Magnetic fields: Impact on the rotation curve of the Galaxy

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ABSTRACT

We quantify the effects of magnetic fields, cosmic rays and gas pressure on the rotational velocity of H\textsc{i} gas in the Milky Way, at galactic distances between $R_\odot$ and $2R_\odot$. The magnetic field is modelled by two components: a mainly azimuthal magnetic component and a small-scale tangled field. We construct a range of plausible axisymmetric models consistent with the strength of the total magnetic field as inferred from radio synchrotron data. In a realistic Galactic disc, the pressure by turbulent motions, cosmic rays and the tangled turbulent field provide radial support to the disc. Large-scale (ordered) magnetic fields may or may not provide support to the disc, depending on the local radial gradient of the azimuthal field. We show that for observationally constrained models, magnetic forces cannot appreciably alter the tangential velocity of H\textsc{i} gas within a galactic distance of $2R_\odot$.

Key words: galaxies: haloes — galaxies: kinematics and dynamics — galaxies: magnetic fields — galaxies: spiral — dark matter

1 INTRODUCTION

The interstellar medium in galaxies contains three basic constituents: ordinary matter, cosmic rays and magnetic fields. Studies of the vertical distribution of gas and synchrotron emission in the solar neighbourhood show that cosmic rays and magnetic fields influence the spatial distribution of gas providing efficient support against the gravitational force (e.g., Ferrière 2001; Cox 2005). In the radial direction, gradients in the pressure may produce a difference between the rotational velocity of the gas $v_\phi$ and the real gravitational circular velocity $v_c$, defined as $v_c^2 \equiv R d\Phi/dR$. Here $R$ is the galactocentric radius and $\Phi$ the gravitational potential. The asymmetric drift, defined as $v_\phi^2 - v_c^2$, measures this difference. In a gaseous disc in equilibrium, the asymmetric drift is a consequence of the support by thermal, turbulent and magnetic pressures as well as the pressure due to cosmic rays (e.g., Parker 1966; Spitzer 1978). In galaxies with circular velocities $v_\phi > 50$ km s$^{-1}$, the asymmetric drift corrections to derive the real gravitational circular velocity from the observed rotational velocity are not applied because they are small as compared to uncertainties due to inclination, warps, non-circular motions, etc (e.g., de Blok & Bosma 2002). Only for low-mass galaxies with $v_\phi < 50$ km s$^{-1}$, corrections for the asymmetric drift must be taken into account (e.g. Dalcanton & Stilp 2010).

In this approach, magnetic effects on the gas are modelled as a pressure term in the asymmetric drift. However, gas can also experience an additional force due to the magnetic stress of a large-scale magnetic field. Using a stationary cylindrical model, Nelson (1988) argued that the dynamical effects of magnetic fields can be very significant, yielding rotational velocities significantly higher than the gravitational orbital velocity, because of the inward force due to the magnetic tension. His model, however, predicted unrealistic radial velocities of the gas ($\sim 200$ km s$^{-1}$ at $R \sim 30$ kpc), because of the magnetic torque. Assuming a purely azimuthal magnetic field, Battaner et al. (1992) derived the magnetic field strength as a function of galactocentric radius required to explain the rotation curve of M31 without any dark matter. Still, the field needed is so strong that the magnetic pressure in the vertical direction would cause the gaseous disc to flare unacceptably (Cuddeford & Binney 1993) and, thus, magnetic fields are not a real alternative to dark matter.

In a more conventional scenario, Sánchez-Salcedo (1997a) combined the effects of an azimuthal magnetic field of strength $\sim 1\mu$G with an isothermal dark halo to fit reasonably well the detailed shape of the rotation curve of the dwarf galaxy NGC 1560. By constructing models that match boundary conditions at infinity, Sánchez-Salcedo & Reyes-Ruiz (2004) found that the magnetic contribution cannot boost the azimuthal speed of the gas by more than $\sim 20$ km s$^{-1}$ at the outermost point of H\textsc{i} detection.

