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Ambipolar diffusion in the solar atmosphere

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ABSTRACT

The process of non-linear ambipolar diffusion in the region overlying the solar surface can be an effective mechanism for producing sharp magnetic structures and current sheets. These may be the sites responsible for the occurrence of connectivity of magnetic field lines, and the subsequent explosive input of energy for heating of some of the features in the atmosphere of the Sun..

Key words: diffusion – Sun: atmosphere – Sun: magnetic fields.

1 INTRODUCTION

The role of ambipolar diffusion in the weakly ionized interstellar medium in the formation of current sheets or of small-scale magnetic structures and the subsequent decay of the magnetic field has been examined by Zweibel (1988) and Brandenburg & Zweibel (1995). Earlier, Mestel & Spitzer (1956) explored the process of ambipolar diffusion for the escape of magnetic flux from dense clouds. Ambipolar diffusion can take place in a fully ionized plasma too, where the more energetic electrons, owing to their motion relative to the ions, produce an electric field in such a direction as to slow down the electrons. The combined diffusion of both the electrons and the ions then occurs at a rate governed by the ion diffusion rate. The role of this type of ambipolar diffusion has been investigated in some applications to solar physical problems (McKee, Winglee & Dulk 1990; Scudder 1996, 1997). The role of ambipolar diffusion in a partially ionized medium such as prevails in the solar photosphere and the overlying regions has not been studied in any detail (Parker 1979). The standard model (e.g. Vernazza, Avrett & Loeser 1981) of the solar photosphere and the chromosphere (Fontenla, Avrett & Loeser 1990; Cox 2000) reveals the existence of a variety of neutral atoms at different heights. Heavy atoms such as oxygen, magnesium and silicon are dominant at photospheric heights, whereas the chromospheric regions are mainly populated by neutral and ionized hydrogen.

The presence of active regions with strong magnetic fields produces a relative drift between the charged and the neutral particles which can cause an effective diffusion of the magnetic field through the convective term in Faraday's induction law. In this Letter, we estimate the ambipolar diffusion rate at different heights in the solar atmosphere and compare it with the Coulomb diffusion rate. We then go on to propose the possible formation of sharp magnetic structures or current sheets owing to the predominant effect of the ambipolar diffusion. These current sheets with their relatively short resistive decay time-scales may serve as the generic sites for development into explosive energy events.

2 AMBIPOLAR DIFFUSION RATE

We take a system consisting of electrons, ions and neutrals with mass densities ρ_e, ρ_i and ρ_n in the presence of a magnetic field B at a temperature T. The charged species experience the hydromagnetic forces and transmit them to neutrals owing to collisions amongst them. The equations of motion of ions and neutrals in the magnetohydrodynamic limit (space charge and electron mass $\rightarrow 0$) are

$$\frac{\partial \boldsymbol{V}_i}{\partial t} + (\boldsymbol{V}_i \cdot \nabla)\boldsymbol{V}_i = \frac{(\nabla \times \boldsymbol{B}) \times \boldsymbol{B}}{4\pi\rho_i} - \frac{\nabla p_i}{\rho_i} - \gamma_{in}(\boldsymbol{V}_i - \boldsymbol{V}_n) + \boldsymbol{g}, \quad (1)$$

$$\frac{\partial \boldsymbol{V}_n}{\partial t} + (\boldsymbol{V}_n \cdot \nabla)\boldsymbol{V}_n = -\frac{\nabla p_n}{\rho_n} - \gamma_{ni}(\boldsymbol{V}_n - \boldsymbol{V}_i) + \boldsymbol{g}, \quad (2)$$

where the subscript i stands for ions and n stands for neutrals, γ_{in} is the ion–neutral collision frequency, and other symbols have their usual meaning. Now, subtracting equation (2) from (1), and neglecting the non-linear and pressure terms, gives

$$\frac{\partial}{\partial t}(\boldsymbol{V}_i - \boldsymbol{V}_n) = \frac{(\nabla \times \boldsymbol{B}) \times \boldsymbol{B}}{4\pi\rho_i} - (\gamma_{in} + \gamma_{ni})(\boldsymbol{V}_i - \boldsymbol{V}_n). \quad (3)$$

Defining $\boldsymbol{V}_D = \boldsymbol{V}_i - \boldsymbol{V}_n$ as the relative drift velocity between ions and neutrals, we find from equation (3), in the steady state,

$$\boldsymbol{V}_D = \frac{(\nabla \times \boldsymbol{B}) \times \boldsymbol{B}}{4\pi\rho_i \gamma}, \quad (4)$$

where $\gamma = \gamma_{in} + \gamma_{ni}$.

