Localized magnetic reconnection as a cause of extraplanar diffuse ionised gas in the galactic halo

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ABSTRACT

Many observations indicate the occurrence of ionised gas in the distant halos of galaxies (including our own). Since photoionisation by stars (mainly O stars, young or evolved low-mass stars depending on the kind of galaxy) does not seem to be exclusively responsible for the ionisation of the hydrogen filaments that should otherwise cool fast and recombine quickly, the question arises which extra energy source can produce the quasistationary ionisation. We show that stationary localized magnetic reconnection in current filaments may contribute to the ionisation of the extraplanar halo gas. In these filaments magnetic energy is dissipated. Consequently, the ionised as well as the neutral component are heated and re-ionised on a time scale significantly shorter than the recombination time scale. The amount of energy required for efficient re-ionisation can in principle easily be provided by the free magnetic energy. We present quasi-static models that are characterized by plasma temperatures and densities that agree well with the observed values for the diffuse ionised gas component of the interstellar medium. Plasma-neutral gas fluid simulations are made to show that the recombination induced dynamical reconnection process indeed works in a self-regulatory way.

Key words: Diffuse Ionised Gas, Galactic Halo, Magnetic Reconnection

1 INTRODUCTION

During the last decade it became obvious that the existence of a diffuse ionised gas (DIG) component is of importance for our understanding of the interstellar medium. This compo-
ponent is widely spread in the Galactic Halo (cf. Mezger 1978; Reynolds 1990), in the disk halo interface of spiral galaxies (e.g. Dettmar 1990; Rand et al. 1990) and in irregular, active and early type galaxies (recent reviews on the detection of DIG are given by Walterbos 1991 and Dettmar 1992, 1995). The detection of the DIG component of the interstellar medium gives rise to the ionisation problem: What are the energy sources that keep the DIG ionised? In the case of the extraplanar Galactic DIG, for example, recombination has to be balanced by an energy input of about $10^{42}$ ergs$^{-1}$ at maximum (Dettmar 1992). Several suggestions for the solution of this problem can be found in the literature, among them photoionisation by O and OB stars (Matthias 1986; Sivan et al. 1986), by white dwarfs (Sokolowski and Bland-Hawthorn 1991) and by decaying neutrinos (Sciama and Salucci 1991), shock heating (Sivan et al. 1986) and microflares (Raymond 1992). In an alternative approach the existence of DIG is interpreted in terms of the cooling phase of galactic fountains (Slavin 1993; Shapiro and Benjamin 1993). However, the proposed processes are seemingly not sufficient to resolve fully the ionisation problem in the different parameter regimes. Photoionisation by decaying neutrinos seems to be inappropriate to explain the measured line ratios (Dettmar and Schulz 1992). Photoionisation by OB stars also seems to be questionable for NGC 891 for the same reason (Dettmar and Schulz 1992). Additionally, special geometric conditions are necessary to channel the photon flux from the disk O stars to the distant extraplanar DIG in the Galactic Halo (for a discussion of the problems of different explanations see Dettmar 1992).

In this contribution we consider a very general process that may help to solve the ionisation problem: heating and ionisation by magnetic reconnection. The reconnection process has been proved to be an efficient heating process in quite different cosmical plasma regimes. It was shown, e.g., that this process can explain the X-ray emission of boundary regions of high-velocity-clouds hitting the Galactic disk (Zimmer et al. 1997a, b), that it explains the small-scale solar coronal heating in bright points (Priest et al. 1993; Birk et al. 1997; Dreher et al. 1997), that it can influence the temperature of accretion disks in active galactic nuclei (Lesch 1990) and may result in auroral heating in the Earth’s ionosphere (Birk and Otto 1997).

