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Ambipolar diffusion and the detectability of recombination emission from protostellar disks

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Abstract. The emission measure of a region ionised by ambipolar diffusion in the vicinity of a protostellar disk is given, and the possibility of detecting such a region in recombination radiation is considered.

Key words: stars: formation – stars: magnetic fields

1. Introduction

Remnant magnetism of carbonaceous chondrite meteorites implies that the magnetic field where they formed had a strength of as much as 7 Gauss (Levy & Sonnett 1978). If a dynamo creates a field of such a strength in a protostellar disk, the disk may have a more tenuous corona with a magnetic field of comparable strength maintained by the convective transport and buoyant rise of flux tubes. Levy & Araki (1989) have suggested that such processes may have played rôles in the establishment of a corona around the protosolar disk. We identify conditions under which ambipolar diffusion, the relative motion of ions and neutrals driven by magnetic forces, occurs at a high enough speed to create around a protostellar disk an ionised region that is observable in recombination radiation.

In Sect. 2 we present calculations giving, as a function of density, the magnetic force per unit volume required for ambipolar diffusion to maintain a high fractional ionisation. Sect. 3 concerns recombination radiation detection limits.

2. Ambipolar diffusion induced ionisation

Γ is used to signify the magnitude of the magnetic force per unit volume. In steady state,

$$\Gamma = F_{\rm i,elas.scat.} \tag{1}$$

where inertial terms have been neglected and $F_{\rm i,elas.scat.}$ is the force transferred to ions per unit volume per unit time due to elastic collisions with neutrals, and is given by Eq. (3.1) in Draine (1986) if the $\alpha^{\rm th}$ fluid and the $\beta^{\rm th}$ fluid consist of ions and neutrals respectively. We consider a nonmolecular pure hydrogen medium. For similar assumptions the ion temperature is given by

$$G_{\rm i,elas.scat.} = 0 \tag{2}$$

where $G_{\rm i,elas.scat.}$ is the energy transferred to the ion fluid per unit volume per unit time due to elastic collisions and is given by Eq. (3.7) in Draine (1986).

In ionisation equilibrium

$$\alpha_{\rm a}\, n({\rm H})\, n({\rm H}^+) \;+\; \zeta_{\rm b}\, n({\rm H}) = \alpha_{\rm r} \left[n({\rm H}^+)\right]^2 \tag{3}$$

where $\zeta_{\rm b}$ is a background ionisation rate assumed so that for low values of Γ some ionisation occurs, $n({\rm H})$ and $n({\rm H}^+)$ are the number densities of H and $\rm H^+$ respectively, $\alpha_{\rm r}$ is the recombination rate coefficient, and $\alpha_{\rm a}$ is the ionisation rate coefficient due to ambipolar diffusion given by Eqs. (25) through (27) and (29) of Draine et al. (1983). We assumed $T_{\rm n} = T_{\rm e} = 10^4$K, where $T_{\rm n}$ and $T_{\rm e}$ are the neutral and electron temperatures. In the evaluation of $F_{\rm i,elas.scat.}$ and $G_{\rm i,elas.scat.}$, we used expressions for the elastic scattering cross section for low and high ion-neutral relative speeds, as recommended by Draine (1986). In fact, over the range of calculations for which we present results, errors of only a few per cent were found when we used the high-speed form of the elastic cross sections at all relative speeds.

Fig. 1 presents results for $\langle v_{\rm in}\rangle$, the magnitude of the mean relative velocity between ions and neutrals, as a function of Γ. Fig. 2 contains plots of $x_{\rm i}$, the fractional ionisation, as a function of Γ. In each figure, the curves are labelled with the number density of neutrals, $n_{\rm n}$. As mentioned above, we assumed values for $T_{\rm n}$ and $T_{\rm e}$. They are probably higher than would be appropriate where $x_{\rm i}$ is very low; then at most they should most likely be several thousand degrees, as for low $x_{\rm i}$ the material in a disk is probably mostly molecular and cooling due to dissociation will limit the neutral temperature to about 4000K. For low values of Γ, we have consequently somewhat overestimated $x_{\rm i}$. When $1 - x_{\rm i} \ll 1$, the neutral temperature is close to the ion temperature we have calculated, whereas in reality the ion temperature is near the electron temperature which cooling by line emission keeps near 10^4K. Thus, because of the symmetry of $F_{\rm i,elas.scat.}$ and $G_{\rm i,elas.scat.}$ for ions and neutrals of the same mass, we have probably made good estimates of $x_{\rm i}$ for very high values of Γ. In any case, the point that $x_{\rm i}$ goes up by many orders of magnitude

