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Synchrotron radiation from molecular clouds

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Observations of the properties of dense molecular clouds are critical in understanding the process of star-formation. One of the most important, but least understood, is the role of the magnetic fields. We discuss the possibility of using high-resolution, high-sensitivity radio observations to measure the *in-situ* synchrotron radiation from these molecular clouds. If the cosmic-ray (CR) particles penetrate clouds as expected, then we can measure the B-field strength directly using radio data. So far, this signature has never been detected from the collapsing clouds themselves and would be a unique probe of the magnetic field. Dense cores are typically ~ 0.05 pc in size, corresponding to $\sim$arcsec at $\sim$kpc distances, and flux density estimates are $\sim$ mJy at 1 GHz. They should be detectable, for example with the Square Kilometre Array.

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PoS(CRISM2014)036

1. Introduction

It is very difficult to measure the detailed properties of dense molecular clouds, and perhaps the most difficult property is the magnetic field - its strength and geometry. The most common method is via Zeeman splitting of radio-frequency HI, OH, and CN lines or masers, which gives the magnetic field strength along the line-of-sight, $B_{\rm los}$ (Crutcher 2012). Other methods are also difficult, which include using measurements of optical and near-infrared polarisation (extinction along the line-of-sight) and sub-mm polarised thermal dust emission (difficult from the ground) (Poidevin et al. 2013).

An alternative method of probing the magnetic field is via synchrotron radiation (Brown & Marscher 1977; Marscher & Brown 1978; Orlando & Strong 2013), which has rarely been mentioned in the literature in relation to molecular clouds. Synchrotron radiation is produced primarily by relativistic CR electrons when decelerated by magnetic fields. The intensity of synchrotron radiation depends only on the number and energy spectrum of CR electrons and the magnetic field strength perpendicular to the line-of-sight. We know the energy spectrum of CRs (Ackermann & et al. 2012), at least on average at energies of relevance to radio synchrotron emission ($\sim$GeV), and we know that the CR density varies slowly throughout the Galaxy and can penetrate dense molecular clouds at these energies and above (Brown & Marscher 1977; Marscher & Brown 1978; Umebayashi & Nakano 1981).[1] Gamma-ray observations of molecular clouds probing CR protons at theses energies (via pion-decay) indicate that this is indeed the case, since the fluxes are as expected from the general interstellar CR density; electrons and protons propagate in the same way for the same rigidity, which corresponds to the same same kinetic energy in the relativistic range. Electrons lose energy more rapidly than protons but this is not a large effect for pc-size clouds. In molecular clouds, the magnetic field has been measured to be significantly amplified (Crutcher 1999). Therefore, in principle, the synchrotron intensity should give a detectable signature, which could be used as a probe of the magnetic field. This is a direct way of measuring the total magnetic field strength, including the irregular (turbulent) component, which most other indicators (Zeeman, optical polarisation) are not directly sensitive to, since they measure the regular (Zeeman) or ordered (optical polarisation) field.[2] Polarised synchrotron could provide additional information, including the ordered vs anisotropic random component and projected angle of the magnetic field on the sky.

It is therefore somewhat surprising that very little attention has been given to using synchrotron as a probe of molecular clouds. Jones et al. (2008) observed two nearby (3–4 kpc) dense cold starless cores (G333.125–0.562 and IRAS15596–5301) with ATCA at 1384 and 2368 MHz, to try to detect secondary leptons.[3] They found upper limits of ~ 0.5 mJy/beam and constrained the B-field strength to $B < 500\,\mu$G. However, this is still compatible with the scaling of $|B|$ and $n_{\rm H}$ - more

[1] There have been claims that GeV CRs cannot fully penetrate the densest clouds, thus suppressing the CR diffusion coefficient (Jones et al. 2008; Protheroe et al. 2008; Jones et al. 2011).

[2] Other indirect measures of the random component exist, such as the Chandrasekhar-Fermi method, which uses the dispersion of the measured polarisation angles to probe the magnetic field in the plane of the sky (Chandrasekhar & Fermi 1953; Watson et al. 2001; Crutcher et al. 2004). See also Hildebrand et al. (2009) and references therein for further extensions.

[3] In this article, we focus on primary CR electrons, although the conversion into secondary leptons could be significant (Dogel' & Sharov 1990).

PoS(CRISM2014)036

sensitivity is required. Protheroe et al. (2008); Jones et al. (2011) only found upper limits from Sgr B2 after subtraction of the dominant thermal emission. The only possible candidate so far is from the G0.13–0.13 molecular cloud detection, which was detected at 74 MHz, with an associated CO hotspot (Yusef-Zadeh et al. 2013). However, a displacement between the radio position and molecular core suggests it could be from a different region of space.