The idea that galactic magnetic fields can alter the rotation curves of spirals has been revived recently. Beck (2007)
suggests that the low decrease of the magnetic field energy density in the galaxy NGC 6946 to large radii may affect the gas dynamics in the outer galaxy. Recently, Ruiz-Granados et al. (2010, 2012) claim that large-scale magnetic fields can provide enough radial confinement of the gas to explain the rising-up in the H\textsc{i} rotation curve detected in some galaxies. Moreover, they argue that the shape of the H\textsc{i} rotation curves of M31 and the Milky Way are fitted better if the contribution of the large-scale (mainly azimuthal) magnetic field is included. Tsiklauri (2011) uses a bisymmetric spiral configuration to model the magnetic field of the Milky Way and concludes that the magnetic pinching effect may be important for $R \geq 15$ kpc. Jalocha et al. (2012a,b) suggest that the mass-to-light ratio in the discs of the galaxies NGC 891 and NGC 253 are more realistic if the contribution of the large-scale and a small-scale isotropic random field $b$ is included. It is assumed that the magnetic field can be decomposed into an average part $\bar{B}(R)$ varying only on the large scale and a small-scale isotropic random field $b$, so that $\langle b^2 \rangle = 0$. We will refer to $\langle b^2 \rangle^{1/2}$ as the strength of the random (or turbulent) magnetic field. At scales larger than the coherence length of the small-scale magnetic field, it is useful to define the strength of the total magnetic field as $B_{\text{tot}}^2 = \bar{B}^2 + \langle b^2 \rangle$. In the equilibrium configuration, we assume that the regular magnetic field consists of a planar magnetic field $\bar{B}(R) = (\bar{B}_R, \bar{B}_\phi, 0)$ (in cylindrical coordinates), with $\bar{B}_R \ll \bar{B}_\phi$. We further assume that the radial velocity of the gas, $v_R$, is much smaller than $v_\phi$, and thus it can be ignored; so the velocity in the disc is $v = (0, v_\phi, 0)$ in cylindrical coordinates\footnote{This is an approximation because the magnetic field creates a torque, unless $\bar{B}_R = 0$, leading to a radial inflow of gas (Sánchez-Salcedo 1997b).}. In principle, each component of the interstellar gas can rotate at different velocity. Since we are only interested in the rotation curve of neutral atomic gas, we will consider the dynamics of this component and ignore the presence of molecular hydrogen gas. In the Milky Way, this is a good approximation especially at $R > 10$ kpc because it is at these galactic distances where the neutral atomic hydrogen is dominant in the mass budget of the interstellar gas.

Because of the symmetry around $z = 0$, we take that all the derivatives with respect to $z$ are negligible near the midplane of the disc. Under these circumstances, the radial component of the motion equation of the gas at $z = 0$ reads

\[ v^2_\rho = v^2_e + v^2_g + v^2_{\text{mag}}, \]

where $v^2_{\text{mag}}$ is the contribution of the regular (azimuthal) magnetic field:

\[ v^2_{\text{mag}} = \frac{1}{8\pi R \rho} \frac{d}{dR} \left( R^2 \bar{B}_\phi^2 \right) = \frac{R}{4\pi} \left( \frac{\bar{B}_\phi^2}{R} + B_\phi \frac{d\bar{B}_\phi}{dR} \right), \]

and $v^2_g$ is the contribution by pressure gradients,

\[ v^2_g = \frac{R dP_T}{\rho dR}, \]

where $\rho$ is the gas volume density at the midplane and $P_T(R) = P_g + P_b + P_{\text{CR}}$ is the total gas pressure consisting of the gas kinetic pressure (thermal plus turbulent), the magnetic pressure $P_b$, arising from the random magnetic field component plus also the pressure by cosmic rays $P_{\text{CR}}$ (the pressure by radiation will be ignored). More specifically, the kinetic pressure $P_g$ is given by

\[ P_g = \rho \sigma^2, \]

where $\sigma$ is the H\textsc{i} line width in the radial direction, which is approximately constant or slightly decreasing with $R$ in the outer parts of the H\textsc{i} discs, typically $\sigma \simeq 6 - 8$ km s$^{-1}$ (e.g., Dib et al. 2006, and references therein; see Blitz & Spergel 1991 and Burton 1992, for our Galaxy). The spatially averaged magnetic pressure by the turbulent field is taken as

\[ P_b = \frac{\langle b^2 \rangle}{8\pi}, \]

Finally, the cosmic-ray pressure is expected to be proportional to magnetic pressure:

\[ P_{\text{CR}} = \frac{\mu \bar{B}_{\text{tot}}^2}{8\pi}, \]
where $B_{\text{tot}}$ is the strength of the total magnetic field (that is, $B^2_{\text{tot}} = B^2 + (b^2)$) and $\mu$ is a constant of the order of 1. This is justified by minimum-energy-type arguments (e.g., Beck et al. 1996).

We want to stress that $v_\phi^2$ and $v_{\text{mag}}^2$ are not necessarily positive quantities. For instance, an unmagnetized isothermal disc with a radially decreasing density has $v_\phi^2 < 0$, which signifies that it provides pressure support to the disc (i.e., $v_\phi < 0$) because it produces a force pointing outward. From Equation (2), it is simple to see that the magnetic tension imposes an inward force, i.e. $v_{\text{mag}}^2 > 0$, provided that the azimuthal magnetic field decays radially not faster than $1/R$. Note that in the axisymmetric case with $B_\phi = 0$, the divergence-free condition implies $B_R \propto 1/R$. Therefore, if the magnetic pitch angle is constant with radius, we infer $B_\phi \propto 1/R$, implying that $v_{\text{mag}} = 0$. Consequently, a radial decay of $B_\phi$ slower than $1/R$ requires a pitch angle decreasing with $R$.

