Planet. Space Sci., Vol. 34, No. 4, pp. 387–389, 1986
Printed in Great Britain.

0032–0633/86 $3.00+0.00

CONCERNING THE PROBLEM OF COLLISIONAL HEATING OF THE INTERSTELLAR HELIUM FLOW BY SOLAR WIND PROTONS

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(*Received in final form* 13 *November* 1985)

Abstract—In the past heating by elastic collisions with the solar wind protons of the interstellar helium flow into the heliosphere has been a subject of consideration by several authors. The approaches used in this context are critically analysed in this paper and it is shown that the concept of a continuous momentum transfer is not likely to be applicable. It is argued in contrast that large angle deflections though being rare events give the predominant contributions to the momentum transfer to the neutral helium atoms. This may have consequences for a progressed modelling of the interstellar helium distribution in the heliosphere.

For several years the development of the theoretical modelling of neutral interstellar gases in the heliosphere was stagnating due to the belief that the underlying processes are adequately described. However, the conventional models are challenged nowadays by some physical incompatibilities that they are leading to when applied to some recent results of optical experiments reviewed by Fahr (1983), Bertaux (1984), Dalaudier *et al.* (1985), Lallement *et al.* (1985). Especially the temperatures of interstellar helium is derived as to be much higher than that of interstellar hydrogen: a puzzling fact in view of all possible phases of the interstellar medium. To cope with this unsatisfactory situation both new space experiments including direct interstellar helium detection (Rosenbauer *et al.*, 1984) and new theoretical approaches (Baranov *et al.*, 1979; Gruntman, 1982; Ripken and Fahr, 1983; Fahr *et al.*, 1985) are pushed forward.

Especially the direct detection of interstellar helium atoms inside the solar system is considered as an "experimentum crucis" since *in situ* measurements of the local velocity distribution function is the best means to rule out the existing ambiguities (Gruntman, 1980; Gruntman and Leonas, 1983; Rosenbauer *et al.*, 1984). Besides the net solar gravitation one of the main forces imprinting on the characteristics of the helium atom flux and on the trajectories of helium atoms in the heliosphere is the collisional interaction with the solar wind protons which was treated as leading to an effective heating by Fahr and Lay (1974); Wallis (1975); Holzer (1977); Fahr (1978) and Kunc *et al.* (1983). This heating was found to be non-negligible and thus deserves some attention.

In the above-mentioned papers the collisional heating effect is envisaged as a continuous momentum- and energy-transfer process affecting the interstellar helium atom on its way from the local interstellar medium to the point of interest in the solar system. The net energy (momentum) transfer to such an atom has been calculated by the product of the average energy (momentum) transfer in a collision and the average number of collisions. This transfer thus has been assumed to occur as a continuous process along the atom trajectory.

In the frame of this approach the effect of the elastic collisions consequently is obtained as an increase of the interstellar helium flux temperature. The temperature is defined as a specific moment of the local velocity distribution function and the continuous transfer approach results in a widening of the velocity distribution function. This widening can be considered roughly equal to the net energy transferred to the average helium atom.

This continuous transfer approach was felt to be justified by the dominance of very distant and therefore very numerous large impact parameter collisions with the solar wind protons. In contrast the aim of this short note is to show that such an approach should be applied with some care. This average number of collisions S which an interstellar helium atom suffers during its flight from the local interstellar medium ("infinity") to the heliospheric point (R, θ) (Fig. 1) may be given by

$$S = \frac{\bar{N}_{SW} R_0^2}{\rho_0 V_0} \int_0^{\theta} \langle Q(V_{\rm rel}) V_{\rm rel} \rangle \, d\theta \qquad (1)$$

where $\bar{N}_{SW} = 5 \text{ cm}^{-3}$ is the solar wind proton density

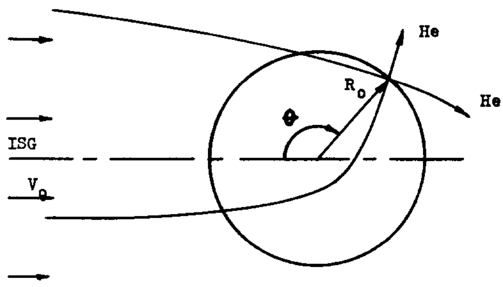

FIG. 1. INTERSTELLAR HELIUM ATOM TRAJECTORIES INSIDE THE SOLAR SYSTEM.

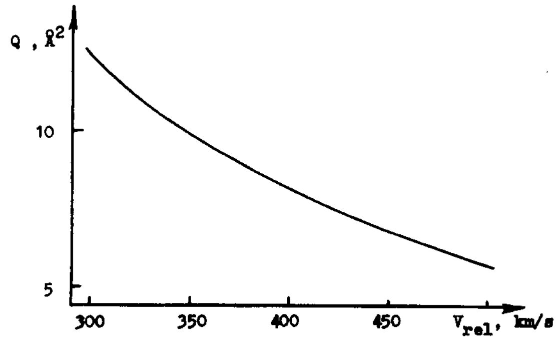

FIG. 3. THE DEPENDENCE OF THE TOTAL ELASTIC SCATTERING CROSS-SECTION ON THE IMPACT VELOCITY FOR H^+–He SYSTEM.

at 1 a.u. and a $1/R^2$-dependence of N_{SW} on R is assumed. $V_0 = 20$ km s^{-1} is the velocity of the relative motion between interstellar gas and the Sun, $R_0 = 1$ a.u. is the distance between the Earth and the Sun, $Q(V_{rel})$ = total elastic collision cross-section for protons and helium atoms with the relative velocity V_{rel} considered to be constant, ρ_0 = "impact" parameter for a helium atom trajectory approaching the Sun and reaching the point (R, θ). The angle θ is counted from the direction antiparallel to V_0 (upwind direction).

