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Structure of Diffuse Emission in the Spitzer Galactic First Look Survey

James G. Ingalls, William T. Reach, Alberto Noriega-Crespo, and Sean J. Carey

Spitzer Space Telescope Science Center, California Institute of Technology, 1200 East California Boulevard, MS 220-6, Pasadena, CA 91125

M.-A. Miville-Deschênes, F. Boulanger

Institut d'Astrophysique Spatiale, Université Paris, bât. 121, 91405, Orsay, France

Abstract. The density and velocity structure of the interstellar medium (ISM) must be understood to address many astrophysical problems. We summarize the spatial statistics of $24\,\mu$m emission for 10 diffuse fields in the *Spitzer* Galactic First Look Survey. In almost all regions we analyzed, the x and y spectral indices are nearly equal, implying that the density structure in emitting regions is isotropic. All but one spectral index we measure is shallower than the index predicted by the theory of Kolmogorov (1941). We discuss the implications of our results in the light of recent simulations of magnetized and non-magnetized hydrodynamic turbulence.

1. Turbulence and the Density Structure of the Interstellar Medium

The density and velocity structure of the interstellar medium (ISM) and the physical processes which govern them must be known to address many astrophysical problems, such as: star formation and related statistical measures like the Initial Mass Function; the interaction of stellar winds with their environment; the structure of supernova remnants; and confusion noise in extragalactic observations.

The structure of an interstellar cloud is described by the energy spectrum of fluctuations in the velocity, $E(k)$, as a function of Fourier spatial wavenumber, k. The Kolmogorov (1941) theory of incompressible nonmagnetized hydrodynamic turbulence has an energy spectrum, $E(k) \propto k^{-5/3}$. The energy and measured D-dimensional power spectra are related by $P(k) \propto E(k)^{1-D}$, so a medium undergoing Kolmogorov turbulence would have a 3D power spectrum of $P \propto k^{-11/3}$. Slices (2D) through the medium would yield $P \propto k^{-8/3}$.

Since the velocity field of the ISM is turbulent and governed by random statistics, the density field will be shaped by those statistics, although it will not necessarily reproduce them. In astronomical images without velocity information (assuming optically thin emission), we measure the integrated density field weighted by the line of sight emissivity as a function of 2D position. Under constant emissivity conditions, this is proportional to the column density.

Table 1. $24\,\mu$m Spatial Statistics of GFLS Fields

Field Center	Approx. Size [deg]	β_x	β_y	Comments
$G105.6-1.3$	1.02×0.22	1.82 ± 0.01	1.90 ± 0.03	LDN 1187, 1189
$G105.6+0.35$	0.68×0.25	1.86 ± 0.02	1.32 ± 0.08 1.83 ± 0.04	LDN 1190, 1192, 1194
$G105.6+2.0$	1.51×0.18	1.77 ± 0.03	1.80 ± 0.04	LDN 1179, 1180, 1185
$G105.6+4.0$	0.68×0.20	$1.7\ \ \pm0.1$ 2.83 ± 0.03	$1.7\ \ \pm0.1$ 3.18 ± 0.03	LDN 1184, 1186, 1188, 1191, 1193
$G105.6+8.0$	1.04×0.12	1.09 ± 0.05 1.76 ± 0.04	1.01 ± 0.10 1.88 ± 0.07	Cepheus Flare
$G105.6+16.0$	1.51×0.25	1.17 ± 0.09 2.23 ± 0.06	1.36 ± 0.04 2.05 ± 0.08	Cepheus Flare
$G254.4-9.0$	0.54×0.25	1.55 ± 0.09 2.51 ± 0.03	$1.6\ \ \pm0.1$ 2.36 ± 0.03	Gum Nebula
$G254.4-5.0$	1.51×0.25	1.32 ± 0.01	1.30 ± 0.02	Gum Nebula
$G254.4-2.0$	0.82×0.20	1.32 ± 0.03 2.15 ± 0.12	1.31 ± 0.04 $1.9\ \ \pm0.2$	Gum Nebula
$G254.4+0.0$	1.51×0.20	2.41 ± 0.02	2.40 ± 0.04	Gum Nebula

2. The *Spitzer* Galactic First Look Survey

We estimate the spatial power spectrum of the density field of the ISM using data from the *Spitzer* Galactic First Look Survey (GFLS). The survey consisted of rectangular strips centered on two Galactic longitudes and sparsely spaced in latitude. The strips crossed a number of known molecular and atomic clouds, including 13 Lynds Dark Nebulae (LDN; Lynds 1962), the Cepheus Flare, and the Gum Nebula. Ingalls et al. (2004) describe the power spectral analysis of the GFLS region centered on $G254.4-9.0$, part of the Gum Nebula. Here we summarize the spatial statistics of $24\,\mu$m emission for all 10 diffuse fields in the survey with detectable signal (Table 1). The area analyzed encompasses a total of 2.66 square degrees, or about 0.01% of the sky.

