MODEL CALCULATIONS OF SOLAR WIND EXPANSION INCLUDING AN ENHANCED FRACTION OF IONIZING ELECTRONS

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Abstract. Collective interactions of the solar wind and newly ionized interstellar gas cause turbulent electron heating to ionizing energies analogous to laboratory experiments on the critical ionization velocity effect. Implications for solar wind and interstellar gas dynamics are calculated by simultaneously solving continuity equations for solar wind protons, interstellar hydrogen atoms, and energetic electrons. Electron impact ionization is shown to be practically as important as photoionization, giving rise to a stronger deceleration and heating of the distant solar wind, a weaker terminating shock, a smaller stand-off distance of the heliopause, and implying higher densities of the outer solar wind and the interstellar neutral gas.

It is known from laboratory experiments (Danielsson, 1973; Himmel et al., 1976) that counterstreaming of a magnetized plasma and a marginally ionized neutral gas results in considerably enhanced ionization of the neutrals and strong braking of the relative motion if a critical velocity $v_c=(2W/m_i)^{1/2}$ is exceeded (W=ionization energy of the gas, m_i=ion mass of the moving species). The physical mechanism envisaged to explain this "critical ionization velocity effect" is a transfer of ion free kinetic energy to ambient electrons via turbulent heating, e.g. through a modified two-stream instability, subsequent ionization of the neutral gas by the energetic electrons, assimilation of the newly formed ions into comotion with the plasma after a short time determined by the instability growth rate, and deceleration of the plasma. By comparing typical parameters of laboratory experiments, the Apollo 13 lunar impact event (Lindeman et al., 1974), and the heliosphere (Tab. 1), it can be shown that this mechanism must also operate in the interaction region of the solar wind and the interstellar neutral gas (Petelski et al., 1979). - Consequences for the heliospheric

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Table 1. Comparison of parameters (l_{ch}=characteristic length, v_{rel}=plasma-neutral gas relative velocity, n_n/n_p=neutral gas /plasma density, B=magnetic field, T_e=background electron temperature, $E_{e,f}$=fast electron kinetic energy (estimated for the heliosphere to be at the lower edge of the laboratory energies), $\sigma_{e,f}$=fast electron impact ionization cross section).

Parameter	Lab.	Apollo 13 Lunar Impact	Heliosphere 1 AU	10 AU	100 AU
Gas	He	plastics (≈80a.m.u.)	H		
l_{ch} (m)	0.1	2×10^5	1.5×10^{11}	1.5×10^{12}	1.5×10^{13}
v_{rel} (ms^{-1})	4×10^5	3.3×10^5	4×10^5	4×10^5	3×10^5
n_n (m^{-3})	10^{20}	10^{12}	2×10^3	5×10^4	1×10^5
n_p (m^{-3})	10^{18}	3×10^6	5×10^6	5×10^4	7.5×10^2
B (T)	0.5	3.6×10^{-8}	5×10^{-9}	5×10^{-10}	1.0×10^{-10}
T_e (K)	5.8×10^4	1.2×10^5	1.5×10^5	4×10^4	$>10^4$
$E_{e,f}$ (eV)	100	50	27		
$\sigma_{e,f}$ (m^2)	3.5×10^{-21}	2×10^{-20}	5×10^{-21}		

parameters are assessed by simultaneously solving the coupled continuity equations for the mass, the momentum, and the energy of solar wind protons, the mass of interstellar hydrogen atoms, and the number of ionizing electrons created by critical velocity effects, the proton source terms being calculated from photoionization, charge exchange, and fast electron impact ionization. To simplify the algorithm, a constant energy transfer factor of 0.35 as well as a constant fast electron energy of ≈30 eV are assumed in compliance with laboratory findings. Furthermore, critical velocity phenomena in the heliosphere are presupposed to involve the modified two-stream instability, the growth rate of which is set to the lower hybrid frequency. It is ascertained that the electrons of the outer solar wind are effectively prevented from adiabatically cooling to non-ionizing energies. Accordingly, a significantly stronger deceleration of the solar wind, a weaker radial decrease of its density, and a steeper radial increase of the solar wind proton temperature and the interstellar hydrogen density are obtained than calculated from photoionization and charge exchange alone. Also, the solar wind terminating shock is weakened, or even eliminated if the asymptotic interstellar hydrogen density is raised to 0.285, and the radius of the heliopause is reduced (cf. Fig. 1 and