To study the distribution of mass of a certain galaxy, we need $v_\phi$, which is the circular speed of a test particle, but what we observe is the azimuthal velocity of the gas $v_\phi$. For which values of $v_\phi^2 + v_{\text{mag}}^2$ is the correction to the rotation curve significant? As guide numbers, if we observe that the gas rotates at a given galactocentric radius with a tangential velocity of $v_\phi = 230$ km s$^{-1}$ and $v_\phi^2 + v_{\text{mag}}^2 \approx 9000$ km$^2$ s$^{-2}$, then the gravitational circular velocity is $v_c \approx 210$ km s$^{-1}$. Hence, values of $9000$ km$^2$ s$^{-2}$ produce a boost of 20 km s$^{-1}$. On the other hand, if $v_\phi^2 + v_{\text{mag}}^2 = -9000$ km$^2$ s$^{-2}$, then $v_c = 249$ km s$^{-1}$. For a low-mass galaxy with $v_\phi = 120$ km s$^{-1}$, a value of $v_\phi^2 + v_{\text{mag}}^2 \approx 4400$ km$^2$ s$^{-2}$ implies that $v_c = 100$ km s$^{-1}$. It is $v_\phi^2 + v_{\text{mag}}^2$ that we want to calculate in the Milky Way.

3 THE MILKY WAY AS A TEST CASE: MODELS

The determination of the distribution of H$\text{I}$ volume density and the magnetic structure of our Galaxy has been improved significantly over the last two decades. Therefore, our Galaxy is a natural laboratory to quantify the effects of magnetic fields in the gas dynamics (see also Vallée 1994). In order to estimate $v_\phi^2$ and $v_{\text{mag}}^2$, we need to know the azimuthally averaged radial distribution of the H$\text{I}$ volume density at the midplane, and the radial profile of both $B_\phi$ and $\langle b^2 \rangle$.

The azimuthally averaged H$\text{I}$ volume density at the midplane has been derived by Nakaniishi & Sofue (2003, hereafter NS) using the Leiden/Dwingeloo survey, the Parkes survey and the NRAO survey. More recently, Kalberla & Dedes (2008, hereafter KD) inferred the average H$\text{I}$ density at the midplane excluding extra-planar gas, using the Leiden/Argentine/Bonn (LAB) H$\text{I}$ line survey, which combines the southern sky survey of the Instituto Argentino de Radioastronomía (IAR) with an improved version of the Leiden/Dwingeloo survey. NS and KD used different assumptions to derive the H$\text{I}$ structure of the Milky Way. NS chose as Galactic constants $R_\odot = 8$ kpc and $v_\odot = 217$ km s$^{-1}$, and adopted a slightly declining rotation curve to convert the observed brightness temperature distribution to density, whereas KD used $R_\odot = 8.5$ kpc and $v_\odot = 220$ km s$^{-1}$ and an almost flat rotation curve. In addition, NS assumed cylindrical rotation along $z$, whereas KD adopted a “lagging” halo. A discussion about the impact of the different assumptions on the H$\text{I}$ distribution can be found in Kalberla et al. (2007).

In Figure 1 we plot the midplane H$\text{I}$ density distributions versus $R/R_\odot$, as derived in NS. We see that the density decays exponentially beyond 1.5$R_\odot$. On the other hand, KD found that, for $7 \leq R \leq 35$ kpc, the midplane H$\text{I}$ density can be approximated by $n_{\text{HI}} = n_{\odot} \exp(-(R-R_\odot)/R_H)$ with $n_{\odot} = 0.9$ cm$^{-3}$ and $R_H = 3.15$ kpc. For comparison, we also plot the exponential fit as derived by KD, in Figure 1. We see that the major discrepancies between NS and KD occur inside 1.5$R_\odot$. KD derived an H$\text{I}$ plateau in surface density of 10$M_\odot$ pc$^{-2}$ at the inner Galaxy, which fits better to what is known for external galaxies than the saturation value derived in NS, of 2$M_\odot$ pc$^{-2}$. Therefore, we will use KD as our reference H$\text{I}$ gas model but also refer to NS to explore the effect of systematic uncertainties in the the derivation of the midplane H$\text{I}$ density. In order to include 28% of helium and 1.5% of heavier elements, we will convert $n_{\text{HI}}$ in mass density using the relation $\rho = 1.4m_p n_{\text{HI}}$, where $m_p$ is the proton rest mass (e.g., Ferrière 2001; Cox 2005).

