Effects of Primordial Magnetic Helicity and Detection Possibilities

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Papers:

- C. Caprini, R.Durrer, T.K., 2004, PRD, 69, 063006
- A. Kosowsky, T.K., G. Lavrelashvili, B.Ratra, 2005, PRD, 71, 043006
- T. K. and B.Ratra, 2005, PRD, 71, 103006
- T. K., G. Gogoberidze, and B. Ratra, 2005, PRL, 95, 151301
- T. K. and T. Vachaspati, 2005, astro-ph/0511373

New Views of the Universe

What is Magnetic Helicity?

- Helicity reflects symmetry breaking - magnetic lines are twisted
- The theory of helical motions has been developed in turbulence

  J.O.Hinze, 1975, "Turbulence"

  R.H. Kraichnan, 1973, J. Fluid. Mech.

- Magnetic helicity definition (through vector potential B=r X A)

$$\mathcal{H} = \frac{1}{V}\int_V d^3x \mathbf{A}\cdot\mathbf{B}$$

Do we observe magnetic helicity in the Universe?

Astrophysical Observations
(Mirror symmetry breaking)

- Sun magnetic field
- Active galactic nuclei
- Jets

How we observe magnetic helicity

- The polarization of emitted synchrotron radiation

T.A. Ensslin, 2003; J. P. Valee, 2004

Magnetic Helicity Generation

- Cosmological Sources – Phase transitions

Cornwall, 1997; Field and Carroll 2000; Giovannini 2000, Vachaspati 2001, Sigl 2002, Campanelli and Giannotti 2005

- MHD Processes in Astrophysical Plasma

Vishniac and Cho, 2001; Brandenburg and Blackman, 2002; Subramanian, 2003; Banerjee and Jedamzik, 2004, Semikoz and Sokoloff, 2005

- Turbulence

Christensson, Hindmarsh, and Brandenburg, 2002; Verma and Ayyer, 2003, Boldyrev, Cattaneo and Rosner 2005;

Magnetic Field Statistical Properties

$$\begin{aligned}\langle B_i(\mathrm{x}+\mathrm{r})B_j(\mathrm{x})\rangle = &\quad M_N(r)\left[\delta_{ij} - \frac{r_i r_j}{r^2}\right] + M_L(r)\frac{r_i r_j}{r^2} \\ + &\quad M_H(r)\varepsilon_{ijl} r_l,\end{aligned}$$

The parts of the magnetic field spectrum

Normal $M_N(r)$ Ã $F_N(k)$;
Longitudinal $M_L(r)$ Ã $F_N(k)$
Helical $M_H(r)$ Ã $F_H(k)$
The energy density $E(r)$ Ã $F_N(k)$

$$\begin{aligned}&\langle B_i^*(\mathrm{k})B_j(\mathrm{k}')\rangle = \\ &\qquad (2\pi)^3\delta(\mathrm{k}-\mathrm{k}')\left[P_{ij}F_N(k) + i\varepsilon_{ijl}\frac{k_l}{k}F_H(k)\right].\end{aligned}$$

How could we measure magnetic helicity?

- **Direct test**

  (Faraday Rotation)

NO

Ensslin and Vogt, 2003;
Campanelli et al., 2004;
Kosowsky, Kahniashvili, Lavrelashvili, and Ratra, 2005

- **Un-direct test**

  (through induced specific effects)

Difficult, BUT possible

Kahniashvili and Ratra, 2005
Kahniashvili, Gogoberidze, and Ratra, 2005
Kahniashvili and Vachaspati, 2005

Metric Perturbations from Magnetic field

$$G_{ik} = 8\pi G T_{ik}$$

- **Scalar mode** **(density perturbations)**

  no contribution from magnetic helicity into the scalar part of the stress-energy tensor

