Cosmic-ray propagation models: 3D magnetic fields and interstellar emission in radio

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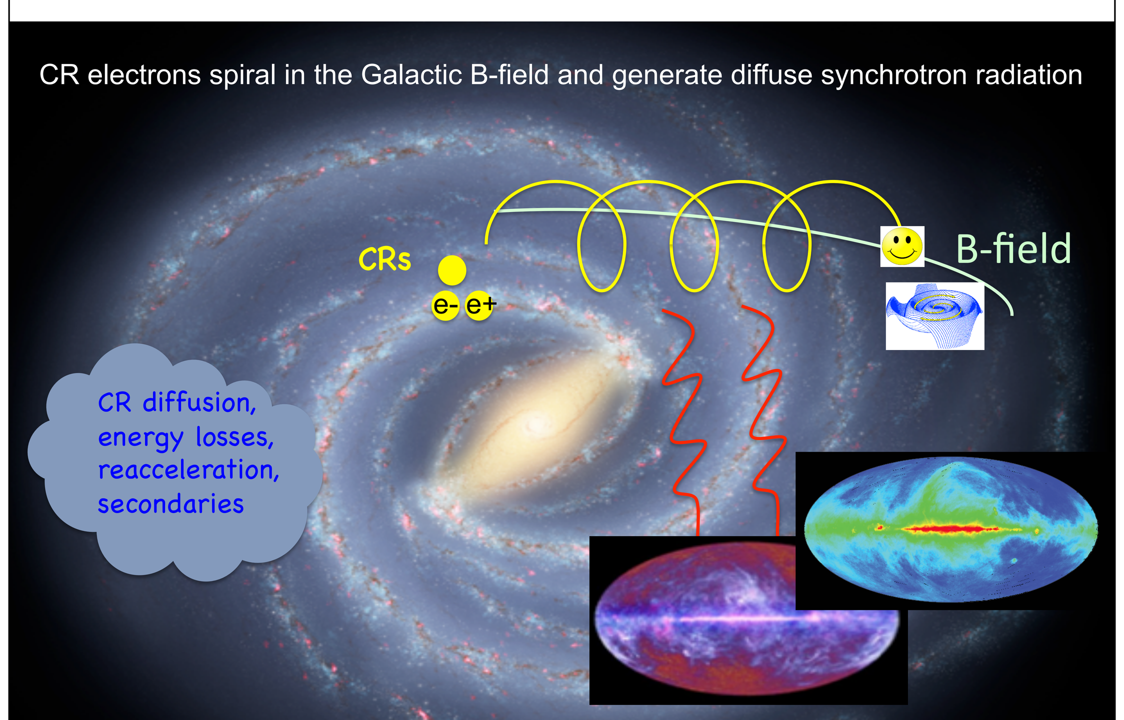
Abstract

Magnetic fields (B-fields) are responsible for cosmic-ray (CR) energy losses and diffusion in our Galaxy. Hence they affect interstellar emission from radio to gamma rays. Comparison of these emissions with models are the best way to characterize CRs. The problem is that the role of the strength and orientation of the B-fields has not been adequately accounted for when comparing Fermi-LAT data to models. This limitation came from our poor knowledge of the B-fields and the complexity in the modeling the emission. Nowadays the superb all-sky Fermi-LAT data call for a proper treatment of this issue.

We present our recent extension of the GALPROP code to model 3D synchrotron emission both in temperature and polarization. We can now account for sophisticated 3D B-field models. We describe and show examples including realistic B-fields models for both regular and random components. Induced synchrotron emission in temperature and polarization is predicted and compared with present radio and microwave observations. Our recent results on regular and random B-fields, CR electrons spectra, and their propagation and distribution in the Galaxy are presented.

Cosmic Rays and Synchrotron

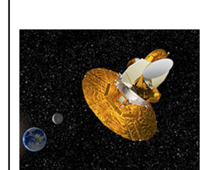
CR electrons spiral in the Galactic B-field and generate diffuse synchrotron radiation



CR electron spectral index <-> Synchrotron spectral Index
B-field intensity and CR electron density <-> Synchrotron Intensity
CR electrons of energy 0.5-20 GeV <-> Synchrotron of frequencies 20 MHz-100 GHz

Ingredients

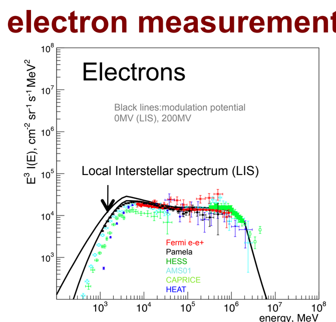
Radio and microwave data



WMAP:
- Polarization maps (U, Q)
- Temperature maps

Radio Surveys:
- Collection of ground based radio surveys
- 408 MHz (Haslam et al.)