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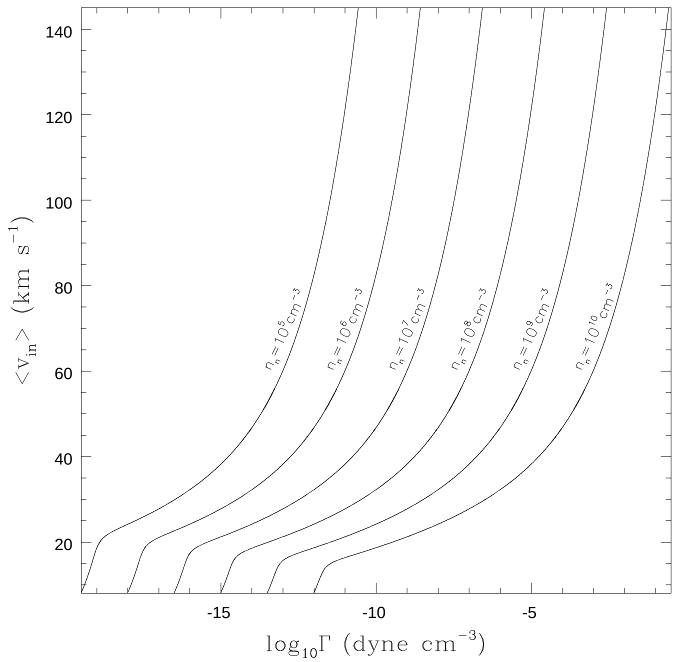

Fig. 1. Ion-Neutral Relative Speed

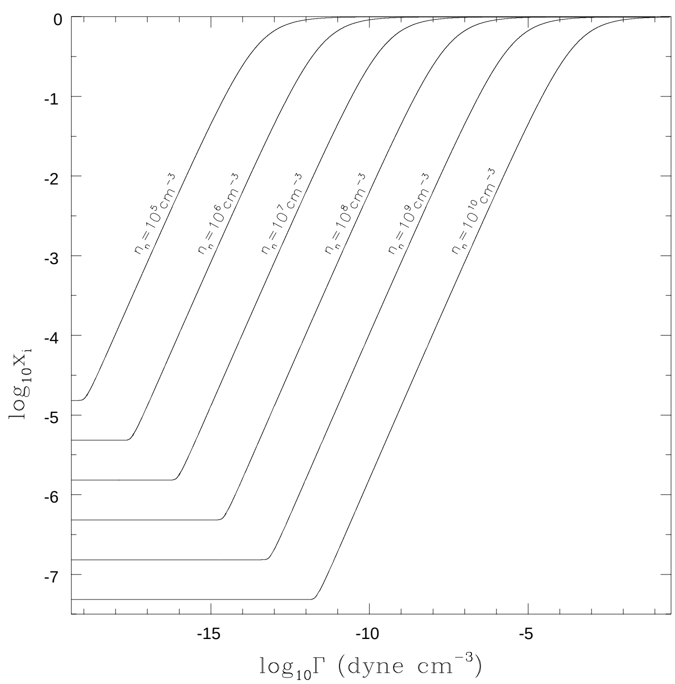

Fig. 2. Fractional Ionisation

but $\langle v_{\rm in} \rangle$ only increases roughly from $20{\rm km\,s^{-1}}$ to $50{\rm km\,s^{-1}}$ as Γ changes by many orders of magnitude is secure.

To get a reasonable approximation for the value of Γ required for ambipolar diffusion to induce sufficient ionisation that $1 - x_{\rm i} \ll 1$, one may take $\Gamma = \Gamma_{\rm i}$ where

$$\Gamma_{\rm i} \approx 10^{-9}\ {\rm dyne\,cm^{-3}} \left(\frac{n_{\rm n}}{10^7\ {\rm cm^{-3}}} \right)^2 \qquad (4)$$

The magnetic force will have a magnitude given roughly by twice the magnetic pressure divided by the length scale associated with changes in the field. This yields

$$\Gamma \approx 5 \times 10^{-11}\ {\rm dyne\,cm^{-3}} \left(\frac{B}{10\ {\rm Gauss}} \right)^2 \left(\frac{L}{1\ {\rm A.U.}} \right)^{-1} \qquad (5)$$

The value of Γ required to induce sufficient ionisation that $1 - x_{\rm i} \ll 1$ would be lowered by an order of magnitude if the critical velocity ionisation phenomena proposed by Alfvén (1954, 1960) were to operate efficiently. This effect has been studied in the laboratory (e.g. Piel et al. 1980) and observed in near-Earth space experiments (e.g. Deehr et al. 1982). However, Formisano et al. (1982) have suggested that in cases in which the ion gyrofrequency is large compared to the ionisation frequency, given by their Eq. (4), the fraction of an ion's kinetic energy that goes into the production of ions via the critical velocity ionisation mechanism is small. In a region where $B > 1$ Gauss and $n_{\rm n} < 10^{13}\ {\rm cm^{-3}}$, the critical velocity ionisation mechanism can be neglected if Formisano et al. (1982) are correct.