The magnetic field of the Galaxy has been studied through synchrotron emission, Faraday rotation, optical polarization and Zeeman splitting. The strength of the total magnetic field averaged in azimuth, $B_{\text{tot}}$, was obtained from the surface brightness of synchrotron emission at 408 MHz. In the radial interval between 3.5 kpc and 17 kpc (using $R_\odot = 8.5$ kpc), and assuming energy equipartition between magnetic fields and cosmic rays, the strength of the total magnetic field in the disc can be fitted by

$$B_{\text{tot}, \odot} = B_{\text{tot}, \odot} \exp \left( -\frac{R - R_\odot}{R_B} \right),$$

where $B_{\text{tot}, \odot}$ is the total magnetic field near the Sun, which is about $6 \pm 2 \mu$G, and $R_B = 12$ kpc (Beck et al. 1996; Strong et al. 2000; Beck 2001; Ferrière 2001; see also Jansson & Farrar 2012 using WMAP7 22 GHz data). Since there is no reliable observational measurement of the magnetic
field strength beyond $2R_\odot$, we will restrict our analysis to $R < 2R_\odot$, the same interval studied in Ruiz-Granados et al. (2012).

In order to estimate $v_{\text{mag}}^2$ and $P_b$ we need to separate the ordered magnetic field and the turbulent magnetic field components. Starlight and synchrotron polarization data suggest that the local ratio between the regular and the total magnetic fields is $0.6 - 0.7$ (e.g., Berkhuijsen 1971; Brouw and Spoelstra 1976; Heiles 1996; Beck 2001). This implies that the regular magnetic field is $4 \pm 1 \mu G$ at the Solar radius. On the other hand, from Faraday rotation of pulsars and radio sources, Han et al. (2006) derived a regular field strength of $2.1 \pm 0.3 \mu G$ at the Sun position. Possible explanations for the difference between the equipartition estimate and the value inferred from pulsar data were discussed in Heiles (1996) and Beck et al. (2003). Since our aim is to place upper limits on the magnetic effects, we will take the value derived from polarization measurements, $\bar{B}_\odot \equiv \bar{B}_\varphi(R_\odot) \approx 4 \mu G$, as a generous value.

The radial profile of $\bar{B}_\varphi$ is not well constrained by observations. In the inner Galaxy ($3 \text{kpc} < R < R_\odot$), the ordered magnetic field gets stronger at smaller Galactocentric radius, probably as $R^{-1}$ or $R^{-2}$ (Heiles 1996). Han et al. (2006) used an exponential function to fit the ordered magnetic field and found a scale radius of $8.5 \pm 4.7 \text{kpc}$ in the radial interval between $3 \text{kpc}$ and $R_\odot$. For the outer Galaxy ($R > R_\odot$), there is no quantitative estimate of its exact $R$ dependence, except that $\bar{B}_\varphi \lesssim \bar{B}_\text{tot}$. As already said, if the magnetic pitch angle is assumed to be constant with $R$, then $\bar{B}_\varphi \propto R^{-1}$. At $R < 2R_\odot$, this radial decay is consistent with WMAP7 22 GHz data (Jansson & Farrar 2012).

In order to illustrate how the results depend on the assumptions, we will explore four different representative magnetic configurations (see Figure 2). In model A, we will assume that $\bar{B}_\varphi$ declines exponentially with $R$, in the outer Galaxy ($R > R_\odot$), with the same scalelength as $\bar{B}_\text{tot}$:

$$B_\varphi(R) = \bar{B}_\odot \exp\left(-\frac{R - R_\odot}{R_B}\right),$$

with $\bar{B}_\odot = 4 \mu G$ and $R_B = 12 \text{kpc}$. As a consequence,
the ratio of the regular magnetic field to the total magnetic field, $\eta$, is constant with radius for $R > R_0$, having a value of $\sim 0.6$. This is a well motivated possibility because constant values for $\eta$ with galactocentric distance have been derived in external galaxies. For instance, in the case of M31, Fletcher et al. (2004) derived $\eta \approx 0.7$ in the radial range 8 to 14 kpc. A rather constant value of $\eta$ within $R < 6$ kpc was found by Beck (2007) for the galaxy NGC 6946. In M33, Tabatabaei et al. (2008) inferred a value of $\eta \approx 0.45$ independent of radius within $R < 7$ kpc.