Whereas we feel that this fundamental process may work in all of the mentioned types of galaxies here we focus on the extraplanar DIG in our Galaxy in order to obtain reliable quantitative results. The principal train of thought is as follows. Extraplanar gas far away from O-stars cools down and recombines effectively. The recombination results in a lower thermal plasma pressure and in a higher rate of electron-neutral collisions. This has a two-
fold influence on gas filaments/clouds threaded by an inhomogeneous magnetic field carrying localized electric currents. For one, the plasma pressure that had balanced the stresses exerted by the magnetic field is reduced leading to a contraction of the current carrying region. If the total current flowing through this domain is approximately conserved then this will automatically lead to a higher current density. Secondly, the increased number of electron-neutral collisions leads to a reduced electrical conductivity, because electron-neutral collisions are the dominant contribution to the conductivity in the halo. In this situation localized dynamical magnetic dissipation (e.g. Parker 1994) that can be regarded as a typical reconnection process is likely to occur. During this process due to the local violation of ideal Ohm’s law magnetic field lines are reconnected and magnetic flux is dissipated. The free magnetic energy is mainly converted into heat via Ohmic dissipation and consequently, the gas is re-heated and can be re-ionised.

In the next section we present simple stationary solutions of the ionisation and energy balance equations of this process. Section 3 is devoted to the application of stationary reconnection theory to the considered ionisation problem, whereas in Section 4 we show results of numerical dynamical simulations of the reconnection process. We sum up and discuss our findings in Section 5.

2 QUASISTATIC STATIONARY HEATING AND IONISATION BY MAGNETIC RECONNECTION: PLASMA DENSITY AND TEMPERATURE PROFILES

In this section we show that heating and ionisation caused by magnetic reconnection gives rise to an ionised gas component in the simplest stationary model available. Though we consider the basic process to be a dynamical one, the investigation of this simple stationary model will provide a first rough estimate of the fraction of ionised gas to be expected. We assume that the velocities of both the ionised and the neutral component are dynamically of no importance and thus can be neglected in a first attempt. We consider a mainly hydrogen quasineutral partially ionised plasma in ionisation equilibrium (not necessarily in local thermal equilibrium) in a steady state. The energetics is assumed to be governed by local Ohmic dissipation during the reconnection process and radiative losses caused by bremsstrahlung and recombination radiation. Accordingly, we have to consider the stationary ionisation and energy balance equations.
\[ \alpha n_p^2 = \nu n_n \]  

(1)

\[ j^2 = \sigma (L_{\text{brems}}^{\text{rad}} + L_{\text{recom}}^{\text{rad}}) \]  

(2)

where \( n_p, n_n, j, L_{\text{brems}}^{\text{rad}}, L_{\text{recom}}^{\text{rad}} \) denote the plasma and neutral gas particle density, the current density and the radiative loss functions (cf. Huba 1994) due to bremsstrahlung \( L_{\text{brems}}^{\text{rad}} = 1.7 \cdot 10^{-25} n_p^2 T_e^{1/2} \text{erg s}^{-1} \text{cm}^{-1} \) (\( T_e \) is the electron temperature measured in eV) and recombination radiation \( L_{\text{recom}}^{\text{rad}} = 1.7 \cdot 10^{-25} E_{\infty} n_p^2 T_e^{-1/2} \text{erg s}^{-1} \text{cm}^{-1} \) (\( E_{\infty} \) is the ionisation energy), respectively. The ionisation frequency \( \nu \) is given by \( \nu = 10^{-5} n_p (T_e/E_{\infty})^{1/2} \exp(-E_{\infty}/T_e)(6 + T_e/E_{\infty})E_{\infty}^{-3/2} \text{s}^{-1} \) whereas the recombination rate (dominated by radiative recombination) is \( \alpha = 5.2 \cdot 10^{-14} (E_{\infty}/T_e)^{1/2} (0.43 + 0.5 \ln(E_{\infty}/T_e) + 0.5(E_{\infty}/T_e)^{-1/3}) \text{cm}^3 \text{s}^{-1} \) (cf. Huba 1994). By \( \sigma \) we denote the collisional conductivity due to electron-neutral collisions (cf. Huba 1994) \( \sigma = 2 \cdot 10^{14} n_p e^2/m_e n_n (kT_e/m_e)^{1/2} \text{s}^{-1} \) where \( e, m_e \) and \( k \) are the elementary charge, the electron mass and the Boltzmann constant. The local filamentary structure of the magnetic field and the associated electrical current are assumed to be of the Harris sheet type (Harris 1962) for simplicity (we assume the magnetic field to vary in the \( y \)-direction):