The magnetic induction equation is written as

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{V}_i \times \boldsymbol{B}) - \nabla \times (\lambda_{Cou} \nabla \times \boldsymbol{B}), \quad (5)$$

where $\lambda_{Cou} = c^2/4\pi\sigma$ is the Coulomb magnetic diffusivity and σ is the electrical conductivity. On substituting for $\boldsymbol{V}_i$, equation (5)

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becomes

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times [(\boldsymbol{V}_{\mathrm{D}} \times \boldsymbol{B}) + \boldsymbol{V}_{\mathrm{n}} \times \boldsymbol{B} - \lambda_{\mathrm{Cou}} \nabla \times \boldsymbol{B}]$$

$$= \nabla \times \left[\boldsymbol{V}_{\mathrm{n}} \times \boldsymbol{B} + \frac{(\nabla \times \boldsymbol{B}) \cdot \boldsymbol{BB}}{4\pi \rho_{\mathrm{i}} \gamma} - (\lambda_{\mathrm{Cou}} + \lambda_{\mathrm{Amb}}) \nabla \times \boldsymbol{B}\right], \quad (6)$$

where

$$\lambda_{\mathrm{Amb}} = \frac{B^2}{4\pi \rho_{\mathrm{i}} \gamma} \quad (7)$$

is the ambipolar diffusivity. The ambipolar diffusion facilitates the formation of sharp magnetic structures in two ways. In the first place, more flux is advected into small-B regions as $V_{\mathrm{D}} \alpha (-\nabla B^2)$; secondly, this piled-up magnetic flux cannot be smoothed out by ambipolar diffusivity as it is zero in the null-field region. The thickness of any current sheet that arises because of non-linear processes such as ambipolar diffusion is controlled by the Coulomb diffusivity, λ_{Cou}. The ambipolar diffusivity arising from its dependence on the magnetic field and the mass density of the ions has a spatial derivative, which can provide free energy to excite the rippling instability in a finite field region. This is analogous to the rippling instability arising from the gradient of the Coulomb resistivity. The outcome in both cases is reconnection and the formation of current sheets (Priest & Forbes 2000).

In order to make numerical estimates of λ_{Amb} and λ_{Cou} we need to know the densities of ions, neutrals and electrons. In the solar atmosphere with non-monotonic changes of temperature, ions with positive and negative charges in their different ionization states coexist. For the sake of illustration of the ambipolar diffusion, we assume in this work that all ions have a unit positive charge. The overall charge neutrality then dictates that the number density of the ions N_{i} is equal to the number density N_{e} of the electrons. Thus the total number of particles N can be written

$$N = N_{\mathrm{n}} + N_{\mathrm{i}} + N_{\mathrm{e}} \simeq N_{\mathrm{n}} + 2N_{\mathrm{e}}, \quad (8)$$

where N_{n} is the number density of the neutral particles such as that of hydrogen and all other atoms. Here N_{i} accounts for protons and all other singly charged ions. Again, although there are ions of different atomic species, for our purpose, we take the representative mass of an ion to be the mass of a proton m_{p}. Thus the partially ionized photospheric plasma is made up of electrons, singly charged positive ions each of an effective mass m_{p} and the neutral particles each of mass $m_{\mathrm{n}} \simeq m_{\mathrm{p}}$.

