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Turbulence in the diffuse magneto-ionized medium: observational aspects

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Abstract. Turbulence in the interstellar medium is ubiquitous. The turbulent energy density in the gas is significant, and comparable to energy densities of magnetic fields and cosmic rays. Studies of the turbulent interstellar gas in the Milky Way have mostly focused on the neutral gas component, since various spectral lines can give velocity information. Probing turbulent properties in the ionized gas, let alone in magnetic fields, is observationally more difficult. A number of observational methods are discussed below which provide estimates of the maximum scale of fluctuations, the Mach number and other turbulence characteristics.

1. Introduction

More than half a century after the discovery that interstellar space is magnetized (Hall 1949; Hiltner 1949), it is still exceedingly difficult to map and characterize these galactic magnetic fields. As most of the interstellar medium is (partially) ionized, magnetic fields are often frozen into the plasma and as such are subject to and influence gas dynamics. The theory of turbulent, magnetized plasma is complex and only partially understood (e.g. Kolmogorov 1941; Goldreich & Sridhar 1995). Observations are by definition indirect and only probe specific field components in specific interstellar environments (see e.g. Zweibel & Heiles 1997). Numerical simulations quickly become computationally expensive due to the intrinsically 3-dimensional problem and a huge range of relevant scales.

In the past couple of years, major progress has become possible due to advances in computational power and technological capabilities, which has enabled new analysis techniques (e.g. rotation measure synthesis, Brentjens & de Bruyn 2005). This review highlights some of the recent results of studies of magnetized interstellar turbulence in the diffuse, warm (ionized) interstellar medium.

2. Studying turbulence in the magneto-ionized plasma

Various observational methods allow estimates of different physical parameters of magnetized turbulence in the ionized gas, which we will discuss below.

Fluctuations in synchrotron emission:
Turbulence is driven at a certain driving scale, or outer scale, after which energy cascades down to ever smaller scales until it is dissipated at the minimum scale. Estimates of this maximum scale of fluctuations are derived from both observed fluctuations in synchrotron emission and from RM structure functions. Note, however, that a maximum scale in fluctuations in synchrotron intensity or rotation measure not necessarily equates to energy injection scales of turbulence.

Small-scale fluctuations in synchrotron total intensity maps have been observed in recent $\sim$ 150 MHz observations with the WSRT and LOFAR radio interferometers.

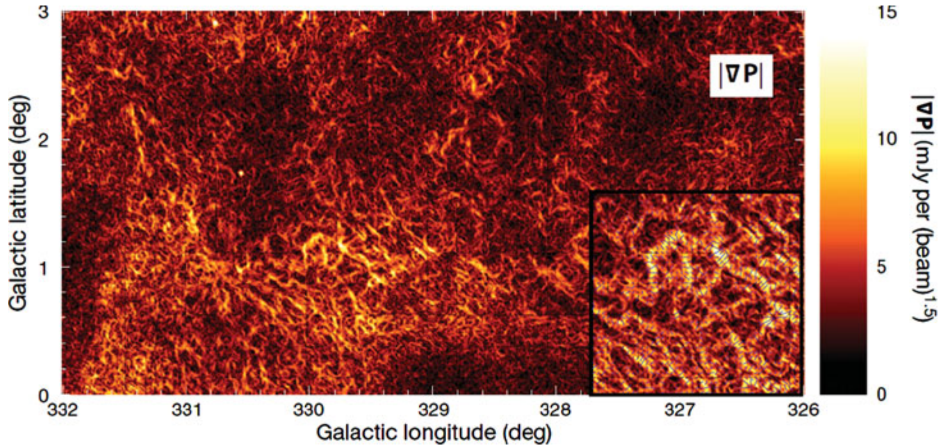

Figure 1. Gradient of the polarization vector as defined in the text (Gaensler *et al.* 2011), for the Southern Galactic Plane Survey Test Region (Gaensler *et al.* 2001). The inset shows the direction of the gradient as mostly perpendicular to the filaments.