\[ j = 7.7 \cdot 10^{-16} \frac{B}{\mu G} \left( \frac{\delta}{p_e} \right)^{-1} \cosh^{-2} \left( \frac{y}{\delta} \right) e_z \text{ statamp cm}^{-2} \]  

(3)

where \( \delta \) is the length scale of the inhomogeneity of the filamentary magnetic field, i.e. the half-thickness of the current layer.

In the case of weakly ionised plasmas \( n_t \approx n_n \), i.e. filaments of diffuse ionised and relatively dense neutral gas, we can approximate the plasma density by means of equations (2) and (3):

\[ n_p = \left( 2.7 \cdot 10^{-23} \frac{B^2 n_t}{\delta^2 \cosh^4(y/\delta)(1 + E_{\infty}/T_e^{1/4})} \right)^{1/3} \text{ cm}^{-3} \]  

(4)

and obtain an equation for the electron temperature by inserting Eq.(4) in Eq.(1):

\[ \frac{6.4 \cdot 10^{15} n_t^{2/3} T_e^{-1/2} E_{\infty} T_e}{E_{\infty}^{5/2}(6 + T_e E_{\infty})} e^{-E_{\infty}/T_e} = \left( 0.43 + 0.5 \ln \left( \frac{E_{\infty}}{T_e} \right) + 0.5 \left( \frac{T_e}{E_{\infty}} \right)^{1/3} \right) \times \right. \]

\[ \left. \times \left( \frac{B^2}{\delta \cosh^4(y/\delta)(1 + E_{\infty}/T_e^{1/4})} \right)^{-1/3} \]  

(5)

that has to be solved numerically. Given a solution for \( T_e \) the other parameters, in particular the degree of ionisation \( n_p/n_n \), can be determined. If we are not dealing with diffuse ionised gas associated with relatively dense neutral gas filaments but with comparable plasma and neutral gas densities we instead have to solve for the set of non-linear algebraic equations:
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\[ n_p^3 + 2.7 \cdot 10^{-23} \frac{B^2 (n_p - n_t)}{\delta^2 \cosh^4 (y/\delta)(1 + E_\infty T_e^{-1/4})} = 0 \]  
(6)

\[ \left( \frac{0.43 + 0.5 \ln \left( \frac{E_\infty}{T_e} \right)}{E_\infty} + 0.5 \left( \frac{T_e}{E_\infty} \right)^{1/3} \right) n_p - 2 \cdot 10^8 \frac{T_e}{E_\infty^{5/2}} \frac{n_t - n_p}{6 + T_e/E_\infty^{1/4}} e^{-E_\infty/T_e} = 0 \]  
(7)

The ionisation energy for hydrogen is \( E_\infty = 13.6 \text{eV} \) and the lower estimate for the magnetic field strength is about \( 5 \mu \text{G} \) from radio data (Beck et al. 1996). The only free input parameters for our calculations are the total particle density \( n_t \) and the half-thickness of the current sheet \( \delta \). If we assume local thermal equilibrium we can calculate the neutral gas density by means of the corona model (cf. Huba 1994), which is applicable for the case of the Galactic Halo, since \( 10^{12} \leq n_p < 10^{16} T_e^{-7/2} \) holds:

\[ \frac{n_n}{n_i^2} = \frac{\alpha}{t} \approx 80 \text{cm}^3 \]  
(8)