CR electron measurements

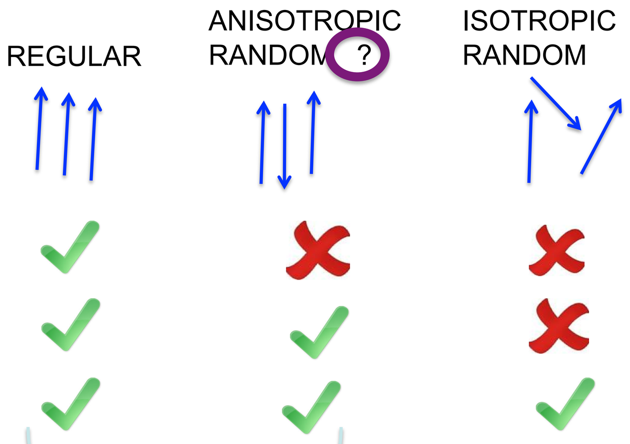


Modeling:

- CR propagation code (GALPROP)
- CR source distribution
- B-fields

B-fields and associated observables

Our knowledge of the Galactic B-field is still uncertain. Large scale (regular) and small scale <100pc (random) B-field are present in our Galaxy. A large scale ordering of the B-field, which originates by stretching or compression of the random field is also supposed to exist (anisotropic random). Disc and halo components are observed.
The following observables are used to constrain intensity and orientation of the B-field components.



REGULAR	ANISOTROPIC RANDOM ?	ISOTROPIC RANDOM	
✓	✗	✗	Rotation Measures
✓	✓	✗	Polarized Synchrotron
✓	✓	✓	Unpolarized Synchrotron

ORDERED (REGULAR and ANISOTROPIC RANDOM)

Latest Improvements in modeling radio

- 3D B-field configuration: random and ordered B-field for disc and halo components
- polarization (Stokes U, Q)
- basic free-free emission model (based on NE2001)
- absorption for the lowest frequencies and the Galactic plane

ALL THIS INCLUDED IN GALPROP ! http://galprop.stanford.edu

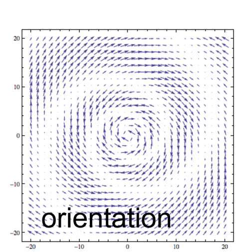
First time models of total and polarized synchrotron emission in the context of CR propagation !

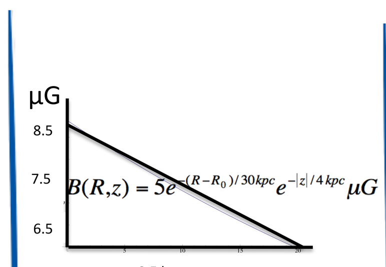
More info in:
Orlando & Strong (2013) MNRAS 436,2127

See also Johannesson's talk, this conference, on 3D source distribution implementation in GALPROP and Orlando's poster, this conference, for the parallel work on radio and gamma-ray with Fermi-LAT.

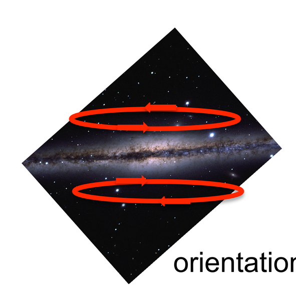
Examples of implemented B-field

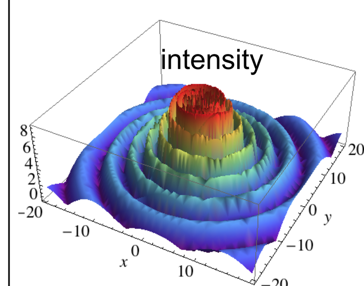
Spiral disc field | **Random field** | **Toroidal halo field**