In a second type of magnetic profiles (labeled as models B1 and B2), we will adopt the same dependence for the azimuthal field of our Galaxy as in Ruiz-Granados et al. (2012):

$$B_\phi(R) = \frac{(R_l + R_0)B_{0,\phi}}{R_l + R}, \quad (9)$$

where $B_{0,\phi} = 4 \mu G$ and $R_l$ is, in principle, a free parameter. To facilitate comparison with previous work, we will take $R_l = 14$ kpc. Models B1 and B2 have the same regular magnetic field as given in Eq. (9) but differ in the random magnetic component. In model B1, we will assume that $\eta$ is constant with radius, and has a value of 0.66, rather similar to model A. Thus, $\langle b^2 \rangle = (\eta^2 - 1)B_{0,\phi}^2 = 1.3B_{0,\phi}^2$. In model B2, the mean square turbulent field $\langle b^2 \rangle$ is obtained as the difference between the total magnetic field as inferred from synchrotron emission and the regular magnetic field, that is $\langle b^2 \rangle = B_{tot,\phi}^2 - B_{0,\phi}^2$, where $B_{tot,\phi}$ is given in Eq. (7) with $B_{tot,\phi} = 6.9 \mu G$.

Finally, we consider a fourth model (labeled as model C) in which we assume that there is equipartition between the magnetic pressure in the random field and the dynamical pressure, that is $P_b = P_g$ at any radius in the range $R_0 < R < 2R_0$. This is expected in turbulent discs where turbulent motions in the gas tangle the magnetic field. The equipartition condition determines $\langle b^2 \rangle$ as a function of radius. Once $\langle b^2 \rangle$ is derived, the coherent magnetic field $B_\phi$ is then obtained as $B_{0,\phi}^2 = B_{tot,\phi}^2 - \langle b^2 \rangle$.

Figure 2 shows the radial profiles for both the strength of the azimuthal large-scale magnetic field and the strength of the small-scale random field $\langle b^2 \rangle^{1/2}$, for the different models. We have assumed that $R_0 = 8.5$ kpc. Note that the magnetic profiles in model C depend on the adopted midplane H i density; to make easier the discussion, we show the magnetic profiles for our reference KD density profile. For comparison, we also plot the total magnetic field as derived from synchrotron emission (Beck et al. 1996; Beck 2001; Ferrière 2001). By construction, models A, B2 and C fit very well the strength of the total magnetic field at $R > 7$ kpc. Bearing in mind that the error in the determination of $B_{tot,\phi}$ from synchrotron emission data is 30%, we can see that models B1 are compatible with it at $R > 7$ kpc.

In model A, the azimuthal magnetic field varies between $4 \mu G$ at $R_0$ to $2.0 \mu G$ at $2R_0$, and has $\eta \approx 0.6$ constant with radius. In model B1, $B_\phi$ varies between $4 \mu G$ and $2.9 \mu G$, and $\eta$ is also constant with radius $\eta \approx 0.66$. Model B2 has the same azimuthal magnetic field as model B1 but $\eta$ increases radially from 0.58 at $R_0$ to 0.9 at $2R_0$. In model C plus the KD density profile, the azimuthal magnetic field varies between $4.6 \mu G$ at $R_0$ to $3.1 \mu G$ at $2R_0$, and $\eta$ increases from 0.68 to 0.9. Finally, in model C plus the NS density profile, $B_\phi$ varies between $6.3 \mu G$ at $R_0$ to $3.4 \mu G$ at $2R_0$, and $\eta \geq 0.9$ at any radius between $R_0$ and $2R_0$. Thus, in models B2 and C, the magnetic field at $2R_0$ is dominated by the regular component. We should note here that the different radial profiles for $B_\phi$ are realistic for a finite radial interval, $R_0 < R < 2R_0$, but there is no reason to assume that they are equally realistic at large $R$ (e.g., Sánchez-Salcedo & Reyes-Ruiz 2004).

### 4 ESTIMATING THE CONTRIBUTIONS TO THE ROTATION CURVE

#### 4.1 Results

We will start our discussion by considering the effect of the azimuthal magnetic field in the rotation curve, $v_{rot}^2$. Figure 3 shows $v_{mag}^2$ as a function of $R$ for the different models. We see that the shape of $v_{mag}^2$ as a function of $R$ depends critically on the adopted profile for $B_\phi$. In models A and C, $v_{mag}^2$ is positive at small galactocentric radii but turns out to negative values beyond a certain radius. Using Eqs. (2) and (8), it is simple to show that, in model A, $v_{mag}^2 < 0$ at $R > R_B$. On the other hand, $v_{mag}^2$ is positive at any radius in models B1 and B2. The sign of $v_{mag}^2$ at $2R_0$ is model-dependent and there is no clear preference for a model with $v_{mag}^2 > 0$ over another with $v_{mag}^2 < 0$ at $2R_0$. Since, according to Equations (2) and (3), the strength of the radial force (per unit of mass) by magnetic effects and cosmic rays is proportional to $\rho^{-1}$, the exact values for $v_{mag}^2$ and $v_{rot}^2$ depend on the H i gas model. If the NS profile is used, $v_{mag}^2$ at $2R_0$ ranges between $-200$ km s$^{-2}$ to 400 km s$^{-2}$ depending on the model, whereas it varies between $-100$ km s$^{-2}$ to 220 km s$^{-2}$ when the KD profile is used. Therefore, it has a minor effect on the rotational velocity of the gas; the corresponding correction is $\sim 0.5 - 1$ km s$^{-1}$ at $2R_0$. At this galactocentric radius, the correction by $v_{mag}^2$ is comparable to the correction by the kinetic pressure of the gas. For instance, consider the H i gas model of KD. The pressure correction is