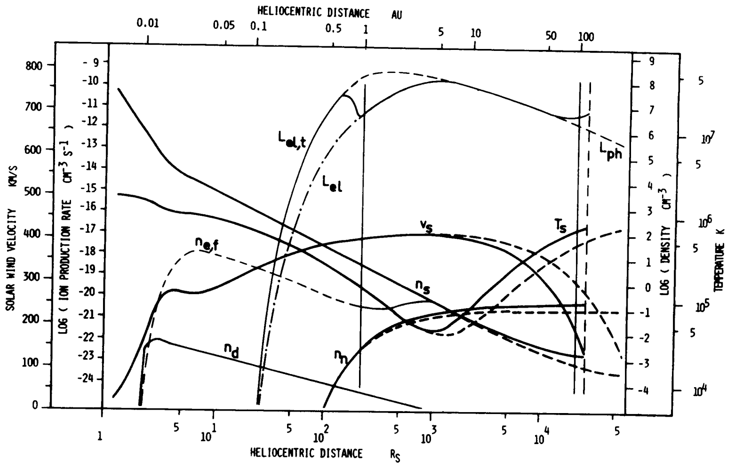

Figure 1. Heliospheric parameters along the stagnation line; ----: standard results exclusively based on photoionization and charge exchange, ——: results including v_c effects. ($n_s/v_s/T_s$=solar wind density/velocity/proton temperature, $L_{ph}/L_{el}/L_{el,t}$=photoionization rate/electron impact ionization rate due to v_c effects/total electron impact ionization rate including ionizations by naturally hot electrons inside 0.8 AU, $n_{e,f}$=density of fast electrons energised by v_c effects, n_d= density of dust-generated hydrogen)

Table 2. Comparison of standard data based on photoionization and charge exchange alone with critical velocity data.

Parameter	Standard	Critical velocity	Change
$v_{s,sh}$ (m s^{-1})	2.8×10^5	1.9×10^5	- 32%
$T_{s,sh}$ (K)	5×10^5	6.5×10^5	+ 30%
$M_{MA,sh}$	3.8	2.3	- 39%
r_{sh} (AU)	118	98	- 17%
$n_{s,sh}$ (m^{-3})	5.7×10^2	1.4×10^3	+146%
$n_{n,\infty}$ (m^{-3})	1.0×10^5	1.7×10^5	+ 70%

($v_{s,sh}/T_{s,sh}/n_{s,sh}$=solar wind parameters at the shock, $M_{MA,sh}$=solar wind magnetoacoustic Mach number at the shock, r_{sh}= shock distance, $n_{n,\infty}$=asymptotic interstellar hydrogen density)

Tab. 2). Coupling between the instability growth time and the thermalization time of newly created protons allows one to choose other instabilities with a wide range of growth times without any major effect on the model. In situ measurements of electron energy spectra and interstellar hydrogen densities in the outer solar wind are recommended to test these results.

References.

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DISCUSSION

Ahluwalia: What are the relative contributions of charge exchange, photoionization, and ionization by fast electrons? If I remember correctly, charge-exchange is the dominant process. I have a second question: I note that according to your calculations the heliospheric boundary is at ~100 A.U. How much would the boundary shift, if only charge exchange is considered?

Petelski: On average, the charge exchange rate is 2.5 to 3 times larger than the photoionization rate which in turn is comparable to the electron impact ionization rate if the critical ionization velocity process is assumed to operate in the solar wind.

If only charge exchange is considered, the shock radial distance is increased by 20 AU (and the shock Mach number is doubled) over the standard case.

Tandon: In your model proton temperature near the sun comes out to be higher than a few times a million, °K. Comment, please.

Petelski: In our model, a solar wind temperature of 1.5×10^6K is adopted close to the sun.