These non-detections can be partly understood due to the relatively weak (typically mJy or less) signal that is expected to come from *in-situ* synchrotron emission inside the cloud itself. This is due to the fact that on large scales ($\sim$ 1–10 pc), the magnetic fields in clouds appear to be relatively weak ($\sim 10\,\mu$G) while strong fields are on scales much smaller than this ($\sim$ 0.05 pc) resulting in a weak flux signal. Also, most of the collapsing clouds ("cores") are located at low latitudes where there is significant confusion from background synchrotron and free-free emission. Nevertheless, high resolution and high sensitivity observations could allow molecular clouds to be mapped in some sight-lines. This may also shed light on CR penetration into the densest clouds, which sometimes appear as a radio dark cloud (RDC) (Yusef-Zadeh 2012). Note that recent high-resolution 5/20 GHz JVLA observations of the Galactic centre cloud G0.216+0.016 have detected compact ($<$ 2.2 arcsec, or sub-pc) non-thermal sources, which may be the signature of in-situ synchrotron radiation from secondary CR electrons (Jones 2014).

In this chapter we briefly review the physics of synchrotron radiation and magnetic fields, and the relation that appears to exist between them in molecular clouds.

2. Synchrotron radiation

Synchrotron radiation is emitted primarily by relativistic cosmic-ray electrons spiralling in the Galactic magnetic field. It is this radiation that often dominates the radio sky at frequencies below a few GHz. The theory of synchrotron radiation is well understood. For a power-law distribution of electron energies,

$$N(E)dE = N_0 E^{-\gamma} dE \;, \tag{2.1}$$

the emissivity, j_ν, of synchrotron radiation is given by

$$j_\nu \propto N_0 B^{(\gamma+1)/2} \nu^{(1-\gamma)/2} \;, \tag{2.2}$$

where B is the magnetic field strength, N_0 is the number density of electrons, γ is the power-law index of electron energies, and ν is the observing frequency. Highly Relativistic (GeV and above) CR electrons are expected to penetrate dense clouds freely (Umebayashi & Nakano 1981). If the electron energy spectrum is a power-law with index γ then the observed synchrotron radio emission spectrum is also a power-law with slope $\alpha = (\gamma-1)/2$ (flux density $S \propto \nu^{-\alpha}$). The cosmic ray electron spectrum at energies of order GeV can be approximated by a power-law with slope $\gamma \approx$ 2.5–3.0 (Strong et al. 2011), which corresponds to a synchrotron index $\alpha \approx$ 0.8 to 1. This is indeed the typical spectral index observed at GHz frequencies (Reich & Reich 1988; Platania et al. 1998).

It can also be seen that the emissivity scales as $B^{(\gamma+1)/2}$, which means it goes as approximately B^2. This is of relevance to molecular cloud collapse, since the magnetic field is expected

PoS(CRISM2014)036

to be significantly amplified during collapse, and thus could give a detectable signal from *in-situ* synchrotron radiation.

3. Magnetic fields in collapsing clouds

The role that magnetic fields play in the processes of molecular cloud and star formation has been debated for decades. Theoretical studies suggest that magnetic fields play an important if not crucial role in the evolution of interstellar clouds and the formation of stars. In summary, magnetic fields provide magnetic support against cloud collapse. There are various models of star formation and the details of the magnetic field are always important. For example, the core of a cloud can become unstable due to ambipolar diffusion, collapsing to form stars, while the envelope can remain in place. The connection between the core and the surrounding envelope by magnetic field lines can transfer angular momentum outward and make it possible for stars to form. Other star formation models have the dissipation of magnetised turbulence as a controlling factor in star formation. Measuring the magnetic field is a key observation that allows us to infer i) whether supersonic motions are Alfvenic, and ii) the relative importance of the gravitational, kinetic and magnetic densities in dense clouds (Crutcher 1999). These observables thus allow us to test star formation models such as ambipolar diffusion and turbulence (Crutcher 2012; Lazarian et al. 2012).