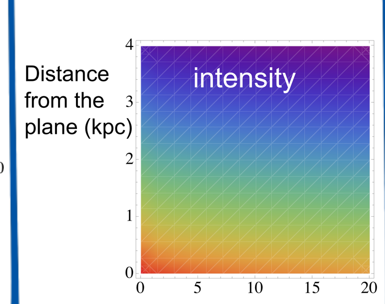


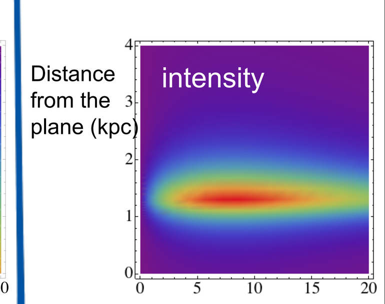


$B(R,z) = 5e^{-(R-R_\odot)/30kpc}e^{-|z|/4kpc}\,\mu G$



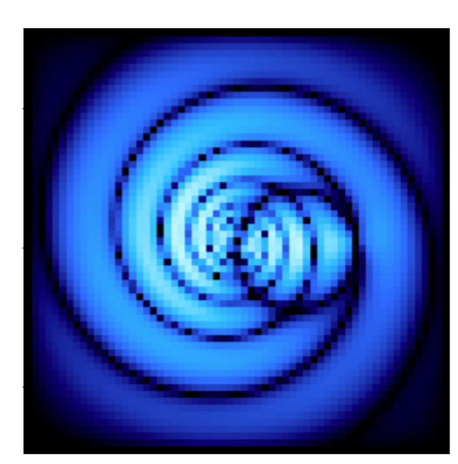


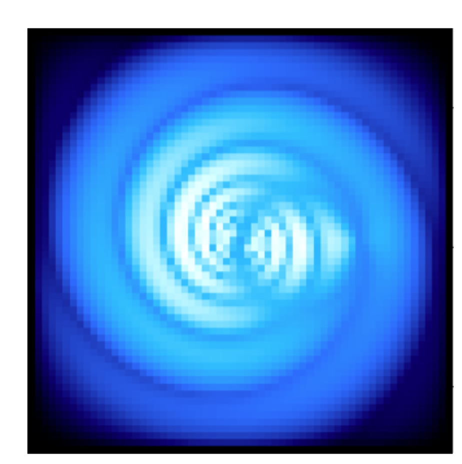




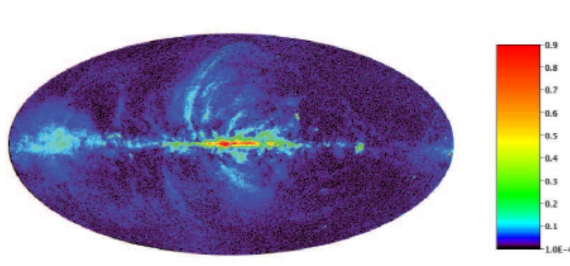
Examples of modeled emissivity

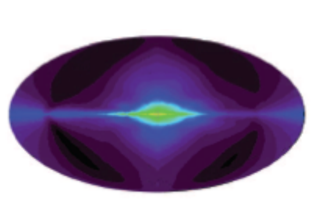
Examples of synchrotron emissivity for a spiral regular B-field (left) and for a spiral regular B-field plus a random B-field (right). The shape of the emissivity reflects the shapes of the spiral arms of the B-field, while the diffuse component is due to the random B-field. The black circle where the emissivity is zero on the right-center of the figures is where the regular B-field is parallel to the observer's line of sight from the observer point of view in the solar system. The Sun is at the center of that circle.



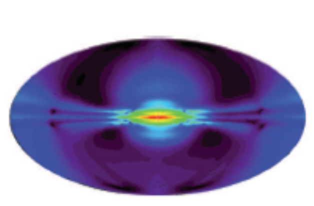


Tracing ordered B-field: some examples

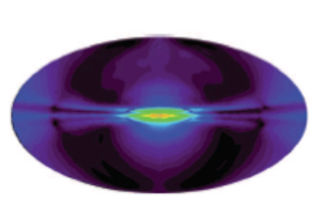




Sun et al. 2008, 2010



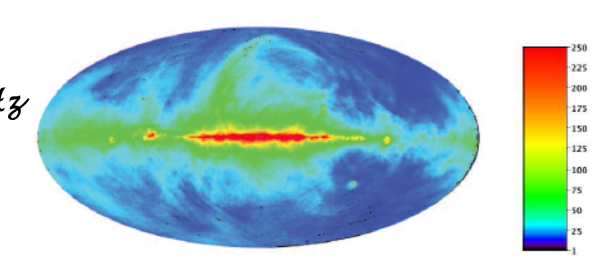
Pshirkov et al. 2011 (ASS B-field)

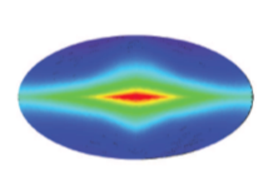


Pshirkov et al. 2011 (BSS B-field)

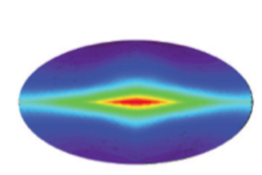
Different ordered B-fields

Tracing total B-field: some examples

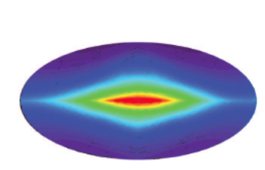




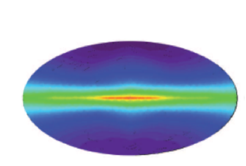
Z=10 kpc



Z=4 kpc



Lorimer 2006



Case & Bhattacharya 1998

Different propagation halo size (CR source distribution from Strong et al. 2010)

Different CR source distribution (z=4 kpc)

B-fields are the same for all models

Results

Based on Orlando & Strong 2013 MNRAS 436,2127 and Strong, Orlando and Jaffe 2011 A&A, 534, 54

CR electron spectrum:
- Break in local interstellar electron spectrum from <2 to ~3 @ few GeV
- Injection spectrum < few GeV is harder than 1.6

B-fields
- Tested the sensitivity to different formulations of the regular B-field based on the literature. Their best-fit intensity was obtained.
- Confirmation of an anisotropic random component of the B-field, as assumed in previous works
- Local random B-field of 4.7 - 5.3 μG

CR propagation and distribution:
- Standard reacceleration models are more challenging in reproducing synchrotron observations than pure diffusion models (due to more secondaries)
- A flat CR source distribution in the outer Galactic plan resembles the data best
- Preference of a halo height larger than 4 kpc in order to fit the high-latitude synchrotron data

REFERENCES: Case G.L., Bhattacharya, D., ApJ, 504, 761
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