Fig. 1 shows the spatial profiles of the electron temperature \( T_e \), plasma density \( n_p \) and neutral gas density \( n_n \) for \( n_t = 1 \text{cm}^{-3} \) and \( \delta = 10^{-11} \text{pc} \) (upper row), \( n_t = 0.15 \text{cm}^{-3} \), \( n_t = 0.15 \text{cm}^{-3} \) and \( \delta = 10^{-10} \text{pc} \) (middle row) and \( n_t = 0.5 \text{cm}^{-3} \) and \( \delta = 10^{-10} \text{pc} \) but a higher magnetic field of \( B = 30 \mu \text{G} \) (lower row) that in this case may result locally, e.g. from dynamical compression. In all cases the electron temperature is close to the observed value of the HII-temperature \( T_i \sim 10000 \text{K} \). The electron and ion temperatures should not differ significantly since electron-ion collisions leads to a thermalization on a time scale of \( \nu_e^{-1} = 10^{10} \text{s} \ll t_{\text{recom}} \). For \( n_t = 1 \text{cm}^{-3} \) the central ionisation rate is \( \sim 60\% \) which agrees quite well with observed values in some Galactic DIG regions. The dependence of the central electron temperature and plasma density on the length scale \( \delta \) is illustrated in Fig. 2. The lines represent the central plasma density for \( n_t = 1 \text{cm}^{-3} \) (dashed-dotted), \( n_t = 0.5 \text{cm}^{-3} \) (solid) and \( n_t = 0.15 \text{cm}^{-3} \) (dashed). The central electron temperature is indicated by triangles (for the case \( n_t = 1 \text{cm}^{-3} \)), diamonds (for the case \( n_t = 0.5 \text{cm}^{-3} \)) and asterisks (for the case \( n_t = 0.15 \text{cm}^{-3} \)).

From our idealized model we conclude that magnetic reconnection may account for the existence of extraplanar ionised gas with observed densities \( n_p \approx 0.01 - 0.5 \text{cm}^{-3} \) provided that the magnetic reconnection process takes place in filaments of the thickness of \( \delta = 10^{-11} - 10^{-9} \text{pc} \).
3 STATIONARY HEATING AND IONISATION BY MAGNETIC RECONNECTION: TIME SCALES AND ENERGETICS

In relatively low resistivity plasmas the simplest kind of steady magnetic reconnection, Sweet-Parker reconnection, is usually too slow to account for the observed phenomena. The characteristic dynamical dissipation time $\tau_{\text{rec}}$ is (cf. Parker 1994):

$$\tau_{\text{rec}} = \frac{\Delta}{v_A} S^{1/2}$$

(9)

where $S$ is the Lundquist number $S = \Delta v_A / \eta$ and $\Delta$ is the width of the considered current filaments. For a half thickness of the current layer of $\delta = 10^{-9}$ pc for our application we obtain $\tau_{\text{rec}} \approx 8 \cdot 10^{19}$ s which is much larger than the recombination time scale $t_{\text{recomb}} = 1/(\alpha n_p) \approx 10^{13}$ s (Dettmar 1992), i.e. steady Sweet-Parker reconnection would not prevent the extraplanar gas from recombining totally.

However, magnetic reconnection can convert magnetic energy into heat on a much faster time scale, if reconnection does not operate along the entire width of the homogeneous current filament. In our situation this stronger localization of the dissipative process may result, e.g. from slight anisotropies of recombination along the widths of the current filaments. In this situation Petschek-like reconnection (Petschek 1964; Parker 1994) rather than the relatively slow Sweet-Parker reconnection operates. The velocity of the reconnection process $u_P$ is given by (Parker 1994):

$$u_P = \frac{v_A}{\ln S} = 5.6 \cdot 10^6 u$$

(10)

and the dissipative region $\Delta'$ is much smaller than $\Delta$ with a lower limit estimated by

$$\Delta' = \frac{\Delta (\ln S)^2}{S} = 5 \cdot 10^3 \text{cm}$$

(11)

For a dissipative region of the order of the half-thickness of the current sheet $\delta \sim \Delta$ the reconnection time scale is $\tau_{\text{rec}} = 4 \cdot 10^4$ s. We conclude that a Petschek-like localized reconnection process can result in heating and thereby ionisation of the extraplanar gas fast enough to prevent it from recombining totally. It should be note that the newer generation of reconnection regimes, i.e. almost uniform reconnection (Priest and Forbes 1986) and nonuniform reconnection (Priest and Lee 1990) are able to liberate the magnetic energy even more quickly.