These fluctuations follow a power spectrum with spectral index $\alpha = -1.84$ at multipoles $\ell \sim 110 - 1300$ (Bernardi *et al.* 2009; Iacobelli *et al.* 2013). Following Cho *et al.* (2002), who calculate different spectral indices in large-spatial-angle and small-spatial-angle limits, Iacobelli *et al.* (2013) find that the maximum scale of fluctuations in the synchrotron-emitting medium must be $L \lesssim 20$ pc. Earlier estimates of maximum scales in the magneto-ionized medium vary from $L \sim 50 - 150$ pc for synchrotron fluctuations at the North Galactic pole (Dagkesamanskii & Shutenkov 1987), to $L \lesssim 10$ pc in spiral arms from rotation measure structure functions (Haverkorn *et al.* 2008), to $L \sim 1$ pc within the nearest few 100 pc, derived from TeV cosmic ray anisotropy (Malkov *et al.* 2010).

Polarization gradients:

Polarization gradients are a recently defined diagnostic of small-scale changes in conditions in the ISM along a one-dimensional boundary (Gaensler *et al.* 2011), a generalization of the depolarization canals first discussed more than a decade earlier (Haverkorn *et al.* 2000). The gradient of the polarization vector $\mathbf{P}$ is defined as

$$|\nabla \mathbf{P}| = \sqrt{\left(\frac{\partial Q}{\partial x}\right)^2 + \left(\frac{\partial U}{\partial x}\right)^2 + \left(\frac{\partial Q}{\partial y}\right)^2 + \left(\frac{\partial U}{\partial y}\right)^2}$$

where Q and U are Stokes parameters and x, y are coordinates on the sky. A map of the polarization gradient in a 18-square-degree region close to the Galactic plane is given in Fig. 1. It shows that polarization gradients form a web of narrow filaments. Numerical simulations show that the statistics of polarization gradients change quantitatively with varying Mach number $\mathcal{M}$ in the medium (Burkhart *et al.* 2012). This analysis shows that the turbulence probed in Fig. 1 has $\mathcal{M} \lesssim 2$, so that the medium is subsonic or transonic. This confirms statistical analysis of Hα measurements (Hill *et al.* 2008). These conditions seem to be similar across a large part of the sky (Iacobelli *et al.* 2014).

Rotation measure structure functions:

The second-order structure function of rotation measure is defined as a function of angular scale θ as $D_{\rm RM}(\theta) = \langle(\mathrm{RM}(\xi) - \mathrm{RM}(\xi + \theta))^2\rangle_\xi$, where the angular brackets indicate averaging over all sky-projected coordinates ξ. RM structure functions have been used to prove that RM fluctuations cannot be explained by electron density fluctuations

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alone, but need small-scale magnetic fields as well (Minter & Spangler 1997). Stil *et al.* (2011) and Iacobelli (2014) provided maps of structure function slope and amplitude for the entire northern and southern sky, respectively. Their results were similar, concluding that structure function amplitudes are strongly increasing towards the Galactic plane, but slopes much less so. Stil *et al.* (2011) gave the interpretation that the structure function amplitudes reflect structure along the entire line of sight, whereas the slopes are determined by local structure mostly. Some determinations of RM structure functions indicate or suggest a broken power law (Simonetti *et al.* 1984; Minter & Spangler 1997; Stil *et al.* 2011). Minter & Spangler (1997) explain the break in their particular region in the sky by the transition from 2D to 3D turbulence. Oppermann *et al.* (2012) provide an averaged RM power law over the complete sky, noting that it is in agreement with earlier, locally varying, results. Haverkorn *et al.* (2008) interpret different structure functions in spiral arms and in interarm regions as different outer scales of fluctuations. However, interpretation of structure function slopes is still highly non-trivial, as (local) discrete structures could distort the determination of slope, amplitude and/or maximum scales.

3. Conclusions

Although it is difficult to attach firm conclusions about interstellar turbulence from observations of the warm, ionized, magnetized medium, useful information is definitely obtained from Hα measurements, synchrotron emission and Faraday rotation. Interstellar turbulence in the magneto-ionized gas is subsonic or transonic. Maximum scales of fluctuations in electron-density-weighted magnetic field seem to be position dependent, with the largest scales ($\sim$ 100 pc) in the halo and smallest ($\sim$ 10 pc) close to the Galactic midplane, possibly even smaller in spiral arms. RM structure functions are indicative of power law power spectra; breaks in these power spectra may indicate (local) transitions from 2D to 3D turbulence.

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