Triggered Star Formation in a Turbulent ISM
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Observations of turbulence in the diffuse interstellar medium

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Abstract. The warm neutral medium, warm ionized medium, and cool neutral medium all show strong evidence for turbulence as a process dominating their structure and motions on a wide range of scales. The spatial power spectra of density fluctuations in all three phases are consistent with a Kolmogorov slope. Turbulence in the magnetic field in the diffuse medium can also be measured through the structure function of the Faraday rotation measure. With new surveys, new analysis techniques, and new telescopes, in the next few years it will be possible to measure the structure function of the magnetic field over a similarly wide range of scales. This will give a complete picture of the turbulence as a magneto-acoustic process.

Keywords. ISM: structure, ISM: clouds, ISM: evolution, ISM: kinematics and dynamics, ISM: magnetic fields

1. Introduction

One of the great stories of Galactic astronomy is how successive generations of stars are enriched by increasing abundances of heavy elements formed in other stars that lived and died long before. Understanding how long it takes for gas ejected by stellar winds and supernova remnants to return to new star formation regions, what the intermediate stages are, and how the gas mixes through the Galaxy along the way, requires a more detailed model of the interstellar medium (ISM) than we have. Modelling cloud formation and phase changes in the ISM leads to an appreciation that turbulence is a fundamental process that determines how the gas evolves. Many observations show the effects of this turbulence. The challenge to observers is to measure the quantities that are needed for a theoretical understanding of the physics that drives it.

The diffuse ISM, including the warm ionized medium, the warm neutral medium, and the cool neutral (atomic) medium, fills most of the volume of the Galactic plane. Tracers of these phases show the big structures: spiral arms and interarm regions, and the somewhat smaller shells, filaments, and chimneys that mottle the disk of the Milky Way on scales of tens to hundreds of parsecs. Many of these structures are apparently deterministic, as, for example, an expanding shell of gas shows an ordered density and velocity field that suggests a past origin and a predictable future evolution. The onset of turbulence is a breakdown of this deterministic structure into a random or stochastic process, in which only the statistics of the density or velocity field have significance. It is not always easy to tell from the observations where and on what scale this transition happens.

The word turbulence denotes something much more specific than a random or disordered velocity field. Saying that the ISM is turbulent suggests that there is a physical process underway in which kinetic energy is transferred from larger to smaller scale motions (the "cascade"). Measuring the statistics of the structure of the ISM from a survey does not establish that turbulence is the process that generates this structure.

Interpretation of the observations is generally based on an assumed paradigm for the turbulent process.

2. Measurements of small scale structure

Whatever the resolution, observations of the interstellar medium show structure on all angular scales accessible to the telescope. This is generally true for all tracers, line and continuum, and in all directions. But the structure may be stronger or weaker, and it may be caused by spatial variations in density, velocity, temperature, ionization, radiation field strength, magnetic field strength, or other physical parameters of the medium. There are many ways to characterize the random fluctuations that appear on maps of a given observable quantity, such as the brightness temperature of a spectral line. One of the simplest to understand is the spatial power spectrum (P_1, P_2, or P_3 depending on the number of dimensions in the calculation), and its Fourier conjugate, the spatial autocorrelation function, which is closely related to the structure function (Lee and Jokipii 1974, Rickett 1977, Crovisier and Dickey 1983, Cordes and Rickett 1998, Lazarian and Pogosyan 2000, Goldman 2000, Miville-Deschenes *et al.* 2003).

There are many other mathematical functions that have proven useful for describing the small scale structure in ISM surveys. Two that are particularly well suited to spectral line surveys are the spectral correlation function (Rosolowsky *et al.* 1999, Ballesteros-Paredes *et al.* 2002, Padoan *et al.* 2003) and principal component analysis (Heyer and Schloerb 1997). There has been a great deal of work on the fractal geometry of the ISM, mostly directed toward molecular clouds, but with some applications to the diffuse medium (Westpfahl *et al.* 1999, Stanimirović *et al.* 1999, Elmegreen *et al.* 2001). The comprehensive review articles of Elmegreen and Scalo (2004) and Scalo and Elmegreen (2004) give a thorough discussion of turbulence in the ISM in general, including both observational and theoretical perspectives. One compelling approach is to characterize the structure in the density or velocity field in terms of a spectrum of magneto-acoustic waves (Ferriere *et al.* 1988, Cho *et al.* 2002, Heitsch *et al.* 2004). This is well suited to situations where the magnetic field is dynamically dominant over the gas pressure, which may be quite common in the interstellar medium.