- **Vector** **(vorticity perturbations, Alfven waves)**

Non-zero contribution ! CMB anisotropies

- **Tensor** **(gravitational waves)**

Maximal helicity cosmological effects

- Significant reduction for parity-even power spectra C_l^{TT}, C_l^{EE}, C_l^{TE}, and C_l^{BB} (comparing with the non-helical case);

- Comparable (by amplitude) cross correlations between temperature-E-polarization and temperature-B-polarization
  C_l^{TE} ' C_l^{TB} (from a magnetic field);

- Comparable by amplitude cross correlations between temperature-B-polarization and E-B-polarization
  C_l^{TB} ' C_l^{EB} if $l < 60$; otherwise $C_l^{TB} >> C_l^{EB}$

Faraday rotation angle and B-polarization signal due to the faraday rotation depends ONLY on a symmetric piece of the magnetic field spectrum (Kosowsky et al., 2005)

Combining Rotation Measure data with the precise data of the CMB fluctuations (parity-odd power spectra) can limit the magnitude of primordial magnetic helicity (Kahniashvili and Ratra, 2005)

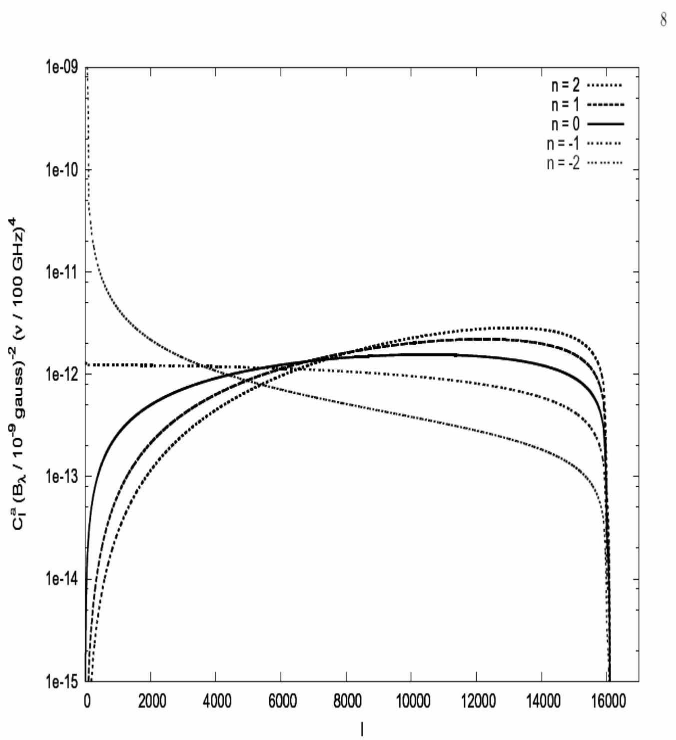


FIG. 1: The angular power spectrum of the Faraday rotation angle, C_l^α, induced by a stochastic magnetic field. The curves in order of decreasing amplitude on the right side of the plot correspond to magnetic field power spectral indices $n_B = 2, 1, 0, -1$, and -2. The magnetic fields have been normalized to a nanogauss at the smoothing scale $\lambda = 1$ Mpc.

