MULTI-WAVELENGTH SIGNATURES OF COSMIC RAY INTERACTIONS AS A PROBE OF THE MAGNETIC FIELDS IN MOLECULAR CLOUDS

Energetic **cosmic rays** can interact with **molecular clouds**. **Hadrons** can undergo pion-producing interactions which decay to emit **gamma-rays**, while **leptons** cool via **synchrotron** emission. Their **propagation** is regulated by the structure of the **magnetic fields** within the cloud, which can be probed by polarized radio synchrotron radiation.

This poster outlines how gamma-ray emission could be used to **constrain** the local **cosmic ray density** within a molecular cloud, allowing the **polarized radio emission** to reveal crucial information about the strength, orientation and structure of the **internal magnetic fields**, which are important to regulate **star-formation**.

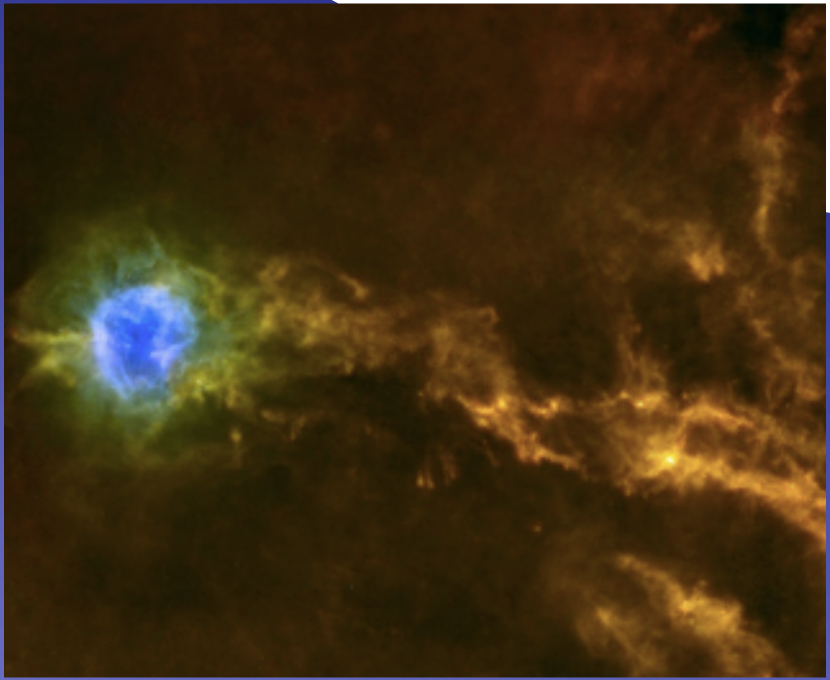

***Figure 1**: The IC 5146 star-forming region with Herschel. This region contains many star-forming filaments at various stages of their evolution, making it an interesting observational target to study the role of magnetic fields. Credit: ESA (2011)*

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Motivation

- Magnetic fields are an important ingredient in molecular clouds and are thought to have a role in regulating the collapse of gas and influencing star-formation
- However, their structure is difficult to probe and currently relies on polarization of light by dust, or the polarized emission from dust itself – a method which is less sensitive to shielded, dense regions where magnetic fields are very important
- New methods to reliably probe these fields alongside existing approaches are therefore desirable

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Background

- Dense regions of molecular cloud cores are observed to have ionization rates of around 10^{-17} s^{-1}, even though they are shielded from ionizing interstellar radiation fields
- This ionization is attributed to cosmic rays irradiating the cloud from the interstellar medium
- These cosmic rays are comprised of protons and electrons. The protons can interact to produce pions, then high-energy (GeV) gamma-rays, while the electrons can cause polarized radio synchrotron emission, where the polarization is governed by the orientation of the local magnetic field vector in the cloud
- Multi-wavelength programs with future generations of radio and gamma-ray telescopes should be sensitive enough to detect both the radio and gamma-ray structure and strength to be observed in more detail