The ion–neutral collision frequency can now be expressed as (Zweibel 1988)

$$\gamma = (\rho_{\mathrm{n}} + \rho_{\mathrm{i}}) \langle \sigma U \rangle / m_{\mathrm{i}} + m_{\mathrm{n}}$$

$$= (N - N_{\mathrm{e}}) \frac{\langle \sigma U \rangle}{2}. \quad (9)$$

The ambipolar diffusion time τ_{Amb} for a characteristic spatial scale L is found to be

$$\tau_{\mathrm{Amb}} = \frac{L^2}{\lambda_{\mathrm{Amb}}} = \left(\frac{B^2}{4\pi \rho_{\mathrm{i}} \gamma}\right)^{-1} L^2$$

$$= \left[\frac{B^2}{4\pi m_{\mathrm{i}} N_{\mathrm{e}} (N - N_{\mathrm{e}}) \langle \sigma U \rangle / 2}\right]^{-1} L^2. \quad (10)$$

We take for the cross-section $\sigma \simeq 10^{-16}\,\mathrm{cm}^2$ and for the neutral particle velocity

$$U = (2K_{\mathrm{B}} T / m_{\mathrm{n}})^{1/2} \simeq 4 \times 10^5 T_3^{1/2}\,\mathrm{cm\,s^{-1}} \quad (11)$$

for $T = T_3 \times 10^3$ K. For a magnetic field $B \simeq B_{100} \times 10^2$ G we find

$$\tau_{\mathrm{Amb}} = 4 \times 10^{-38} N_{\mathrm{e}} (N - N_{\mathrm{e}}) B_{100}^{-2} T_3^{1/2} L^2 \mathrm{s}. \quad (12)$$

The Coulomb diffusion coefficient λ_{Cou} for a partially ionized medium is given by (Priest 1982)

$$\lambda_{\mathrm{Cou}} \simeq \frac{5.2 \times 10^{11} \ln \Lambda}{T^{3/2}} \left(1 + 5.2 \times 10^{-11} \frac{N_{\mathrm{n}} T^2}{N_{\mathrm{e}} \ln \Lambda}\right) \mathrm{cm^2\,s^{-1}}.$$

The Coulomb diffusion time τ_{Cou} for a characteristic spatial scale L is found to be (for the Coulomb logarithm $\ln \Lambda = 10$)

$$\tau_{\mathrm{Cou}} \simeq \frac{0.76 \times 10^{-7} T_3^{3/2}}{\left[1 + 5.2 \times 10^{-6} \frac{(N - 2N_{\mathrm{e}})}{N_{\mathrm{e}}} T_3^2\right]} L^2\,\mathrm{s}. \quad (13)$$

We give the values of various solar parameters (Cox 2000) along with estimates of the ratio of the ambipolar diffusion time τ_{Amb} and the Coulomb diffusion time τ_{Cou} for different heights in Table 1. In the solar atmosphere the magnetic field B is expected to decrease with height. In order to fix this vertical variation we have made use of the fact that the plasma β – the ratio of the thermal pressure and the magnetic pressure – is much larger than unity at the photosphere and decreases to a value less than unity at chromospheric heights and beyond. For a magnetic field of 100 G at zero height, we find $\beta \simeq 391$. We assume an exponential fall of β with height by demanding that, at a height of ~2017 km, β attains a value $\beta_0 \lesssim 1$. For the sake of numerical estimates we have chosen two typical values of β_0 to be 0.1 and 1.0 as shown in Table 1. The process of ambipolar diffusion ceases to be effective at a height ≥2000 km, beyond which the plasma becomes nearly fully ionized and the neutral particle density becomes vanishingly small. A new insight into the nature and location of the solar coronal heating mechanism has been provided by recent observations from the *SOHO* and *TRACE* missions. The inhomogeneously structured solar corona is made up of a large number of loops of different sizes. The earlier theoretical models envisaged a

Table 1. Values of various solar parameters (Cox 2000) along with estimates of the ratio of the ambipolar diffusion time τ_{Amb} and the Coulomb diffusion time τ_{Cou} for different heights.