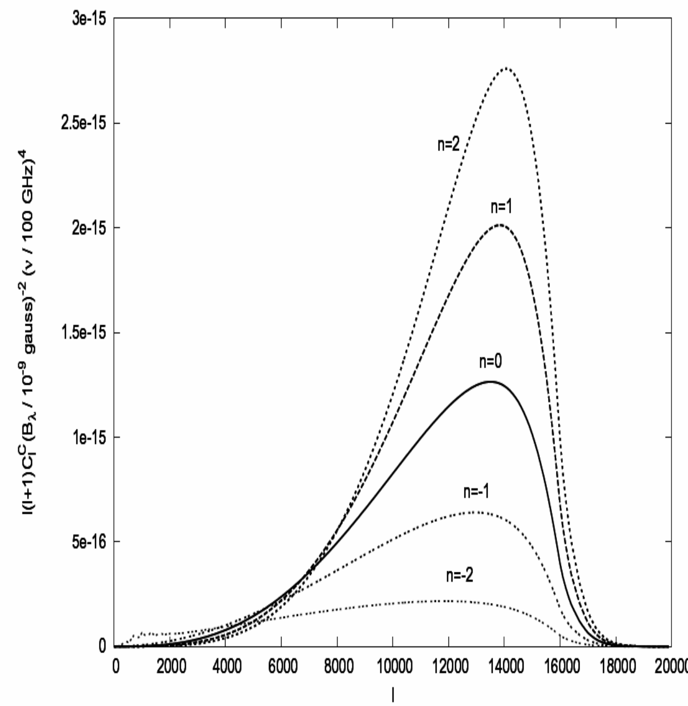


FIG. 2: The C-polarization power spectrum of the microwave background induced by the Faraday rotation field in Fig. 1,
with the magnetic field normalization scale $\lambda = 1$ Mpc.

Primordial Magnetic Helicity Detection via Cosmological Observations

WARNING

Even for primordial magnetic field

with maximal helicity such effects may be detectable

if

the current magnetic field amplitude is at least

10^{-9} – 10^{-10} Gauss on Mpc scales.

Relic Gravitational Waves Polarization

IF

there is symmetry breaking (parity violation)
in the source for gravitational waves,

THEN

the relic gravitational waves background
would be circularly polarized.

$$\ddot{h}_{ij}(\mathbf{k},t) + k^2 h_{ij}(\mathbf{k},t) = 16\pi G\ \Pi_{ij}(\mathbf{k},t),$$

GW equation ignoring the Universe expansion (short duration of the source)

This result is applicable for any kind of primordial helicity, i.e., for primordial helical turbulence or a helical magnetic field.

Relic gravitational waves background

Kahniashvili, Gogoberidze, and Ratra, 2005

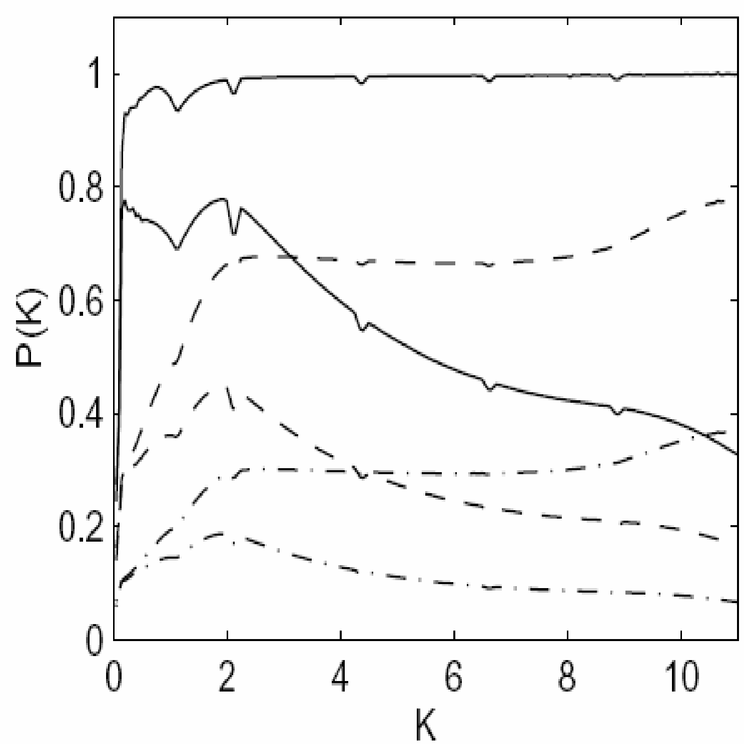
$$\mathcal{P}(k) = \frac{\langle h^{+\star}(\mathbf{k})h^{+}(\mathbf{k}') - h^{-\star}(\mathbf{k})h^{-}(\mathbf{k}')\rangle}{\langle h^{+\star}(\mathbf{k})h^{+}(\mathbf{k}') + h^{-\star}(\mathbf{k})h^{-}(\mathbf{k}')\rangle} = \frac{\mathcal{H}(k)}{H(k)}.$$