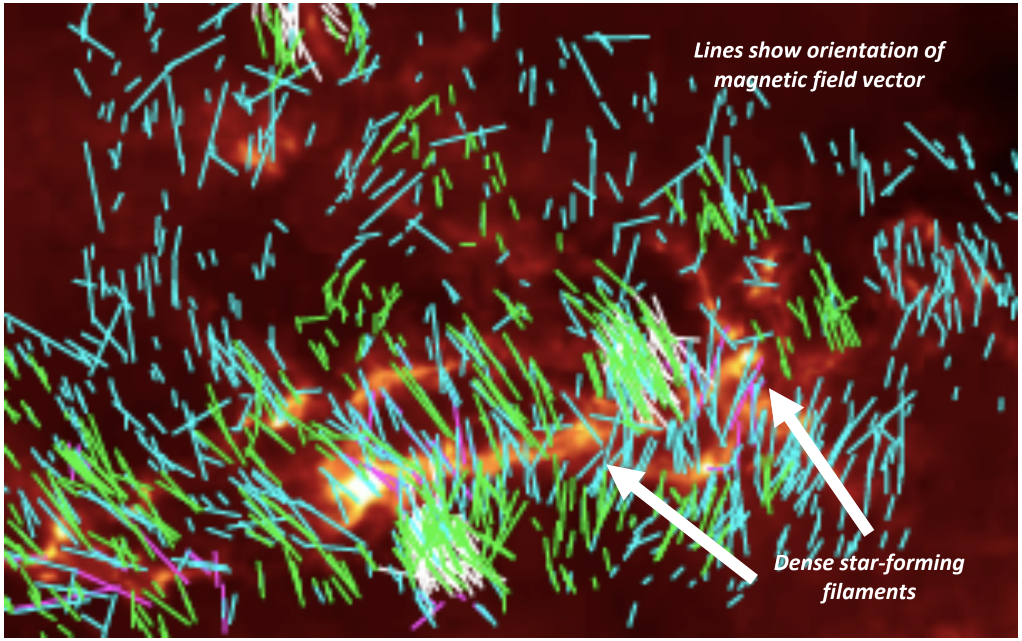

Figure 2**: Sub-region of the filamentary cloud IC 5146 illustrating the multi-scale magnetic field fluctuations regulating cosmic ray propagation. Credit: **Jia-Wei Wang (ASIAA); Wang et al. 2019, reproduced with permission.

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Theory

- Magnetic fields govern the propagation of charged cosmic rays through a molecular cloud, which can be modelled using the transport equation

$$\frac{\partial n}{\partial t} - \nabla \cdot [D(E, \mathbf{s}) \nabla n] + \nabla \cdot [\mathbf{v} n] + \frac{\partial}{\partial E}[b(E, \mathbf{s}) n] = Q(E, \mathbf{s}) - S(E, \mathbf{s})$$

- n is the (spectral) number density of the cosmic ray species (electron or proton)
- D is the diffusion parameter, which quantifies the diffusion rate of a charged particle of energy E through the ambient magnetic field (at some position s) – this may be estimated empirically (see below)
- **v** is the velocity of the ambient (magnetized) semi-ionized gas
- Q(E, **s**) is the cosmic ray injection (source) term, specifying the production rate of cosmic rays within the cloud - typically this is negligible
- S(E, **s**) is the sink term, or absorption term, of cosmic rays predominantly accounting for hadronic pion-producing (pp) interactions for protons, and is negligible for electrons
- b(E, **s**) is the cooling term, quantifying the energy loss rate of the particles due to radiative cooling (for electrons) and ionization losses
- **Solution** can be found numerically using a modified Runge-Kutta scheme if assuming the system has reached a steady-state and adopting a Milky-Way influx of cosmic rays into the cloud to set the boundary conditions. The resulting proton and electron distributions n(E, **s**) can then be used to calculate the radio synchrotron and gamma-ray emission from the cloud.

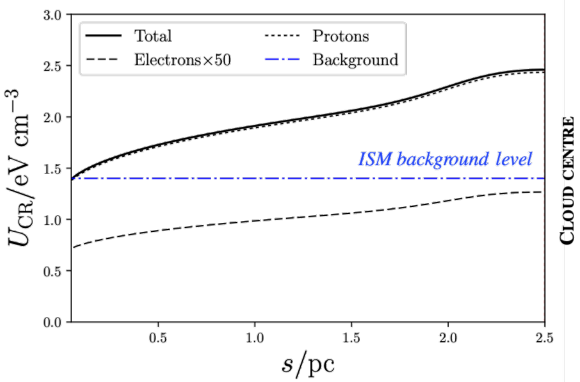

***Figure 3**: Solution for the cosmic ray transport equation showing energy densities of electrons and protons through an idealized molecular cloud model (Owen, On, Wu & Lai, 2020)*