Height	Temperature T (K)	Mass density ρ (g cm^{-3})	Total $N = \rho/m_{\mathrm{p}}$ (cm^{-3})	Electron density N_{e} (cm^{-3})	$\tau_{\mathrm{Amb}}/\tau_{\mathrm{Cou}}$ $\beta_{2017} = 0.1$	$\tau_{\mathrm{Amb}}/\tau_{\mathrm{Cou}}$ $\beta_{2017} = 1.0$
0	6520	2.77×10^{-7}	1.73×10^{17}	7.697×10^{13}	0.65	0.65
525	4400	4.87×10^{-9}	3×10^{15}	2.413×10^{11}	2×10^{-3}	0.3×10^{-2}
1065	6040	5.07×10^{-11}	3×10^{13}	1.047×10^{11}	2×10^{-6}	6.7×10^{-6}
1580	6900	2.32×10^{-12}	1.4×10^{12}	5.535×10^{10}	1×10^{-6}	5.2×10^{-6}
2017	8400	2.82×10^{-13}	1.7×10^{11}	4.313×10^{10}	7×10^{-8}	0.7×10^{-6}
2218	10 000	1.31×10^{-14}	0.8×10^{10}	6.65×10^{9}	–	–

fairly even and uniform heating extending over the whole length of the coronal loops (Rosner, Tucker & Vaiana 1978). X-ray observations of the diffuse corona also validate this model in that the uniform heating best describes the observed temperature variations along large loops (Priest et al. 1998). Recent *TRACE* observations, however, of the smallest microflares and nanoflares suggest a component of heating near the footpoints of the small and active region loops (Aschwanden, Nightingale & Alexander 2000; Parnell & Jupp 2000). This would place the heating source in the lower atmosphere of the Sun within about 10 000 km of the photosphere. Observations with the extreme-ultraviolet imaging telescope on board *SOHO* have also highlighted the role of numerous microflares in feeding the magnetic energy into the extended loops of the corona and heating it to temperatures of the order of $1–2 \times 10^6$ K. In our picture the ambipolar diffusion process operating in the layers extending to about 2000 km above the solar surface leads to the formation of sharp magnetic structures and current sheets. These are the sites that should result in the explosive release of energy in microflaring events near the base of the loops, which could effectively feed heat into the extended coronal regions.The energetics of such a mechanism may be worked out if we assume a typical ambipolar diffusion time of 10 s for a magnetic field of $\sim$100 G in a volume with a linear size of about 2000 km to produce energy at the rate of $10^{27}\,\mathrm{erg\,s^{-1}}$. This energy may be released near the base of the loops in the form of energetic particles, thermal energy and electromagnetic radiation, and when it reaches coronal heights it gets spread over an area of about $(100\,000\,\mathrm{km})^2$. This would imply a flux of some $10^7\,\mathrm{erg\,cm^2\,s^{-1}}$, which is of the requisite order of magnitude for sustaining the coronal temperatures.

3 CONCLUSION

The non-linear ambipolar diffusion arising from the relative motion of the ions and the neutral particles in magnetized regions overlying the solar photosphere and the lower chromosphere is found to dominate the Coulomb diffusion. This can facilitate the formation of current sheets or magnetic structures with steep gradients which can be favourable sites for the reconnection process, and for the subsequent energy input needed to power explosive events in the chromospheric and coronal regions.

There is sufficient observational evidence for the occurrence of fast reconnection of magnetic field lines in a variety of astrophysical phenomena. Typically, the large physical scales and high electrical conductivities associated with cosmic bodies make the ohmic decay process operate on very long time-scales. On the other hand, an efficient transport mechanism which can steepen the magnetic field configurations can lead to the formation of thin current sheets. The unavoidable magnetic reconnections via resistive processes can thus provide favourable sites for rapid conversion of magnetic energy (Brandenburg & Zweibel 1995). The ambipolar diffusion operating in weakly ionized plasma can conceivably provide a viable mechanism for the explosive release of energy in a number of astrophysical situations. Thus this process could account for a variety of transient events like the micro- and nanoflares on the Sun, flaring activity in the atmospheres of cool M dwarfs, and bursts occurring in the magnetospheres of planets like Jupiter. It is even tempting to speculate that, below the crustal layers of neutron stars, the ambipolar drift of electrons through the gas of free neutrons can lead to the formation of sharp structures and the consequent release of energy through flaring activity.

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