as quantum mechanically indistinguishable or classically distinguishable could lead to significant differences in the meaning and values of the cross-sections. Dalgarno (1960) calculated the momentum transfer cross-section for quantum-mechanically indistinguishable particles in H-H collisions. This approximation is appropriate for a quantum particle assemble when velocities of distinct particles are correlated each with other. However Williams *et al.* (1997) applied this *like-particles* H-H collision momentum transfer cross-section to description of the collisions between distinctly different populations of H atoms. Classical statistics should be used under latter conditions.

We calculated the momentum transfer cross-section for H-H collisions in the 0.01–1000 eV energy range treating colliding particles as classically distinguishable. The interaction potential of Porter and Karplus (1964) was used. Figure 1A compares the calculated momentum transfer, Dalgarno, and charge exchange cross sections as functions of relative velocity of the colliding particles.

3. Mean Free Paths of H Atoms in the Heliospheric Interface

Let us estimate the effect of elastic H-H collisions using the newly calculated cross section. We use the plasma and neutral distributions from the two-shock heliospheric interface model (Baranov and Malama, 1993) (Figure 1B). Two shocks and the heliopause divide the heliospheric interface into 4 regions (Figure 1B), which have different plasma properties. The interstellar atoms are divided into 4 different populations, dependening on the region of their origin: 1 – H-atoms produced in the supersonic solar wind (region 1), 2 – H-atoms produced in the heliosheath (region 2), 3 – the H-atoms produced in the compressed interstellar plasma (region 3), population 4 is the primary interstellar atoms. For details, see Izmodenov (2000) in this issue.

We consider the Boltzmann equation for s-particle gas with the distribution function $f_s(\mathbf{w}_s)$ interacting with t-particle gas with a Maxwell distribution function. Then we evaluate the momentum transfer term $\delta M_s/\delta t$, obtain the mean free path L for s-particles with velocity $\mathbf{w}_s$: $L = w_s^2/(\delta M_s/\delta t)$. and calculate the mean free paths of s-particle ($s = p, 1, 2, 3, 4$) in all four regions. We found that:

1) The mean free path with respect to the momentum transfer of the energetic solar atoms (population 1) is about 10^7 AU with the primary interstellar neutrals. The mean free paths of these atoms with respect to elastic collisions with the other atom populations are even larger.

2) The mean free path of the ‘hot solar’ population (population 2) in the primary interstellar gas is about 2×10^4 AU. This is almost 2 orders of magnitude larger than the size of the heliospheric interface.

3) The mean free path of the populations 3 and 4 with respect to the collisions with energetic ‘solar’ atoms (populations 1 and 2) are $10^5 - 10^8$ AU in the interface, while the mean free path of a secondary interstellar atom (population 3) with respect to the collisions with the primary interstellar neutrals (population 4) is only $\sim 10^3$ AU.

We conclude that: 1) populations 1 an 2 are not efficient in creating hot heliospheric H atom population; 2) for the upwind direction the four introduced atom populations are not mixed in the interface by H-H collisions and momentum and energy can not be transferred from the solar atom populations to interstellar atoms; 3) in the downwind direction the mixture (by H-H collisions) between these populations occur only far away from the Sun at the distances $> 10^5$ AU; 4) the secondary (population 3) and primary (population 4) atoms are mixed at the distances about 1000 AU. For Dalgarno’s cross section the mean free paths are a factor of $10^2 - 10^5$ smaller than for our cross-sections. The only exception is the collisions between atoms of populations 3 and 4 with our cross-sections leading to the mean free paths two times larger.

4. Momentum Transfer Between H Atom Populations

We assume that s-particles also have a Maxwellian distribution function and calculate the momentum transfer term $\delta M_s/\delta t$ for four different populations of H-atoms ($s = H_1, H_2, H_3, H_4$) for collisions with other populations and protons ($t = p, H_1, H_2, H_3, H_4, t \neq s$) For all populations of atoms the momentum transfer terms for charge exchange (‘collisions’ with protons) are much larger (one to several orders magnitude) than the terms for elastic H-H collisions. Therefore, the effect of elastic H-H collisions is negligible. The calculations of plasma momentum transfer terms due to charge exchange with different populations of H-atoms show that the main influence on plasma is by charge-exchange with the primary and secondary interstellar H-atoms. While the effect of the 'solar' energetic atoms is negligible in the solar wind, the source terms of populations 1,2 are only a few times smaller than those of populations 3 and 4 at the heliopause. Energetic solar atoms dominate in the *energy transport* equation. Our numerical Monte-Carlo simulations also show that the influence of solar atoms is increasing with the increasing $n_{p,\infty}/n_{H,\infty}$ ratio.