Consideration of the spatial power spectrum of the variations in interstellar density over a broad range of scale sizes leads quickly to the hypothesis that a turbulent cascade of energy from large to small scales may be at work. Figure 1 (from Armstrong *et al.* 1995) is a compendium of data on the diffuse **ionized** medium. The figure shows the three dimensional power spectrum, P_3, as deduced from various observations, mostly based on the propagation of pulsar signals. Over at least ten orders of magnitude in linear size, a slope of - $\frac{11}{3}$ fits the data adequately. This matches the prediction of the Kolmogorov theory of inertial turbulence in an incompressible medium.

An excellent example of the kind of pulsar data that is used to probe structure in the diffuse ionized medium is the twenty year time series of dispersion measure (proportional to the line of sight integral of electron density) toward the millisecond pulsar B1937+21 (Ramachandran *et al.* 2006). The autocorrelation function of these data provide the structure function, which shows a remarkably straight power law over two orders of magnitude in time lag, which translates directly to distance offset. The scales measured are 0.3 to 100 AU. Converting this structure function to an autocorrelation function and taking the Fourier transform gives the spatial power spectrum.

The neutral atomic gas in the ISM is best traced with the λ21-cm line of HI. In emission, this is easy to map on angular scales of $1'$ and larger, as has been done for wide areas of the Galactic plane in three recent mosaic surveys, the Canadian Galactic Plane Survey

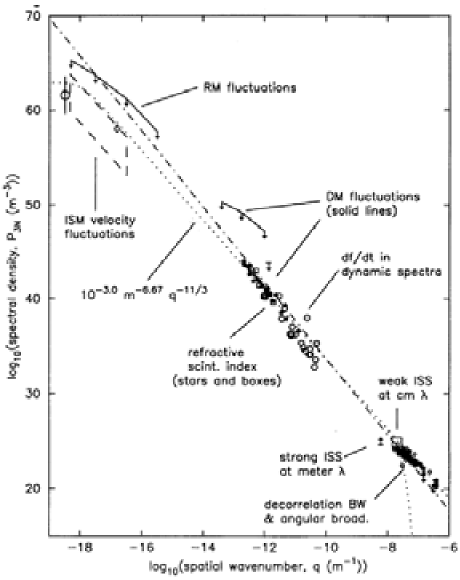

Figure 1. The spatial power spectrum of the ionized medium (Armstrong *et al.* 1996; reproduced by permission of the AAS.)

(Taylor *et al.* 2003), the Southern Galactic Plane Survey (McClure-Griffiths *et al.* 2001, 2005), and the VLA Galactic Plane Survey (Stil *et al.* 2006). From this kind of moderately high resolution data, the spatial power spectrum of the 21-cm emission has been studied for many years (Crovisier and Dickey 1983, Green 1993). In many different directions, observed with many different instruments, the spatial power spectrum consistently gives a power law with spectral index in the range -2.2 to -3. The range of linear scales covered by this kind of observation is typically 0.5 pc to 20 pc. Assuming that a single velocity channel corresponds to a two dimensional slice through the medium (where Galactic rotation translates velocity into distance, whether or not this relation is bi-valued), then the expected power law index is $(-\frac{8}{3})$ for a Kolmogorov cascade, which is very consistent with the observations in most low-latitude directions.

Averaging in velocity steepens the power law, at least in the mosaic survey data, from power law index -2.7, typically, to the range -3 to -4. This is explained by the transition from a thin slice to a thick slice, or three dimensional sample, for which the Kolmogorov slope is $-\frac{11}{3}$ (Stanimirović and Lazarian 2001, Dickey *et al.* 2001, Lazarian and Pogosyan 2000). This is strongly suggestive that the slope of the spatial power spectrum is set by a turbulence process, and not some other random process that modulates the density and/or velocity field. It is interesting also that the neutral medium shows this same power law behavior in very different environments, including the Magellanic Clouds, and even the Magellanic Bridge (Muller *et al.* 2004), where the influence of stellar winds and supernova remnants must be very much weaker than in the solar neighborhood. In the Magellanic Bridge region also the power law steepens, from about -2.25 to -3, with velocity averaging. This similarity of the spatial power spectrum of the turbulence in such different environments raises the question of whether the processes that drive the turbulence have any effect on the spectrum, and the larger question of how much the presence of massive stars is required to drive the turbulence by injecting kinetic energy.