The observational correlation between disk activity (in form of star formation) and the DIG-brightness in the halo is a clear indicator that disk kinetic energy is somehow thermalized in the halo gas. The general scenario suggests that on large scales the interstellar
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medium is characterized by energy equipartition between the dynamical constituents (cosmic rays, turbulence and magnetic fields) (e.g. Ikeuchi 1988). We have shown above that the dissipation of magnetic energy via reconnection is able to sustain a local recombination-reconnection equilibrium, provided that the dissipated magnetic flux is refreshed fast enough, i.e. the magnetic dissipation rate

$$\Lambda_{\text{diss}} = \frac{B^2}{8\pi \tau_{\text{rec}} f_{\text{diss}}}$$

equals the energy input rate caused by disk activity

$$\Gamma = \frac{\dot{E}_{\text{disk}}}{V_{\text{diss}}} f_{\text{in}}$$

where $f_{\text{diss}}$ and $f_{\text{in}}$ denote the efficiency of magnetic field dissipation, which is about $f_{\text{diss}} = 0.1$ for the case of Petschek reconnection, and the fraction of conversion of kinetic energy involved in the disk activity to magnetic fields, respectively. $\dot{E}_{\text{disk}}$ denotes the kinetic disk luminosity and $V_{\text{diss}}$ is the volume in which the following chain of processes takes place:

- Activity in the disk (e.g. supernovae, stellar winds) gives rise to the generation of cosmic rays which in course trigger the Parker (buoyancy) instability, i.e. the disk magnetic field is inflated into the Galactic Halo (Parker 1994). The rate at which magnetic field is extended and magnetic free energy is continuously created is $10^{41}$ ergs$^{-1}$.

- Locally, the magnetic field is compressed until its energy density is comparable to the kinetic energy density of the plasma.

- The magnetic field energy is dissipated in filamentary structures thereby resulting in a re-ionisation of the DIG.

If we assume a reconnection time comparable to the recombination time ($\tau_{\text{rec}} \approx 10^{13}$ s), the condition $\Lambda_{\text{diss}} \approx \Gamma$ leads to

$$V_{\text{diss}} \approx \frac{\dot{E}_{\text{disk}} \tau_{\text{rec}} 8\pi}{B^2 f_{\text{diss}}} \approx 10^{67} \text{cm}^3 f_{\text{in}} f_{\text{diss}} \left[ \frac{\dot{E}_{\text{disk}}}{10^{41} \text{ergs}^{-1}} \right] \left[ \frac{\tau_{\text{rec}}}{10^{13} \text{s}} \right] \left[ \frac{B}{5 \mu \text{G}} \right]^{-2}$$

which corresponds to a sphere with a radius of about 7 kpc for $f_{\text{in}}/f_{\text{diss}} = 10$. In this volume the magnetic energy should be dissipated in a huge number of neighbored individual (observationally non-resolved) reconnection processes as described above. We note that, depending on the actual type of reconnection, the individual heating processes are not restricted to the entire region of the current filaments but efficient heat transport, e.g. due to outflow and shocks, on larger spatial scales is to be expected (e.g. Biskamp 1993). Additionally, the individual reconnection events excite Alfvén waves which can dissipate the energy over lager spatial scales (Champeaux et al. 1997). The scenario we have in mind resembles

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very much the concept of coronal heating by nano flares (Parker 1994; cf. also discussion by Raymond 1992).