$$\frac{R_dP_b}{\rho \, dR} = -\frac{R}{R_H} \sigma^2, \quad (10)$$

which is $\simeq -260$ km s$^{-2}$ at $2R_0$ (using $R_H = 3.15$ kpc and $\sigma = 7$ km s$^{-1}$, see §2 and §3). In the what follows, we discuss and quantify the relative importance of $v_{rot}^2$ as compared to $v_{mag}^2$.

Figures 4 and 5 show the contributions to the tangential velocity of the gas, $v_t^2 - v_c^2$, when the magnetic pressure $P_b$ is included, for different combinations of $P_g$ and $P_{CR}$. Obviously, the curves with $\sigma = 0$ and $\mu = 0$ correspond to $P_b = P_{CR} = 0$ [see Eqs. (4) and (6)]. On the other hand, curves with $\sigma = 7$ km s$^{-1}$ and $\mu = 0$, include the kinetic pressure of the gas and the magnetic forces (i.e., including both the azimuthal and the small-scale components), but not the pressure by cosmic rays. The case $\mu = 1$ describes a situation in which the pressure by cosmic rays is in equipartition with the magnetic pressure. For instance, Ferrière (2001) quotes a midplane value of $\mu = 1.28$ in the vicinity of the Sun. In order to interpret correctly Figures 4 and 5, remind that when $v_t^2 - v_c^2$ is negative, it means that the MHD terms provide support to the disc and, hence, the measured tangential velocity lags the circular velocity of a test particle, i.e. $v_\phi < v_c$. 

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Figure 3. Magnetic contribution to the rotation curve due to the azimuthal magnetic field, \(v_{\text{mag}}^2\), as a function of radius, for models A, B1, B2 and C, using the KD profile (upper panel) and the NS profile (lower panel). The gas rotates at a speed of \(v_\phi = (v_c^2 + v_P^2 + v_{\text{mag}}^2)^{1/2}\).

In our models, the strength of the random field \(\langle b^2 \rangle^{1/2}\) declines with radius and, therefore, the magnetic pressure by this small-scale magnetic field produces a force outwards, giving support to the disc (slower rotation). In models A, B2 and C, this outward force is able to compensate any pinching effect by the azimuthal magnetic field. Thus \(v_\phi^2 - v_c^2 < 0\) at any galactic radius > 7 kpc.

As can be seen in Figure 4 and 5, the effect of magnetic fields in the rotation curve is less important in model B1, even though it presents the highest \(B_{\text{tot}}\)-values at 2\(R_\odot\) (Figure 2). The reason is that the radial profiles of both \(B_\phi\) and \(\langle b^2 \rangle^{1/2}\) in model B1 are more shallow and, thus, the confining effect of \(B_\phi\) is partly balanced by the radial support of the random fields. In model B1, the outward force by the radial gradient of \(P_\phi\) is in balance with the inward pinching force created by \(B_\phi\) at a radius

\[
R_{B1} = \frac{\eta^2}{1 - \eta^2} R_t. \tag{11}
\]

For \(R_t = 14\) kpc and \(\eta = 0.66\), this balance occurs at \(R = 10.8\) kpc. In order to have \(R_{B1} > 20\) kpc in this kind of models, we need \(\eta > 0.76\). In model B2, the equality between the gradient of \(P_\phi\) and the inward force by \(B_\phi\) occurs in a more inner radius. Model B2 illustrates the role of the magnetic pressure by the random field; even if \(\eta \approx 0.9\) at 2\(R_\odot\), the contribution of the random field to \(v_\phi^2 - v_c^2\), which is \(R\rho^{-1} dP_\phi/dR\), is three times larger than \(v_{\text{mag}}^2\).

As already mentioned, the contribution of the kinetic pressure of the gas to the rotation velocity is comparable in magnitude to the magnetic terms and, therefore, it must be
Figure 4. Difference between $v_\phi^2$ and $v_c^2$ for models A, B1, B2 and C, and different combinations of $\sigma$ and $\mu$. For the midplane density we have used the reference KD profile. A negative (positive) value means that the gas rotates slower (faster) than the gravitational circular velocity. Cases with $\sigma = 0$ correspond to ignoring the kinetic pressure of the gas, whereas models with $\mu = 0$ assume that the radial force by the pressure of cosmic rays is null.

