Magnetic field effects on the ISM structure and galactic outflows

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Abstract. The role of magnetic fields in the multi-phase interstellar medium (ISM) is explored using magnetohydrodynamic (MHD) simulations that include energy injection by supernova (SN) explosions and allow for dynamo action. Apart from providing additional pressure support of the gas layer, magnetic fields reduce the density contrast between the warm and hot gas phases and quench galactic outflows. A dynamo-generated, self-consistent large-scale magnetic field affects the ISM differently from an artificially imposed, unidirectional magnetic field.

Keywords. MHD, ISM: kinematics and dynamics, ISM: magnetic fields, ISM: structure, ISM: jets and outflows, galaxies: ISM, galaxies: magnetic fields, galaxies: spiral

Our understanding of global magnetic effects in spiral galaxies remains limited despite a growing appreciation of their significance. Of particular importance is the role of magnetic fields (and of the cosmic rays controlled by them) in galactic outflows and the resulting feedback of star formation on galactic evolution. Studies of magnetic effects in the ISM are hindered by its complex, multi-phase structure and by the complexity of the conversions between kinetic and magnetic energies in random flows (addressed by dynamo theory). Furthermore, observational estimates of magnetic field strength are restricted to the warm and cold ISM phases whereas galactic outflows are driven by the hot gas.

Simulations of the SN-driven ISM have reached a sufficient level of physical adequacy to use them as numerical experiments to explore various effects inaccessible to direct observations. Among such simulations, only a few contain the ingredients (especially differential rotation and stratification) required to simulate large-scale dynamo action (Gressel \textit{et al.} 2008, Gent \textit{et al.} 2013).

We analyse a numerical model of the local ISM, developed by Gent \textit{et al.} (2013), that produces an exponentially growing magnetic field at a scale comparable to the size of the computational domain (1 kpc), starting from a dynamically negligible seed magnetic field and reaching a statistically steady state where magnetic, random kinetic and thermal energy densities are comparable in magnitude. The ISM is represented in three phases separated in terms of specific entropy (or density and temperature) while magnetic field consists of both the mean and fluctuating parts. The SN activity supports a systematic outflow away from the mid-plane. Comparing the ISM properties in the initial and late stages, where magnetic fields are, respectively, negligible and dynamically significant, we can assess the role of magnetic fields in the structure and properties of the ISM. Both stages represent statistically steady states without and with magnetic field, respectively. The most significant magnetic effects are as follows (Evirgen \textit{et al.} 2018).
Table 1. Fits to the outflow speed, of the form (1), at various distances $|z|$ from the mid-plane.

| Distance to the mid-plane [kpc] | $V_0$ [km s$^{-1}$] | $\xi$ | $n$ |
|-------------------------------|------------------|------|----|
| $|z| < 0.15$                  | 11               | 4.4  | 2.7 |
| $0.15 < |z| < 0.3$             | 17               | 2.4  | 2.4 |
| $0.3 < |z| < 0.6$             | 17               | 3.9  | 1.9 |
| $0.6 < |z| < 1.0$             | 11               | 2.5  | 1.5 |

The multi-phase structure. In agreement with the topological analysis of Makarenko et al. (2018), we show that strong local magnetic fields efficiently confine SN remnants, leading to a lower fractional volume of the hot gas (decreasing from 25% to 9% near the mid-plane as magnetic field grows), its lower temperature and higher density (by a factor of 3–10), whereas the total mass of the hot gas varies little. As a result, the density contrast between the warm and hot phases is reduced by almost an order of magnitude.

Outflow speed. As the magnetic field grows, the mean speed of the systematic gas outflow $V_z$ away from the mid-plane decreases from about 20 km s$^{-1}$ for a weak magnetic field to just a few km s$^{-1}$ when magnetic field becomes strong. The decrease is rather abrupt: $V_z$ is only weakly dependent upon the magnetic field when the mean magnetic field $B$ is weaker than that corresponding to energy equipartition with the random gas flow, $B_{eq} = (4\pi \rho v^2)^{1/2}$, where $\rho$ is the gas mass density and $v$ the root-mean-square random speed. However, it then decreases as a rather high power of $B$,

$$V_z \approx V_0 [1 + \xi (B/B_{eq})^n]^{-1},$$

(1)

with the values of $V_0$, $\xi$ and $n$ given in Table 1. In similar simulations, Bendre et al. (2015) also find that the outflow is suppressed by the large-scale magnetic field although they find a weaker dependence of $V_z$ on $B$ with $n = 2$ (and $V_0 \approx 13$ km s$^{-1}$ and $\xi \approx 1.5$ at $|z| = 0.8$ kpc). The value of $V_0$ depends on the supernova rate $\nu$; Bendre et al. (2015) find $V_0 \propto \nu^{0.4}$. We note that the value of $V_0$ at large $|z|$ is likely to be sensitive to the size of the computational domain: simulations of Bendre et al. (2015) in $|z| \leq 2$ kpc find larger values of $V_z$ at $|z| \approx 1$ kpc than in our model where $|z| \leq 1$ kpc.

The importance of dynamo action. The sensitivity of the ISM structure and outflow speed to magnetic field is only obtained in simulations that admit large-scale dynamo action (Bendre et al. 2015, Evirgen et al. 2018). Broadly similar simulations where dynamo action is precluded and a unidirectional magnetic field is imposed (e.g., de Avillez & Breitschwerdt 2005, Henley et al. 2015, Girichidis et al. 2016) do not reveal any similar magnetic effects. This contradiction requires careful analysis; it suggests rather strongly that dynamo action that produces a large-scale magnetic field responding self-consistently to the ISM environment is essential to capture reliably magnetic effects on the ISM.

References

Bendre, A., Gressel, O., & Elstner, D. 2015, AN, 336, 991

de Avillez, M. A., & Breitschwerdt, D. 2005, A&A, 436, 585

Evirgen, C. C., Gent, F. A., Shukurov, A., Fletcher, A., & Bushby, P. 2018, MNRAS, submitted

Gent, F. A., Shukurov, A., Fletcher, A., Sarson, G. R., & Mantere, M. J. 2013, MNRAS, 432, 1396

Girichidis, P., Walch, S., Naab, T., Gatto, A., Wünsch, R., Glover, S. C. O., Klessen, R. S., Clark, P. C., Peters, T., Derigs, D., & Baczyński, C. 2016, MNRAS, 456, 432

Gressel, O., Elstner, D., Ziegler, U., & Rüdiger, G. 2008, A&A, 486, L35

Henley, D. B., Shelton, R. L., Kwak, K., Hill, A. S., & Mac Low, M.-M. 2015, ApJ, 800, id. 102

Makarenko, I., Shukurov, A., Henderson, R., Rodrigues, L. F. S., Bushby, P., & Fletcher, A. 2018, MNRAS, 475, 1843