4 DYNAMICAL HEATING AND IONISATION BY MAGNETIC RECONNECTION: NUMERICAL SIMULATIONS

Finally, we can drop the explicit assumption of a stationary configuration and model the ionisation of the DIG by reconnection with the help of numerical dynamical simulations. These simulations are meant to show that the proposed reconnection scenario indeed can be regarded as a dynamical self-regulating process. The balance equations (note that we are not dealing with standard MHD equations; our analysis rather makes use of a multi-fluid description) that are integrated by means of an explicit difference scheme (for details of the numerical procedure see Birk and Otto 1997) read:

\[ \frac{\partial \rho}{\partial t} = - \nabla \cdot (\rho \mathbf{v}) + \iota \rho_n - \alpha \rho^2 \]  
(15)

\[ \frac{\partial \rho_n}{\partial t} = - \nabla \cdot (\rho_n \mathbf{v}_n) - \iota \rho_n + \alpha \rho^2 \]  
(16)

\[ \frac{\partial (\rho \mathbf{v})}{\partial t} = - \nabla \cdot (\rho \mathbf{v} \mathbf{v}) - \nabla p + (\nabla \times \mathbf{B}) \times \mathbf{B} - \rho \nu \nu (\mathbf{v} - \mathbf{v}_n) + \iota \rho_n \mathbf{v}_n - \alpha \rho^2 \mathbf{v} \]  
(17)

\[ \frac{\partial (\rho_n \mathbf{v}_n)}{\partial t} = - \nabla \cdot (\rho_n \mathbf{v}_n \mathbf{v}_n) - \nabla p_n - \rho_n \nu (\mathbf{v}_n - \mathbf{v}) - \iota \rho_n \mathbf{v}_n + \alpha \rho^2 \mathbf{v} \]  
(18)

\[ \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) - \nabla \times (\eta \nabla \times \mathbf{B}) \]  
(19)

\[ \frac{\partial p}{\partial t} = - \mathbf{v} \cdot \nabla p - \gamma p \nabla \cdot \mathbf{v} + (\gamma - 1) \left[ (\nabla \times \mathbf{B})^2 - \nu \nu \left( p - \frac{\rho}{\rho_n} p_n \right) + \iota p_n - \alpha \rho p \right] \] 
\[ + \left( \rho \nu \nu + \frac{1}{2} (\iota \rho_n + \alpha \rho^2) \right)(\mathbf{v} - \mathbf{v}_n)^2 \]  
(20)

\[ \frac{\partial p_n}{\partial t} = - \mathbf{v}_n \cdot \nabla p_n - \gamma p_n \nabla \cdot \mathbf{v}_n \] 
\[ - (\gamma - 1) \left[ \nu \nu \left( p_n - \frac{\rho}{\rho_n} p \right) + \iota p_n - \alpha \rho p + (\rho \nu \nu_n + \frac{1}{2} (\iota \rho_n + \alpha \rho^2))(\mathbf{v}_n - \mathbf{v})^2 \right] \]  
(21)

In this set of equations \( \rho, \mathbf{v}, p, \nu, \gamma \) denote the mass density, the bulk velocity, the thermal pressure, the elastic plasma-neutral gas collision frequencies and the ratios of the specific heats. The initial configuration is characterized by an ideal plasma and an isothermal homogeneous neutral gas in ionisation equilibrium. The Harris-type current sheet (\( \mathbf{B} \sim \tanh(y)\mathbf{e}_x \)) is balanced by thermal plasma pressure (\( p \sim \text{sech}^2(y) \)).
The dimensions of our numerical box are given by \( x \in [-10, 10] \) and \( y \in [-10, 10] \) in normalized units (half-width of the current layer). The simulations are carried out with 77 grid points in both directions. The numerical grid is chosen non-uniform in the \( x \)-direction with a maximum solution of 0.05.