The total elastic cross-section dependence on V_{rel} was calculated by integrating the differential scattering cross-sections. The upper limit of the integral was taken such as to bring the charge exchange probability of the helium atom in the collision to 1/2. The scattering was then treated semi-classically (JWKB approximation) using the available computer code (Rodinov, 1976). The H^+–He interaction curve was taken from Helbig *et al.* (1970). The typical diffusion and differential scattering cross-sections and the dependence of the total cross-section on V_{rel} are shown in Figs. 2 and 3, respectively. The corresponding dependence of S on θ according to equation (1) for $R = 1$ a.u. is presented in Fig. 4.

The quantity S gives the number of collisional events undergone by the average helium atom, the differential scattering cross-section describes the distribution of the scattering angles χ in such an event whereas the diffusion cross-section characterizes the distribution of the momenta transferred in this event. The physical meaning of the differential scattering cross-section thus is the probability of a scatter by the angle χ while passing through the target. Figure 2 seems to definitely indicate that the fractional contribution to the total momentum transfer cross-section (the area under the curve) by the distant collisions—(small angles correspond to the large impact parameters, i.e. 1 mrad corresponds to that of few angstroms)—is negligible. It can be claimed on this basis that almost all momentum transfers occur in close collisions.

As an example, let us consider a sample of helium

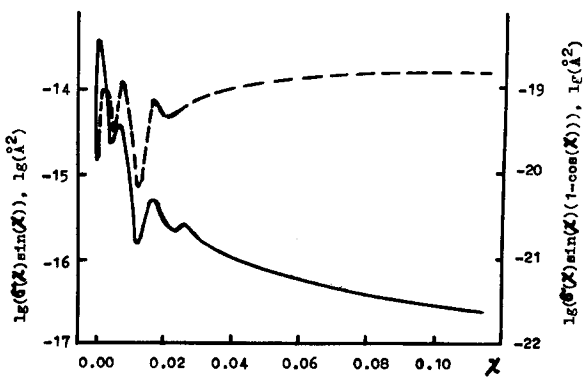

FIG. 2. ELASTIC DIFFUSION (DASHED LINE) AND DIFFERENTIAL (SOLID LINE) SCATTERING CROSS-SECTIONS FOR H^+–He SYSTEM.
Impact velocity—400 km s^{-1}, χ—scattering angle in the centre-of-mass frame.

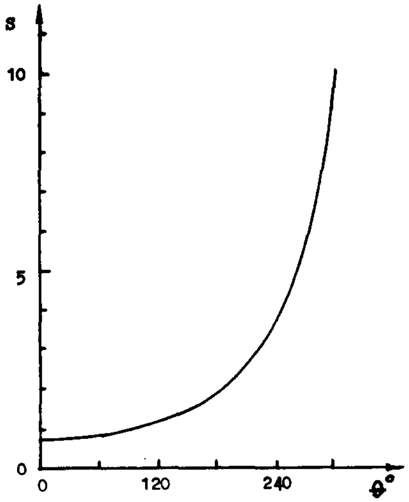

FIG. 4. THE DEPENDENCE OF THE AVERAGE NUMBER OF COLLISIONS S SUFFERED BY AN INTERSTELLAR HELIUM ATOM ON THE POSITION (θ) OF THE POINT WHERE IT CROSSES THE EARTH ORBIT.

atoms and let each of them suffer only one collision with the solar wind protons. Then it can be derived from Fig. 2 that the energy they exchange in collisions is not equally distributed among them. For instance, it could happen that 96% of the atoms would gain 15% of the total kinetic energy transferred to the atoms while another 4% of the atoms would gain 85% of that energy.

To validate the treatment of the collisional heating effect as a continuous transfer of energy a statistically large number of collisions ($S \gg 10$) were needed. If such conditions were fulfilled, the necessary randomization of the momentum transfer would be realized. The demand for large numbers S, as easily seen from Fig. 4, is met at solar distances of $R = 1$ a.u. only for $\theta > 300°$. This fact was not appreciated in previous papers with regard to this problem.

If $S = 0.7$–2, which corresponds to the realistic conditions, the collisional interactions result in a very non-uniform effect on helium atoms. The atoms can be considered moving without continuous interaction with the protons and only very rarely (better even never) elastically colliding with them. However, in case at all a collision occurs, the most probable event then is a very small momentum (energy) transfer to the helium atom. In fact a bulk of the interstellar helium atoms in the flux thereby would accumulate a very small increase of the effective temperature, say 200 K. The widening of the main part of the velocity distribution function would correspond to this value of heating. Such an inferior increase may, however, be neglected in a treatment of the direct detection experiment data. But several per cent of helium atoms would be subject to very significant energy changes (up to a few electronvolt) due to close collisions and they will possibly provide very thin (but rather long) wings in the interstellar helium velocity distribution function. A somewhat open point in the reasoning of this paper is the cut-off at the large impact parameter limit in the integral producing the total elastic collision cross-section. Unfortunately at large impact parameters, i.e. small deflection angles, the differential cross section is known neither by theory nor experiment. Therefore the contributions to the total cross section are fairly uncertain in this range of large impact parameters.

In conclusion, the use of a continuous momentum (energy) transfer approach and of the product of the average energy transfer in a collision and an average collision rate to describe the collisional heating of the interstellar helium flux seems to be questionable. Such an approach may possibly lead to the wrong data interpretation of both the already performed and the forthcoming space experiments.

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