It is interesting to note that Figures 4 and 5 show that the correction to the rotation curve by magnetic fields and cosmic rays increases steeply with galactocentric radius. In particular, if we extrapolate model A to larger galactocentric distances and use the NS gas profile, we would find that the gas at $3R_\odot$ would rotate $\sim 40$ km s$^{-1}$ slower than a test particle on a circular orbit (see Figure 7). However, the magnetic profiles used in our models are based on synchrotron observations at $R < 2R_\odot$. Thus, there is no reason to assume that these profiles are valid at any $R$. In order to explore how $v_\phi$ depends on the adopted magnetic profile, Figure 7 shows $v_\phi$ in models with $\eta = 0.6$ (constant with radius), $\sigma = 7$ km s$^{-1}$ and $\mu = 1$, where the azimuthal magnetic field is described by a double piece-wise exponential profile; $R_B = 12$ kpc at $R < 2R_\odot$ kpc (as in model A) but having a steeper
radial decline beyond $2R_\odot$. We see that when $R_B \approx 6$ kpc in the outer disc ($R > 2R_\odot$), the MHD terms produce a shift in the azimuthal velocity of $\sim 15$ km s$^{-1}$ (the KD density profile was used). On the other hand, if the outer magnetic field declines with a scalelength of 3 kpc, the radial support by cosmic rays and magnetic fields leads to $v_r - v_\phi > 5$ km s$^{-1}$ only between $2R_\odot$ and $2.6R_\odot$. Beyond $2R_\odot$, empirical determinations of the strength/topology of magnetic fields and the H$\text{I}$ rotation curve are challenging and, hence, there is no means of testing the effect of magnetic fields on the H$\text{I}$ azimuthal velocity. Still, one has to consider the vertical confinement of the magnetic fields. Consider model A with a single exponential scalelength of $R_B = 12$ kpc. At $3R_\odot$, the cosmic ray plus magnetic pressure in the midplane is $\sim 0.2 \times 10^{-12}$ dyn cm$^{-2}$. Since the weight of neutral gas cannot account for this large pressure, an additional coronal component should be invoked to provide vertical support. Following the same analysis as Cox (2005) did at the solar neighbourhood, we find that a component with density $0.003$ cm$^{-3}$ exp(-$|z|/z_g$), with $z_g \sim 10 - 12$ kpc, and temperature of $\sim 3 \times 10^5$ K (at $3R_\odot$) could confine the cosmic rays and magnetic field at $3R_\odot$. This coronal layer would probably produce excessive X-ray emission and the total column density of OVI would be orders of magnitude more than is observed looking out of the galactic plane (Cox 2005). It is more simple to assume that beyond the stellar truncation radius, stellar formation is almost nonexistent, so energy in cosmic rays and magnetic fields decays faster with $R$ because the energy input into these components from stellar processes is likely to be less important (e.g., Olling & Merrifield 2000).

### 4.2 Other magnetic models

We have shown that in all our models, the magnetic fields provide support to the disc when the magnetic pressure by the random field component is included (at least beyond a galactocentric distance of 10.8 kpc). If we had adopted $B_\phi = \ldots$
2\mu G instead of 4\mu G, the magnetic pressure by the random field would increase by a factor of 1.6 (in order to account for the synchrotron radio emission), providing more radial support to the disc. Consider, for instance, model A with the KD profile for \( \sigma = 7 \text{ km s}^{-1} \) and \( \mu = 1 \). At \( 2R_\odot \), \( v_P^2 + v_{\text{mag}}^2 \) would change from \(-1850 \text{ km}^2 \text{ s}^{-2}\) for \( B_\odot = 4\mu G \), to \(-2250 \text{ km}^2 \text{ s}^{-2}\) if a lower value \( B_\odot = 2\mu G \) is adopted.

In order for the gas to rotate faster than a test particle, we need \( v_P^2 + v_{\text{mag}}^2 > 0 \). This is possible only in models in which the radial gradients in the pressure created by the random magnetic field and cosmic rays are small. To explore this possibility, we have treated \( R_l \) in model B1 as a free parameter and allowed to vary until \( v_P^2 + v_{\text{mag}}^2 \) reaches a maximum at \( 2R_\odot \). We found that the maximum occurs when

\[ R_l = \begin{cases} \text{dashed line} & \text{at } R = 2R_\odot \text{ for } B_\odot = 4\mu G, \\ \\ \text{dotted line} & \text{at } R = 2R_\odot \text{ for } B_\odot = 2\mu G. \end{cases} \]
Figure 6. Total gravitational circular velocity \( v_c \) (solid line) together with the tangential velocity of the gas \( v_\phi \) after including magnetic fields, gas pressure and cosmic rays in model A (dotted lines). The upper dotted line was derived using the HI density profile from KD, whereas the lower dotted line was calculated using the profile derived in NS. Symbols indicate the observed rotational velocity of HI gas taken from Ruiz-Granados et al. (2012). The contribution of the different mass components to the rotation curve are also shown: bulge (dot-dashed line), stellar disc (long dashed line), gas (short dashed line) and dark halo (triple dot-dashed line). We see that the difference between \( v_\phi \) and \( v_c \) is small as compared to the observational uncertainties.