Detailed measurements of the magnetic field strength and alignment are difficult. However, in recent years, direct measurements of the magnetic field strength have been made. Most notable are Zeeman splitting data (Crutcher 1999; Crutcher et al. 2010) and also sub-mm thermal dust emission (Poidevin et al. 2013). Detailed studies of Zeeman splitting from a sample of molecular clouds indicate that the thermal-to-magnetic pressure $\beta_p \approx 0.04$, implying that magnetic fields are important. Moreover, the measurements showed that magnetic field strengths scale with gas densities as $B \propto n^{\kappa} \approx 0.5$—$0.7$, as shown in Fig. 1. This is close to the theoretical value $\kappa = 0.47$ predicted by models of ambipolar diffusion (Fiedler & Mouschovias 1993). The latest value appears to be $\kappa = 0.65$ (Crutcher 2012) but there is considerable scatter in the measurement (Fig. 1); our best-fitting value applied to detections above 3σ is $\kappa = 0.54 \pm 0.05$, although there could be biases when neglecting non-detections (Crutcher et al. 2010). The large scatter may be related to the fact that Zeeman splitting is only sensitive to the regular (ordered and directional) magnetic field component along the line-of-sight[4]; the B–$n_{\rm H}$ relation may be different for turbulent fields. Furthermore, this trend only occurs above some density $n_0 \sim 300\,{\rm cm}^{-3}$, although this has still to be determined precisely. Clearly more data, and complementary probes of the magnetic field, are needed to make progress in this area.

4. Predictions for synchrotron radiation from collapsing clouds

Given that the synchrotron emissivity scales as $\sim B^2$ and B scales as $\sim n_{\rm H}^{0.6}$, it is logical that it should also scale roughly as the volume density i.e. $j_\nu \propto n_{\rm H}$. From this, one might expect low frequency maps such as the Haslam et al. 408 MHz map (Haslam et al. 1982) to be bright around giant molecular clouds (GMCs) and for molecular clouds to be very bright in high resolution

[4]It is possible to get the total B-field strength when complete line splitting is observed, which is possible with masers (Crutcher 1999).

PoS(CRISM2014)036

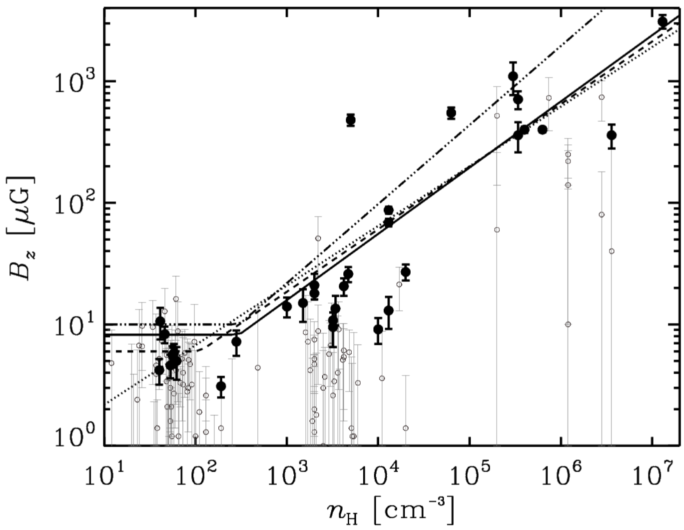

Figure 1: Zeeman splitting measurements of the magnetic field of a number of molecular clouds, plotted against the volume density of molecular gas. Significant ($> 3\sigma$) detections are shown as black filled circles (data taken from Crutcher et al. 2010). There is considerable scatter, yielding various slopes (see overplotted lines) depending on the exact model being fitted. The power-law slope between B_z and density n_H is in the range $\kappa \approx 0.5$–0.7. Our best fit (solid line) for detections greater than 3σ significance yields $\kappa = 0.54 \pm 0.05$ above $n_H = 300\,\mathrm{cm}^{-3}$. Preliminary figure reproduced from a forthcoming publication (Strong et al. 2014).

observations (e.g. VLA, ATCA). We will now use the observed scaling relation of B with n_H to estimate the flux density expected for typical molecular clouds.

We assume that the ambient CR electrons pervade molecular clouds unimpeded and a power-law distribution of CR electron energies with slope γ, and a power-law relation with slope κ between density n_H and B-field strength B above a value $n_0 = 300\,\mathrm{cm}^{-3}$. The synchrotron calculation uses the full formulation using Bessel functions and integrating over the electron spectrum[5]. Using the CR flux model of Strong et al. (2011), the predicted brightness temperature (in mK) at 408 MHz can be be approximated by (Strong et al. 2014):

$$\left(\frac{T_{\mathrm{pred}}}{\mathrm{mK}}\right) = 2.8 \times 10^3 \left(\frac{N_{\mathrm{H}}}{10^{23}\,\mathrm{cm}^{-2}}\right)\left(\frac{n}{300\,\mathrm{cm}^{-3}}\right)^{\kappa(\gamma+1)/2-1}, \tag{4.1}$$

where N_H is the column density (cm^{-2}) and n_H the volume density (cm^{-3}). This corresponds to a predicted integrated flux density (in mJy) at 1 GHz, for a source subtending a solid angle Ω_{src},

$$\left(\frac{S_{\mathrm{pred}}}{\mathrm{mJy}}\right) = 6.6 \times 10^6 \left(\frac{\Omega_{\mathrm{src}}}{\mathrm{sr}}\right)\left(\frac{N_{\mathrm{H}}}{10^{23}\,\mathrm{cm}^{-2}}\right)\left(\frac{n}{300\,\mathrm{cm}^{-3}}\right)^{\kappa(\gamma+1)/2-1}. \tag{4.2}$$