Williams *et al.* (1997) also proposed to use an approximation of the Boltzmann collision integrals, which could describe as a BGK-type approximation. This approximation is based upon on an assumption of a complete randomization of particles velocities in the collisions, without making a distinction between 'strong' and 'weak' collisions.

If one calculates $\delta M_s/\delta t$ for different populations of interstellar atoms using the BGK-like approximation (and our cross section), one would obtain the values that 1-2 order of magnitude larger than for our appoximation. For calculations with the Dalgarno's cross section, the overestimation introduced by the BGK-like approximation is much smaller. This effect can be explained by different functional dependencies of the cross sections and by the BGK-like collision term. It is important that different cross sections lead to qualitative differences. Momentum transfer terms with the Dalgarno's momentum transfer cross section are positive close to the Sun, while the momentum transfer term for our momentum transfer cross section is negative everywhere.

5. Effect of Elastic H-H^+ Collisions

Effect of elastic H-H^+ collisions on the atom and proton distributions in the heliospheric interface was also mentioned by Williams *et al.* (1997). The energies of the colliding particles (H^+,H) can vary in the range from 0.01 eV to 1 keV.

The result of an $H^+ - H$ collision is charge-exchange or elastic scatterring without charge exchange. Figure 1C shows dynamically identical trajectory diagrams of $H + H^+ \longrightarrow H^+ + H$ in the center of mass system. The effective outcome of each diagram is an apparent deflection of the incoming H atom by an angle θ. Figures 1Ca and 1Cb illustrate the dynamical equivalence of charge exchange and elastic scatterring. In Figure 1Ca the nucleus of the incoming H atom loses its electron and is deflected by $\theta = \pi - \theta$, while in Figure 1Cb it is scattered by θ without charge exchange. In absence of spin polarization, the nuclei are indistinguishable, and it is not possible to identify the outgoing H atom with either of the incoming nuclei. Hence, the question of whether charge exchange occurs is actually moot, and the dynamics of any collision can be represented by generalized elastic scattering (Figure 1Cc).

Thus, the collision between an H atom and a proton can be described by following cross sections: 1) $Q_{el}(E)$, $q_{el}(E)$ - the total and momentum transfer cross-sections for elastic scattering of indistinguishable nuclei (Figure 1Cc); 2) $Q_D(E)$, $q_D(E)$ – the total and momentum transfer cross-section for elastic scattering of distinguishable nuclei (for both Figure 1Ca and 1Cb processes); 3) $Q_{ex}(E)$ – the charge exchange cross-section for distinguishable nuclei (Figure 1Ca).

Hodges and Breig (1991) have found the energy dependencies of $Q_{ex}(E)$ for identical particles for energies higher than 0.02 eV. They also showned that for energies higher than 0.02 eV: a) $q_{el} \approx q_D \approx 2Q_{ex}$; b) $Q_{el} = Q_D$; c) $Q_{el} >> q_{el}$. The dynamic influence of the collisional processes on gas is determined by the momentum transfer cross section. Thus, both charge exchange and direct scattering processes are taken into account if the momentum transfer cross section, q, is twice bigger than the total charge exchange cross section, Q_{ex}.

Detail modeling of the $H - H^+$ collision requires consideration of elastic differential cross section $\sigma(E, \theta)$. However, the total charge exchange cross section $Q_{ex}(E)$ is often used in the models (e.g. Baranov and Malama, 1993; Williams *et al.*, 1997). In these models the real charge exchange process (Figure 1Ca) is replaced by an 'ideal' charge exchange process when an atom is not deflected ($\theta = \pi$, $\theta' = 0$). For this 'ideal' process $q_{ideal} = 2Q_{ideal}$. (e.g., Izmodenov *et al.*, in preparation) Thus, if we assume $Q_{ideal} = Q_{ex}$, this 'ideal' charge exchange process is a good presentation of both elastic scattering processes (charge exchange and direct scatter) of hydrogen atoms with proton. Another reason to use the 'ideal' charge exchange approximation is a possibility to use measured total cross sections. It is evident that it is impossible to separate charge exchange process from direct scatter in any experiment.

6. Conclusions

We conclude that:

1) the influence of elastic H-H, H-P collisions is negligible in the heliospheric interface since the dynamical influence of charge exchange is stronger by several orders of magnitude;

2) the use of both the BGK-like approximation of the Boltzmann collision term and the Dalgarno cross section results in overestimating of the effect of elastic collisions;

3) the calculated by us momentum transfer cross section for elastic H-H collisions should be used when Dalgarno's cross-section is not appropriate;

4) it is possible to model the effect of both elastic H-H^+ and charge exchange processes by using 'ideal' charge exchange process when an atom is not deflected ($\theta = \pi$, $\theta' = 0$).

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