- Theoretically possible test:

Circular polarization degree of relic gravitational waves background ! P(k) strongly depends on F_H/F_N

- Requirements:

At least two antennas (LISA) high angular resolution and sensibility



Cosmic Rays: Advantage

- Can detect magnetic helicity in astrophysical objects (galaxies, clusters)
- No limits on the magnetic field amplitude – from spatial isotropy or nucleosynthesis; higher amplitude – larger effect;

What we propose?

Charged particles arrival velocities two-point correlations

Kahniashvili and Vachaspati, 2005

Arrival velocities correlator

- Consider two known sources that are emitting charged particles that arrive on Earth.
- The particles would propagate along straight lines from sources to the Earth – if there is no magnetic field;
- The trajectories bent by the weak magnetic field;

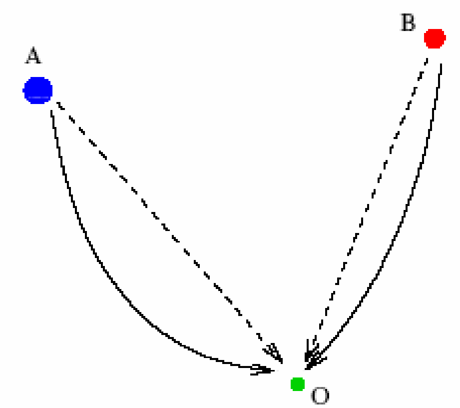


FIG. 1: Two sources A and B emit charged particles that are observed on Earth at O. If there was no ambient magnetic field, the particles would follow straight trajectories (dashed lines). In the presence of a weak magnetic field, the trajectories get bent (solid curves).

Observable velocity correlator

$$\langle v_A^i(T) v_B^{i'}(T') \rangle = v_{0A}^i(T) v_{0B}^{i'}(T') + \langle u_A^i(T) u_B^{i'}(T') \rangle,$$

Lets take our coordinate system as ABO lies to xy-plane, then n || z

$$C^{ii'}(T,T') \equiv \langle u_A^i(T) u_B^{i'}(T') \rangle .$$

- The normal component vanishes if i or i' (but not both) are in z-direction
- The longitudinal component vanishes for all component exempt C_L^{ZZ}
- The helical component is non-zero if one (and ONLY one) of i, i' is along z
- The normal and helical components do not mix; If magnetic field is not helical, a charged particle is as likely to be deflected in the +z –direction as it is to be in the –z-direction by the stochastic magnetic field
- If the helical field breaks the symmetry C_H^{zi} and C_H^{iz} become non-zero

$$C_H^{zi} = -\frac{q_A q_B}{m_A m_B}(\mathbf{v}_{0B} \cdot \mathbf{M}_H)(\mathbf{v}_{0A} \times \hat{\mathbf{z}})^i$$

$$C_H^{iz} = +\frac{q_A q_B}{m_A m_B}(\mathbf{v}_{0A} \cdot \mathbf{M}_H)(\mathbf{v}_{0B} \times \hat{\mathbf{z}})^i$$

where

$$\mathbf{M}_H(T,T') = \int_{t_{A,\text{in}}}^{T} dt \int_{t_{B,\text{in}}}^{T'} dt' \; M_H(r(t,t'))\mathbf{r}(t,t')$$

Conclusion

- Primordial helicity affects the generation of the CMBA
- Primordial helicity generates circularly polarized GWs
- Such effects are possibly detectable, but a high precision of measurements is required
- Ultra high energy cosmic rays may serve as a test for magnetic helicity ! reconstructing initial helicity ! Un-direct test for primordial helicity

THANKS