Table 1 lists some example molecular clouds, using data from Crutcher (1999), with predicted flux densities at 1 GHz. We have used the $B - n_H$ relation above with $\kappa = 0.6$, assume a synchrotron frequency spectral index $\alpha = 1.0$ ($\gamma = +3.0$), and $\Omega_{\mathrm{src}} = \pi/4 \times \theta^2$. Dense molecular clouds have typical densities of 10^5–$10^6\,\mathrm{cm}^{-3}$ in H_2 and linear sizes of ~ 0.05 pc. This gives column densities of $\sim 10^{23}\,\mathrm{cm}^{-2}$. For typical distances of a $\sim$kpc, this corresponds to angular sizes of ~ 10 arcsec.

[5]Software available at http://sourceforge.net/projects/galpropsynchrotron

PoS(CRISM2014)036

Table 1: Molecular cloud data from Crutcher (1999) with estimates of predicted integrated synchrotron flux density S_{GHz} (mJy) at 1 GHz based on the statistical B–n_{H} scaling law (equation 4.2) with $\kappa = 0.6$. The flux density has been scaled to 1 GHz assuming a spectral index $\alpha = -0.8$ ($\gamma = 2.6$). The brightness temperature T_{GHz} is what would be observed with a 51 arcmin beam.

Name	B_z [μG]	n_{H_2} [cm^{-3}]	R [pc]	D [kpc]	θ [arcsec]	T_{GHz} [mK]	S_{GHz} [mJy]
W3 OH	3100	6.31×10^6	0.02	2.0	4.0	0.06	0.05
DR21 OH1	710	2.00×10^6	0.05	1.8	11.2	0.30	0.27
Sgr B2	480	2.51×10^3	22.0	7.9	1149	1200	1000
M17 SW	450	3.16×10^4	1.0	1.8	236	31	27.0
W3 (main)	400	3.16×10^5	0.12	2.0	24.3	0.49	0.43
S106	400	2.00×10^5	0.07	0.6	48.1	0.74	0.65
DR21 OH2	360	1.00×10^6	0.05	1.8	11.2	0.14	0.13
OMC-1	360	7.94×10^5	0.05	0.4	50.3	2.3	2.0
NGC2024	87	1.00×10^5	0.2	0.4	196	14.6	13.0
W40	14	5.01×10^2	0.05	0.6	34.4	0.04	0.03
ρ Oph 1	10	1.58×10^4	0.03	0.1	91.7	0.14	0.13

It can be seen that many of these sources have predicted flux densities of ~mJy. It is interesting to see that a few sources have much larger predicted flux densities (e.g. Sgr B2 at about 1 Jy). However, one has to be careful since these are due to the large physical size assumed (22 pc for Sgr B2). In practice, the collapsing clouds tend to be very small, often clustered, in a parent cloud that is much larger. The magnetic field measured in the densest regions is unlikely to apply to the entire cloud. Thus it is easy to over-estimate the flux density in this way and this appears to be why dense molecular clouds are not bright in low resolution radio surveys such as the Haslam et al. (1982) 408 MHz map. On the other hand, additional synchrotron from secondary leptons could boost the synchrotron level (Protheroe et al. 2008).

Therefore, the predicted flux densities should only be considered order-of-magnitude estimates at this point since the precise values depend very sensitively on the choice of κ and n_0 and on the observed input parameters. Furthermore, the huge scatter about this relation observed in Fig. 1 already indicates that either the measurements are not representative of the mean field, or, the simple $B - n_{\mathrm{H}}$ relationship does not hold. New observations will be crucial for testing this hypothesis.

5. Conclusions and outlook

Both existing and future radio telescopes should be able to detect synchrotron radiation from molecular clouds, and hence provide a new method to measure their magnetic fields. In particular the Square Kilometre Array (SKA) will be well suited for such observations. For details of the SKA prospects, see Dickinson & et. al. (2014), on which part of this article is based.

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PoS(CRISM2014)036

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PoS(CRISM2014)036