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Empirical assessment of cosmic ray propagation in magnetised molecular cloud complexes

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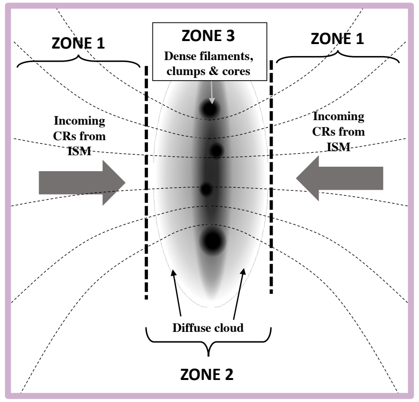
Molecular clouds are complex magnetised structures, with variations over a broad range of length scales. Ionization in dense, shielded clumps and cores of molecular clouds is thought to be caused by charged cosmic rays, which can also heat the gas deep within molecular clouds. Cosmic ray propagation is predominantly diffusive within disordered magnetised media, and the complex magnetic structures in molecular clouds regulate the distribution and effects of cosmic rays within them.

1 Introduction

The interstellar medium (ISM) of galaxies is multi-phase, with complex hydrodynamics and thermal structures spreading over a broad range of scales. Cold, dense neutral molecular clouds (MCs) and filaments are intermingled with hot, tenuous gases in (approximately) pressure equilibrium. These are permeated by magnetic fields with complex configurations and multiple length-scales. In the dense cores of MC complexes, densities are sufficiently high to shield material from much of the ionizing (particularly ultraviolet, UV) interstellar radiation with dust and molecular Hydrogen. However, sustained ionization of rates of up to $\zeta^{\rm H} = 10^{-17} - 10^{-15}\ {\rm s}^{-1}$ are still observed (van der Tak & van Dishoeck, 2000).

This is attributed to cosmic rays (CRs), which would also act to regulate the gas temperature. We consider an empirical propagation and heating model of CRs in MC environments, where CR diffusion is determined from observed flucctuations in polarization angles through MC complexes and used to solve the transport equation through observed clouds and filemantary structures. We assess the level of CR-induced heating through charactistic cloud structures (see Figure 1) in Galactic conditions, and also consider the effect of more intense irradiating fluxes of CRs, as would be found in nearby star-forming galaxies.

Figure 1: Schematic of a molecular cloud, with the large-scale magnetic field indicated by the curved dashed lines, and showing the hierarchical structure of the diffuse cloud, dense filaments and high-density clumps/cores.



2 Method

Optical and near-infrared (NIR) polarisation of starlight through molecular clouds can be used to trace magnetic fields. The diffusion coefficients of CRs through magnetised molecular cloud complexes can be inferred from the observed fluctuations in these optical/NIR starlight polarisations, which can be probed through molecular cloud complexes (see Figure 2, for the Galactic IC 5146 region). The angular dispersion function (second order structure function) of polarization angles as a function of separation distances $S_2(\ell)$ is first computed, and binned according to separation distance ℓ. This can be related to the power spectrum of polarization angle flucctuations in each bin by a Fourier Transform, according to $P(k) = \frac{1}{2}\mathcal{F}[S_2(\ell)]$. We then define a discretized flucctuation statistic as:

$$\mathcal{J}(\lambda_1) \approx k_c^{-1}\sum_{n=1}^{i_b} \frac{\kappa_n}{k_c\lambda_1} P(\kappa_n) + k_c^{-1}\sum_{n=i_b}^{N_{\rm bins}} \frac{k_c\lambda_1}{\kappa_n} P(\kappa_n)$$

Here $\lambda_1 = \lambda_{\rm td}(\omega_{\rm L}/\,\omega_{\rm p,0})$ is the CR resonant scattering length scale parallel to the background magnetic field vector. The turbulent decay length scale is $\lambda_{\rm td} \approx v_{\rm A}\tau_{\rm td}$ (where $v_{\rm A}$ is the Alfvén velocity and $\tau_{\rm td} \approx$ 2 Myr is the turbulent decay timescale). $i_{\rm b}$ is the bin index corresponding to the (normalized) resonant length scale $\lambda_1\, k_{\rm c}$, and κ_n is the normalized wavenumber associated with ℓ_n. $N_{\rm bins}$ is the number of bins. This can be related to the diffusion parameter by the Fokker-Planck coefficients, of which the only non-vanishing one is (if fluctuations are largely parallel the background magnetic field vector):

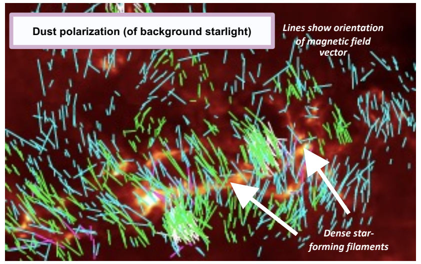
$$P_{\mu\mu} \approx \frac{\mathcal{J}(\lambda_1)}{v_{\rm A}\lambda_1}\left(\frac{\omega_{\rm L} B_0}{B}\right)^2 \mathcal{I}_\perp$$

Here, the CR gyro-frequency is $\omega_{\rm L}$. The normalization $\omega_{\rm p,0}$ is the gyro-frequency of a CR proton at a reference energy of 100 MeV, $B_0 = 1$ mG is the magnetic field normalization, and $\mathcal{I}_\perp = \pi/k_{\rm c}^2$, for $k_{\rm c} = \omega_{\rm p,0}/v_{\rm A}$ as the wavenumber normalization. The diffusion coefficient is then:

$$D \approx \frac{c^2}{8}\left(1-\frac{1}{\gamma^2}\right)\int_{-1}^{1} {\rm d}\mu\, \frac{(1-\mu^2)^2}{P_{\mu\mu}}$$

where c is the speed of light, γ is the CR Lorentz factor, and μ is the cosine of the CR pitch angle. This is then used to solve the transport equation for CRs, subject to boundary conditions set by the irradiating flux.