The initial equilibrium is perturbed by a localized enhancement of the recombination coefficient \( \alpha_{\text{pert}} \sim \text{sech}^2(x)\text{sech}^2(y) \). This perturbation results in a decrease of the thermal plasma pressure and thereby in an inward plasma transport (Fig. 3, upper panel). Magnetic field lines are convected inward, since the frozen-flux condition holds outside the central current filament (Fig. 3, lower panel). A dissipative region forms inside the filament due to the enhanced recombination. The formation of this non-ideal region is modeled by a localized magnetic diffusivity switched on during the temporal evolution. After 100 Alfvénic times \( \tau_A = \sqrt{4\pi \rho \delta / B} \) well developed X-type reconnection results in localized dynamical magnetic dissipation and divergent plasma flow caused by Lorentz forces (Fig. 4). The flow and magnetic patterns have the appearance of flux pile-up reconnection (Priest and Forbes 1986).

During the reconnection process magnetic energy is partly converted into heat via Ohmic dissipation (cf. Fig. 5). Thermalization due to plasma-neutral collisions leads to an increase of the central neutral gas temperature (see equation (21)). Eventually, the neutral gas will be re-ionised by the local magnetic dissipation mechanism.

Our numerical studies show that the recombination induced reconnection indeed can work as a dynamical self-regulating process that, in principle, can keep a significant part of the interstellar medium in an ionised state.

5 SUMMARY AND DISCUSSION

We have suggested a magnetic reconnection model for the solution of the ionisation problem. Similar to Raymond (1992) we assume that the dissipation of free magnetic energy, stored in thin current filaments, plays a crucial role in providing energy input necessary for keeping the DIG ionised. At first sight the existence of such dynamic filaments seems to be a little speculative, since due to restrictions of resolution there are presently no direct observational indications for them. However, there is strong evidence for a filamentary structure of the ISM from the Westerborg survey (Hartmann and Burton 1996) with the filamentary scale lengths appearing to be restricted by the highest resolution, only. We assume that even
higher resolution would show finer structures. Additionally, very fine non-thermally emitting radio filaments, and even substructures of these filaments, have been observed near the Galactic center (Morris 1996 and ref. therein). A very nice example for the omnipresence of filamentary gas structure is the Orion nebula. Subtraction of the continuous spectrum reveals M43 to be a beautiful tangle consisting of astonishingly narrow string like ionized filaments (Yusef-Zadeh 1990). What is more, magnetized plasmas in general seem to have a strong tendency to show a filamentary structure (cf. also discussion by Alfvén 1981) as has become obvious from the investigations of plasma systems that can be observed more closely, e.g. in the auroral ionosphere (e.g. Borovsky and Suszcynsky 1993; Lühr et al. 1994) and the solar corona (cf. Parker 1994). As a matter of fact, the more the observational resolution improves the more evident becomes the filamentation aspect.

Our analysis was carried out in the framework of fluid theory. This should be justified for the calculations given in Sect. 3, in particular, where the assumption of ionisation equilibrium implies a magnetohydrodynamic approach. This approach prove appropriate, one the hand, because the smallest length scale involved $\delta = 10^{-9}\text{pc}$ is much larger than the ion gyro radius $r_i = v_i/\Omega_i = 6 \cdot 10^{-12}\text{pc}$ ($v_i = \sqrt{kT_i/m_i}$ is the ion thermal velocity and $\Omega_i = eB/m_ic$ is the ion gyro frequency) even for the lower estimate of the magnetic field strength $B = 5\mu\text{G}$. On the other hand, the collective behavior is guaranteed even in the almost collisionless regime outside the central current sheets, since $v_A \geq v_i$, where $v_A = B/\sqrt{4\pi\rho}$ is the Alfvén velocity, i.e. in this case typical wave phenomena rather than collisions (as in ordinary hydrodynamics) guarantee the correlation over macroscopic length scales. The latter condition is fulfilled somewhat marginally $v_A \approx v_i \approx 10^6\text{cm/s}$ for the lower estimate of the magnetic field strength and the upper limit of the considered mass density ($\rho = 1\text{cm}^{-3}$), i.e. the worst case in the present context. However, even for the case $v_A < v_i$ a fluid description can still work in a satisfactory way, as can be seen, e.g. in the context of magnetospheric physics (e.g. Schindler and Birn 1986; Baumjohann and Treumann 1997). Additionally, it should be noted that the magnetic reconnection process itself also works in a completely collisionless regime described by kinetic theory (e.g. Biskamp et al. 1995).