Figure 8. Magnetic contribution to the rotation curve due to the azimuthal magnetic field, \( v_{\text{mag}} \), as a function of radius, for \( R_\odot = 8 \) kpc, \( B_\odot = 3 \mu G, R_H = 4 \) kpc and \( R_l = 14.2 \) kpc. These parameters correspond to the best fit model denoted by ISO+MAG in Ruiz-Granados et al. (2012). The values of \( v_{\text{mag}} \) were overestimated by a factor of 18 in Ruiz-Granados et al. (2012).

4.3 Comparison with previous works

Ruiz-Granados et al. (2012) claim that a significant improvement of the fit to the rotation curve of the Milky Way is obtained when magnetic fields are considered. In their model, they only include the azimuthal component and ignore any contribution from the turbulent component of the magnetic field, kinetic pressure or cosmic rays. They use the same expression for the azimuthal magnetic field as that given in Eq. (9) and find the values of \( R_l \) that provide the best fit to the shape of the rotation curve of the Milky Way. They find \( R_l = 14.2^{+2.04}_{-1.7} \) kpc in a mass model with a pseudo-isothermal dark halo and \( R_H = 16.5 \pm 1.1 \) kpc if there is no dark matter at all within a sphere of radius \( 2R_\odot \).

The exact values for \( B_\odot, \rho_\odot, R_\odot \) and \( R_H \) in Ruiz-Granados et al. (2012) differ from those adopted in this paper, but only slightly. They used \( B_\odot = 3 \mu G, R_\odot = 8 \) kpc, \( R_H = 4 \) kpc, a column density of gas at the Sun position of \( 10M_\odot \text{pc}^{-2} \), and a constant vertical scale height of \( 0.2 \) kpc across the disc. Figure 8 shows \( v_{\text{mag}} \), as a function of \( R \), for \( R_\odot = 14.2 \) kpc and the abovementioned values for \( B_\odot, R_\odot, R_H \) and \( \rho_\odot \). A comparison with the corresponding curve reported in figure 2 of Ruiz-Granados et al. (2012) dictates that \( v_{\text{mag}} \) was overestimated by a factor of 18. For a model with \( R_l = 16.5 \) kpc, we obtain \( v_{\text{mag}} \approx 9.5 \) km s\(^{-1}\) at \( 2R_\odot \), which is too small to match the circular velocity without any dark matter (a value of \( v_{\text{mag}} \approx 180 \) km s\(^{-1}\) is required to do so). Even if we neglect the radial support by the cosmic-ray pressure and by the turbulent magnetic field, and only include the kinetic pressure of the gas, we infer \( v_\phi^2 + v_{\text{mag}}^2 \approx -100 \) km s\(^{-2}\) at \( 2R_\odot \) in this model (\( R_l = 16.5 \) kpc). That is unable to provide the desired effect in the rotation curve.

5 CONCLUSIONS

How magnetic effects alter the overall rotation curve of gas in galaxies is a reoccurring theme in the literature. In a re-
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cent paper, Ruiz-Granados et al. (2012) claim that magnetic field forces provide the simplest way to explain the peculiar rising-up of the rotation curve in our Galaxy. Our Galaxy offers a unique opportunity for studying the three-dimensional distribution of neutral gas and magnetic fields in a detail unobtainable in external galaxies. We have explored a range of plausible models to quantify the contribution to the radial support by kinetic gas pressure, magnetic fields, and cosmic rays. We restrict ourselves to the interval $R_\odot < R < 2R_\odot$, because beyond $2R_\odot$ there are no determinations of the strength of the magnetic field. We have shown that, even adopting magnetic field configurations with a regular field of $\sim 3\mu G$ at $2R_\odot$, the rotation curve of our Galaxy is not appreciably altered by magnetic effects. Turbulent motions, cosmic rays and the random small-scale component of the galactic magnetic fields act as pressure, giving support to the disc and, therefore, leading to a rotation a few km s$^{-1}$ slower than the gravitational circular speed. Given the large uncertainties in the rotation speed of the outer parts of the Galaxy, of $\pm 25$ km s$^{-1}$, they can be safely ignored at least within $R < 2R_\odot$.

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