Figure 2: NIR/Optical polarization angle measurements through the IC 5146 Galactic molecular cloud complex. Adapted from Wang et al. 2019 with permission; ApJ 876 42



References: Arzoumanian et al. 2011 A&A 529, L6; Owen et al. 2021 ApJ 913, 52; van der Tak & van Dishoeck 2000, A&A 358, L79; Wang et al. 2017 ApJ 849, 157; Wang et al. 2019 ApJ 876, 42; Yoast-Hull et al. 2015 MNRAS 453, 222; Yoast-Hull et al. 2016 MNRAS 457, L29

For details see full paper:
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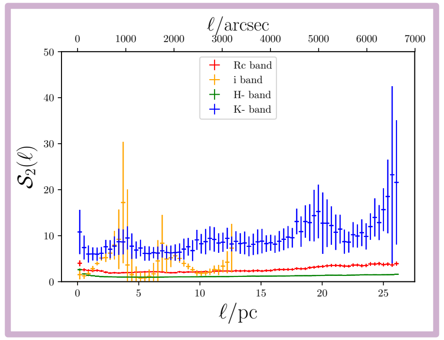
3 Applications

We use the IC 5146 interstellar MC complex, located in Cygnus, to demonstrate our method. The formation of the system is thought to be driven by large-scale turbulence (Arzoumanian et al. 2011), which would introduce perturbations into the magnetic field structure, making it an ideal test case. We use optical and near infra-red stellar polarization observations in four bands (Wang et al. 2017) to trace the magnetic fields and their fluctuations, which we use to empirically determine the diffusion coefficient of CRs through the region (the angular dispersion functions in the 4 observation bands used are shown in Figure 3, where structures on several different scales are evident). We use this to solve the transport equation through 15 of the distinct filamentary structures identified in IC 5146 (Arzoumanian et al. 2011) for which sufficient parametric information is available. The resulting total CR heating rate and equilibrium temperatures (when balancing *only* CR heating against cooling) in the filament ridges is computed. To assess the impact of the irradiating CR flux on the final equilibrium temperature of these filaments, we also consider irradiating fluxes comparable to the ISM of three nearby starburst galaxies, Arp 220, M82 and NGC 253 (estimated from their inferred CR energy densities in Yoast-Hull et al. 2015, 2016).

Figure 3: Dispersion functions calculated for the 4 bands, from Owen et al. (2021). The increasing power at larger scales due to the curved hour-glass magnetic field structure is not shown here as it is not relevant to our fluctuation analysis. Uncertainties are 1 σ Gaussian errors estimated by a Monte Carlo approach with 10,000 perturbations.



4 Results

We find that the filaments of IC 5146 would not experience subtantial heating due to CRs, with equilibrium temperatures being maintained at around 1 K in all cases. As this is lower than expected for dense clumps/clouds, **we conclude that CRs are unlikely to be a dominant heating agent in this system.**

However, if the level of CR irradiation is higher, the impact of CR heating could be more substantial. If we apply our model to the same filamentary structures of IC 5146, but consider levels of CR irradiation to be comparable to the ISM of **nearby starburst galaxies (Arp 220, M82 and NGC 253), the CR heating power could become more substantial** (see Figure 4, top panels). Such heating could raise the filament temperature to boost their Jeans' mass. While this is a crude measure of the maximum stable mass against collapse, it can still give an idea of the size of MCs and resulting stars/stellar clusters. Without CR heating, Galactic clouds could reach around 200 $M_\odot$ before becoming unstable to gravitational collapse. However, with Arp 220 CR energy densities (Figure 4, lower panels), this could be raised by more than an order of magnitude. **This may suggest a delayed onset of star-formation in filaments strongly irradiated by CRs, or even the emergence of a different *top-heavy* mode of star-formation in CR-abundant environments.**

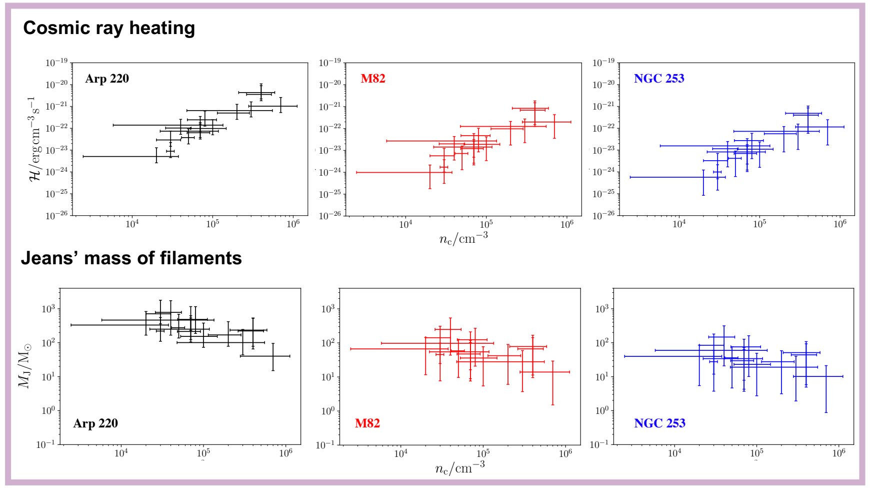


Figure 4: Top row: Heating power by CRs if the filaments of IC 5146 (Arzoumanian et al. 2011) were irradiated by a flux of CRs as that in Arp 220, M82 or NGC 253. Bottom row: Corresponding Jeans' masses for the same filaments, if assuming heating through the clouds is dominated by CRs.