We presented stationary quasistatic solutions that describe the dissipation process. From these solutions we conclude that magnetic dissipation can keep the interstellar medium partially ionised with temperatures of about 1eV. We addressed the question whether the conversion of magnetic energy is fast enough to keep the DIG ionised. We applied stationary reconnection to show that a sufficient amount of stored energy can be dissipated on a time
scale shorter than the recombination time for reasonable physical parameters. Numerical studies support and illustrate our model. Obviously, our approach cannot rule out other re-heating mechanisms, such as photoionisation and wave as well as shock heating, but it shows that magnetic reconnection should be considered as a quite natural alternative and additional process that, in principle, can cause re-ionisation in all kinds of magnetized galactic DIG structures.

Here we assumed that the velocities of the plasma and neutral gas are both dynamically unimportant, so that the recombination-reconnection circle is only intrinsically driven. There is also the possibility that reconnection may be externally driven by plasma motions.

We note that this possibility and the important role of the magnetic field for the DIG is clearly indicated by the observational well established spatial correlation between the $H\alpha$-distribution and the intensity and polarization distribution of the nonthermal radio continuum (Dettmar 1992). Since the radio continuum is due to synchrotron radiation the DIG appears in a magnetized environment, which is driven by the disk activity via star formation, supernova winds etc. These processes transport magnetic field and plasma into the halo and the deposited kinetic energy may then be dissipated in the halo via externally driven magnetic reconnection and subsequent recombination.

Finally we want to mention that the reconnection-recombination circle may be applicable to several other astrophysical situations such as cooling flows and the internal dynamics of molecular clouds, for example.

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Figure 1. Spatial profiles of the electron temperature (measured in eV), the plasma and the neutral gas density for total densities of $n_t = 1 \text{cm}^{-3}$ (upper row), $n_t = 0.15 \text{cm}^{-3}$ (middle row) and $n_t = 0.5 \text{cm}^{-3}$ but $B = 30 \mu \text{G}$ (lower row).

Figure 2. The central plasma density for $n_t = 1 \text{cm}^{-3}$ (dashed-dotted line), $n_t = 0.5 \text{cm}^{-3}$ (solid line) and $n_t = 0.15 \text{cm}^{-3}$ (dashed line) and the central electron temperatures (triangles for $n_t = 1 \text{cm}^{-3}$, diamonds for $n_t = 0.5 \text{cm}^{-3}$ and asterisks for $n_t = 0.15 \text{cm}^{-3}$) as functions of the half-width of the current filament.

Figure 3. The plasma velocity (upper graph) and magnetic (lower graph) field that evolve after $t = 10\tau_A$. Plasma flows inward due to the reduced thermal plasma pressure caused by localized enhanced recombination and magnetic flux is convected towards the dissipative region.

Figure 4. The velocity (upper graph) and magnetic (lower graph) field that evolve after $t = 100\tau_A$. Plasma is accelerated from the X-like reconnection site where the magnetic field is dynamically dissipated.

Figure 5. The Ohmic heating rate (upper graph), the plasma temperature (middle graph) and neutral gas temperature (lower graph) in normalized units (the initial plasma and neutral gas temperatures are chosen 1 in normalized units) after $t = 100\tau_A$. Plasma is heated via Ohmic dissipation. Frictional heating results in heat transfer to the neutral gas which in the course will be ionised.