3. Discussion

A rough approximation of the emission measure of a region in which $x_{\rm i}^2 \approx \frac{1}{2}$ can be obtained if $\Gamma_{\rm i}$ in Eq. (4) and Γ in Eq. (5) are equated, giving

$$\left[n({\rm H^+}) \right]^2 L \approx 10^{13}\ {\rm cm^{-6}\ A.U.} \left(\frac{B}{10\ {\rm Gauss}} \right)^2 \qquad (6)$$

While we do not necessarily attribute the origin of the MWC 349 recombination line maser region at a distance of 1.2 kpc (Cohen et al. 1985) to ionisation by ambipolar diffusion, we note that the emission measure of that region is probably around 10^{15} – $10^{16}\ {\rm cm^{-6}}$ A.U. (Thum & Greve 1997). In fact, the emission measure of a region ionised by ambipolar diffusion in the corona of a disk is likely to be reduced from the value given in (6) as the lengthscale over which the magnetic force varies is likely to grow beyond the density scaleheight as the magnetic flux moves into the corona. The rigorous calculation of such a reduction factor would be very difficult, but one might expect the reduction factor to be of the same order as the number of density scaleheights above the disk the flux must travel (to reach a region where ambipolar diffusion can induce a high fractional ionisation) divided by the ratio of the density scaleheight at that location to the mean density scaleheight up to that location. Given that the density scaleheight will increase significantly in the region where the fractional ionisation due to ambipolar diffusion becomes high, due to a significant temperature increase, the reduction factor may be closer to unity than 0.1. Note that the growth of the lengthscale over which the magnetic force varies does not necessarily imply a great weakening of the field strength, as the corona is likely to be filled with neighbouring flux tubes responding to the forces they exert on one another; indeed, we assume that the corona of a protostellar disk resembles the corona of our Galaxy in that the magnetic field strength in it at a height many times the disk thickness is only modestly less than that in the disk.

Some constraints on the detectability of Paschen recombination line radiation can be inferred from the fact that the weakest lines detected towards NGC 7027 in an integration in that spectral range had strengths of about $1.5 – 2.5 \times 10^{-5}$ that of $\mathrm{H}\beta$ from that source (Baluteau et al. 1995). From that fact and the known properties of NGC 7027 (e.g. Osterbrock 1974), we can conclude that Paschen recombination lines from a source that fills the beam can be detected in a source with an emission measure down to roughly $10^8\ \mathrm{cm}^{-6}\ \mathrm{A.U.}$

We will assume that observations can be made at a diffraction limited resolution of $0.1''$. Thus, so that the central star is not in the field of view the disk of a star at $150\ \mathrm{pc}$ must be observed at 15 and more A.U. from it. As the product of the density and the square of any relevant speed near the midplane of the disk is likely to be about two orders of magnitude less at such a distance than it was where much of the meteoritic material (examined in field strength estimates) cooled, the value of B^2 used in (6) probably should be reduced by a couple of orders of magnitude. A region $1.5\ \mathrm{A.U.}$ across with an emission measure of $10^{10}\ \mathrm{cm}^{-6}\ \mathrm{A.U.}$ would be detectable in Paschen recombination emission if no other source of emission interfered with the observations, and, of course, a number of regions ionised by ambipolar diffusion might together cover a substantial fraction of a disk making detection of such radiation rather easier.

The winds of T-Tauri stars are sources of recombination radiation which may affect the observability of the regions ionised by ambipolar diffusion. The emission measures associated with the winds are of order $10^{10}\ \mathrm{cm}^{-6}\ \mathrm{A.U.}$ as one can infer from Table 5 of Edwards et al. (1987), and a wind will fill a beam. However, much of a wind's emission originates at much higher velocities than those of the ambipolar diffusion regions. Given the proximity of the Taurus cloud, recombination line emission from regions ionised by ambipolar diffusion around protostellar disks may be detectable with instruments to become available in the near future, if the disks are not embedded in material having high extinctions.

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