3. Driving the turbulence

There are many possibilities for the source of the kinetic energy on large scales that drives the turbulence in the diffuse medium. Evaluating the role and relative importance of these different processes is an important challenge to Galactic astrophysicists. It is possible that the magnetic field causes an inverse cascade, in which the energy is injected at small scales and propagates to larger and larger patterns of motion (Pouquet *et al.* 1999). But there are some good observational examples of ordered motions on scales of hundreds of parsecs to one kpc that are in the process of breaking down into disordered, smaller scale irregularities in density and velocity. A striking case is the wall of the huge Galactic chimney, GSH 277+00+36 (McClure-Griffiths *et al.* 2000, 2003). As this is a very old supershell, probably 15 to 20 Myr old, Rayleigh-Taylor instabilities are beginning to cause the dense, cool shell to "drip" into the higher pressure, hot, low density interior. As this process continues the ordered expansion velocities are being deflected by density irregularities into a random velocity field. One of these "drips" contains a CO cloud at the same velocity as the atomic gas in the shell wall. The drip has such a narrow line width in HI that the atomic gas must be quite cool (less than 100 K) in the vicinity of the CO cloud. In this case the morphology is very suggestive that the turbulence in the atomic gas is driving turbulent motions in the molecular cloud. It is important to establish how much of the turbulent molecular cloud kinetic energy is imported from the diffuse medium, brought along with the gas during the process of condensation and molecule formation as a cool atomic cloud makes the transition to the molecular phase.

Emission in the λ 21-cm line traces the column density of the atomic medium, without much weighting by the temperature of the gas. In 21-cm absorption the temperature is much more important; the optical depth is primarily due to the cool gas ($T_{kin} \leqslant 100\,K$) which is about 30% of the total atomic phase. This is an advantage for studying the cool atomic clouds that may be in the process of conversion to molecular gas. It is also much easier to study small scale structure in absorption, since the brightness of the background source may be much higher than the brightness of the line emission. In this way Deshpande (2000) has demonstrated that the spatial power spectrum seen in λ21-cm emission continues to scales of 0.02 pc, from measurements of the absorption toward Cas A. At even much smaller scales, observations with the VLBA show occasional significant variations on angular scales of 10 mas, that correspond to a few hundred AU (Brogan *et al.* 2006). Similar "tiny-scale" structure is seen in Na I absorption in the optical (Lauroesch *et al.* 2000) as is larger scale structure (Meyer and Lauroesch 1999).

An example of a cloud at the borderline between the cool atomic and molecular phases is the Rigel-Crutcher cloud, seen in HI self-absorption (HISA) toward the Galactic center (its distance is 150 to 180 pc, Crutcher and Riegel 1974). Figure 2 shows this cloud as mapped by McClure-Griffiths *et al.* (2006) in the Southern Galactic Plane Survey. The remarkable collection of long filaments is striking. Some have dimensions $\sim$17 pc $\times$ 0.1 pc, for an aspect ratio of 170:1. The filaments are very straight, and very well aligned with the magnetic field direction as deduced from the polarization of starlight (Heiles 2000). McClure-Griffiths *et al.* (2006) estimate the required magnetic field strength if the magnetic energy density is to exceed the gas kinetic energy density, to find a lower limit on B of 30 μG. This is much higher than measurements in the typical diffuse atomic medium (median 6 μG, Heiles and Troland 2005), but similar to field strengths measured in molecular clouds. Assuming that this HISA structure is on the borderline between atomic and molecular clouds, the morphology suggests that one way to carry turbulent energy through this transition is via the magnetic field. This raises the question of what we know about turbulence in the magnetic field elsewhere in the diffuse medium.

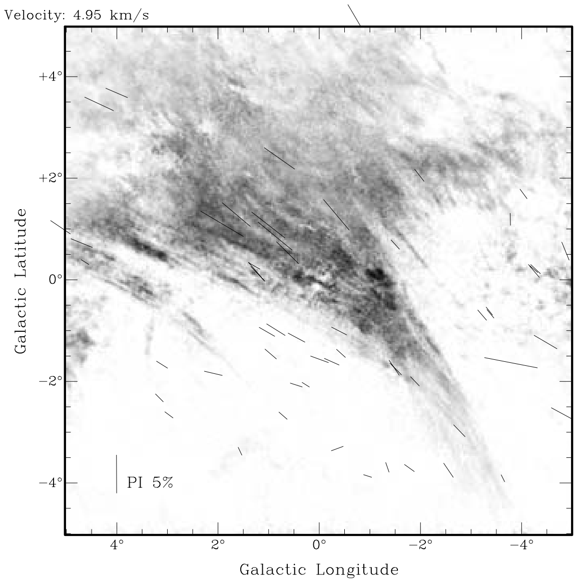

Figure 2. A cold, atomic cloud complex seen in HI self-absorption in the Southern Galactic Plane Survey (McClure-Griffiths *et al.* 2006). Starlight polarization vectors indicating the magnetic field direction are superposed.