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DIFFUSION PARAMETER

- The diffusion of cosmic rays is strongly controlled by the tangled structure of the ambient magnetic fields around which they gyrate and are deflected. The diffusion parameter in the transport equation above can therefore be related to the energy of the particle (via $\boldsymbol{\gamma}$), and the fluctuations in the magnetic field lines (measured by their associated polarization angles) through the molecular cloud (see Owen, On, Wu & Lai 2020 for details):

$$D \approx \frac{c^2}{8}\left(1 - \frac{1}{\gamma^2}\right)\int_{-1}^{1} \mathrm{d}\mu \, \frac{(1-\mu^2)^2}{P_{\mu\mu}} \qquad \text{where} \qquad P_{\mu\mu} \approx \frac{\mathcal{J}(\lambda_1)}{v_{\mathrm{A}}\,\lambda_1}\left(\frac{\Omega\, B_0}{B}\right)^2 \frac{\pi}{{k_{\mathrm{c}}}^2}$$

characterises the fluctuations.

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Emission signatures

From the cosmic ray electron and proton densities, the ratio between the synchrotron and gamma-ray emission can be used to constrain the magnetic field strength. Moreover, the radio polarization gives the local orientation of the magnetic field.

RADIO SYNCHROTRON EMISSION

- Calculated from the energy-integrated cosmic ray electron density and perpendicular magnetic field strength

$$j_{\rm R} \approx \frac{\sqrt{3}e^3 n_{\rm e} B_\perp}{m_e c^2(\alpha_{\rm e}+1)} \left(\frac{m_e c 2\pi\nu}{3eB_\perp}\right)^{-(\alpha_{\rm e}-1)/2} \Gamma\left(\frac{\alpha_{\rm e}}{4}+\frac{19}{12}\right)\Gamma\left(\frac{\alpha_{\rm e}}{4}-\frac{1}{12}\right)$$

- j_R is the spectral radio synchrotron emissivity
- n_e is the (integral) cosmic ray electron density at a specified energy
- $B_\perp$ is the local ambient magnetic field strength perpendicular to the line of sight
- α_e is the cosmic ray electron spectral index (assumed -3.3 at the boundary)
- A ratio of 1% of energy density in the electron cosmic ray component is assumed at the boundary of the cloud (estimated from ISM measurements), specifying the ratio of electron to proton densities through the cloud. Gamma-rays can then be used to estimate the proton density and (hence) the electron density to find the magnetic field strength from j_R.

GAMMA-RAY EMISSION

- Computed from the proton spectrum (from transport equation solution) and ambient gas density as

$$\frac{{\rm d}\dot{n}_\gamma(\epsilon)}{{\rm d}\epsilon} = c\, n_{\rm H}(s)\int_{\gamma_{\rm p}^{\rm th}}^{\gamma_{\rm p}^{\rm max}} \frac{{\rm d}\hat{\sigma}_{{\rm p}\gamma}(\epsilon,\gamma_{\rm p})}{{\rm d}\epsilon}\,\frac{{\rm d}n_{\rm p}(\gamma_{\rm p},s)}{{\rm d}\gamma_{\rm p}}\,{\rm d}\gamma_{\rm p}$$

- where $\gamma_{\rm p} = E_{\rm p}/m_{\rm p}c^2$ is the proton energy, and the integral bounds are between the 0.28 GeV pp pion-production threshold and a maximum of around 1 PeV.
- The inclusive differential gamma-ray production cross-section $d\hat{\sigma}_{p\gamma}/d\epsilon$ is well parameterized from data (see Kafexhiu et al. 2014)
- n_H is the local molecular cloud gas density (being the target for the pp interaction)

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Observational prospects

- Cosmic rays can help to probe magnetic field strengths and structures in molecular clouds
- Dust polarization with ALMA can be used to estimate diffusion parameter *for a target cloud*
- Gamma-ray emission (with Cherenkov Telescope Array's improved sensitivity and angular resolution) can set the cosmic ray normalization *within a target cloud*
- Polarized radio emission (possible with Square Kilometer Array) can then constrain magnetic field structure and strength *if the cosmic ray electron density is known.*

References: *Kafexhiu et al. 2014, PRD 90, 123014 ; Owen, On, Wu & Lai 2020, in prep; Wang et al. 2019 arXiv 1911.11364; ESA (2011) -- see Arzoumanian et al. 2011, A&A 529, L6*

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