4. Turbulence in the magnetic field

There are many ways to estimate the magnetic field strength and direction in the interstellar medium, and a few ways to quantitatively measure the strength of the line of sight component of the field, either in one particular region (using the Zeeman effect, e.g. Heiles and Troland 2005) or integrated along the line of sight (using Faraday rotation, e.g. Weisberg *et al.* 2004). When many measurements are available in the same area, the structure function can be computed. An early study using Faraday rotation measures toward extragalactic sources observed with the VLA was done by Minter and Spangler (1996). They found that the structure functions of the rotation measure and of the emission measure show similar power law behavior on angles of 1^o to 10^o, but at angles smaller than 0.1^o the structure function of the rotation measure steepens. A similar steepening is found by Haverkorn *et al.* (2004), who also find evidence for anisotropy in the structure function, as would be expected if the magnetic field has a mixture of ordered and random components. In further work, Haverkorn *et al.* (2006) find that the slope of the structure function of the rotation measure changes dramatically between spiral arms and interarm regions, with a flatter slope, i.e. more structure on small scales, in the directions dominated by spiral arms. This result is still preliminary, but it suggests that there will be a lot to learn from future studies of the turbulence of the interstellar magnetic field.

A very promising observational technique for measuring the structure of the magnetic field on a wide range of scales is to map the Faraday depth of the diffuse synchrotron emission from the cosmic rays of the Milky Way. Whenever there is linearly polarized emission interspersed with a magnetized thermal plasma, there will be a superposition of continuum emission with multiple Faraday depths, ϕ,

$$\frac{\phi(r)}{\mathrm{rad\ m}^2} = 0.81 \int_{los} \frac{n_e}{\mathrm{cm}^{-3}} \frac{\vec{B} \cdot \vec{dr}}{\mu\mathrm{G\ pc}}$$

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where the integral is taken along the line of sight starting from the observer, as in the analogous definition of optical depth. The different regions contributing to the linearly polarized emission can be separated by taking the Fourier transform of the observed linear polarization along an axis constructed to be linear in $x \equiv 2\lambda^2$, since Faraday rotation causes the Stokes Q and U parameters (components of the linear polarization, $P = Q + \mathrm{i}U$ expressed as a complex number) to be rotated (i.e. multiplied by $e^{\mathrm{i}\phi x}$, giving the Fourier transform relationship

$$P(x) \;=\; \int_{-\infty}^{+\infty} F(\phi)\; e^{\mathrm{i}\phi x} d\phi$$

where $F(\phi)$ is the intrinsic distribution of linearly polarized emission as a function of Faraday depth along the line of sight (Burn 1966, Brentjens and de Bruyn 2005).

This technique allows the construction of a Faraday cube, similar to a spectral line cube but with radial velocity replaced by Faraday depth, ϕ, the conjugate variable to x. As with the ordinary spectral line cube, this third dimension is related to distance, but in a complicated way. Studying this cube tells us about the three dimensional distribution of the magnetized thermal plasma and the polarized emission (de Bruyn *et al.* 2006). Construction of such cubes from low latitude survey data will allow a much more profound interpretation of the diffuse, polarized Galactic emission, with the goal of separating the structure functions of the electron density and the magnetic field.

5. Future observations of the diffuse medium

Over the next decade radio astronomers will be working toward construction of the Square Kilometer Array telescope (SKA); precursor or "phase 1" projects are underway already in several nations. This telescope will have the power to completely measure the spatial power spectra of the ionized medium, the neutral medium, and the magnetic field, with no gaps, over the full range of scales on figure 1 (Dickey *et al.* 2004). The SKA will revolutionize studies of the interstellar medium, through the λ21-cm line and cm-wave molecular lines, through measurements of the propagation of radiation from pulsars and other compact sources, and through sensitive observations of continuum emission in all Stokes parameters. Surveys of the diffuse ISM with the SKA may show the interaction between the spectrum of magneto-acoustic waves and the gas density and velocity fields. The ultimate goal is to trace the connection between turbulence in all phases of the interstellar medium, from the warm ionized medium, to the cool neutral medium, and on to molecular clouds and star formation.

Acknowledgements

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Discussion

BRINKS: You mentioned that shells and bubbles could well, as they disintegrate, be at the basis of the observed Kolmogorov-Smirnov type power spectrum. But then you showed the Magellanic Bridge where no stars or supernovae are around to do the trick. Any idea what might be powering turbulence in such an environment?

DICKEY: It is possible that the turbulence is driven by the large scale dynamics of the clouds and their tidal interaction with each other and with the Milky Way.

GOLDMAN: Don't you think the index is a characteristic of the gas – not the source?

DICKEY: Yes, if we assume that the turbulence is inertial, then conservation of energy might set the spectral index independent of the physical process that drives the cascade on the outer scale.

Y.-H. CHU: There are stars in the Magellanic Bridge. These are blue stars and associations/clusters in the Magellanic Bridge, although there are no current star formation o O stars.

DICKEY: Yes, there are stars. But are there enough to explain the HI structure and motions?