3. Results

Table 1 lists the region centers, the sizes of the areas analyzed, in degrees, as well as the power spectral indices measured along the long (x) and short (y) axes of the $24\,\mu$m surface brightness images. These indices were derived from power law fits of the form $P(k) = Ak^{-\beta}$ to the x and y power spectra in each image, computed from the squared Fourier transform amplitudes of 1D cuts along the x and y axes. For better signal to noise ratio, we coadded the power spectra of all cuts in a given direction. In some cases, spectra showed an obvious break into two power laws (see Ingalls et al. 2004, and §4 for a possible interpretation of the

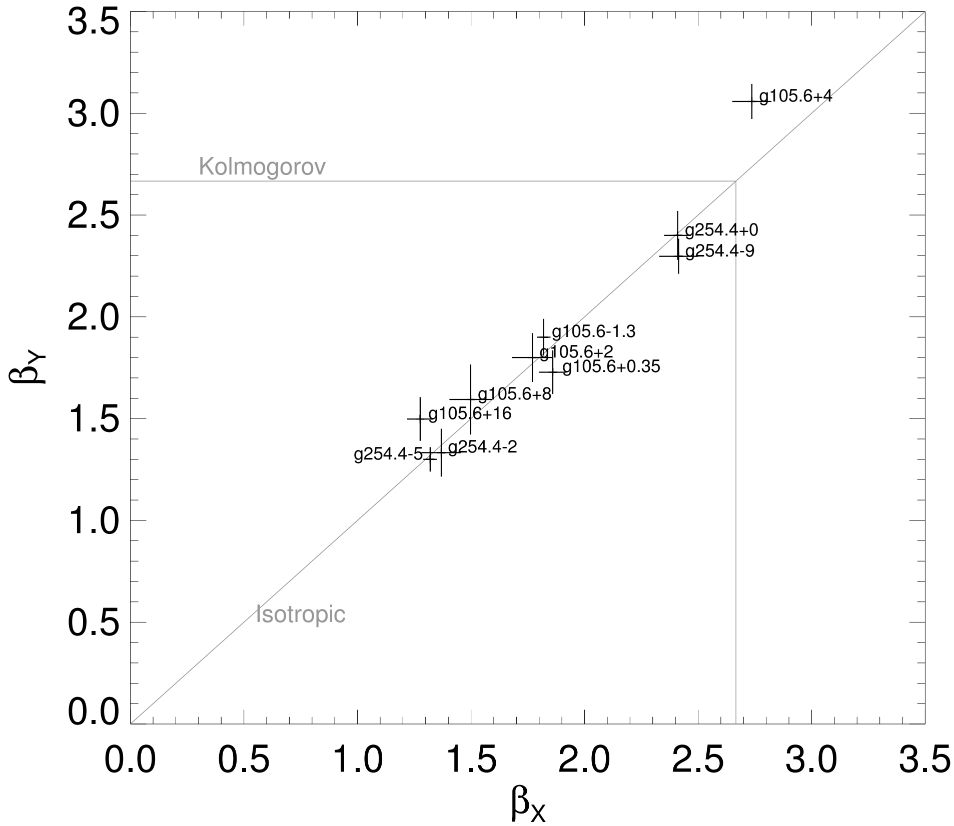

Figure 1. Comparison of the power spectral indices derived in the x and y pixel directions. Error bars represent the $\pm 3\sigma$ formal errors in power law fits to the spatial power spectrum of $24\,\mu$m emission. A gray line with a slope of unity represents isotropic behavior, and the Kolmogorov limit of $\beta^{2\mathrm{D}} = 8/3$ is overlaid on the plot.

spectral break). If two spectral indices were measured, we list both of the indices in Table 1, with the low k indices printed above the high k indices. Figure 1 displays β_y as a function of β_x. In regions where we measured two power laws we plot only the average of the two values, weighted by the Table 1 errors. We superimpose a line with a slope of unity to indicate isotropic behavior. In almost all regions we analyzed, the x and y spectral indices are nearly identical. We also plot in Figure 1 vertical and horizontal lines indicating the x and y indices, respectively, that would be measured for Kolmogorov scaling ($\beta = 8/3$ for a slice). All but one region in our survey has a power spectrum that is shallower than Kolmogorov.

4. Implications: Isotropic, Kolmogorov Sheets?

The indistinguishability of spectral indices measured in orthogonal directions implies that the spatial statistics of the $24\,\mu$m emitting regions are isotropic.

Given that the structure of the ISM is thought to be dominated by magnetohydrodynamic (MHD) phenomena, one might naively expect a preferred direction for the structure, namely the magnetic field direction. Simulations of compressible MHD turbulence by Cho & Lazarian (2003) show that, even though a gas pressure-dominated medium would yield an anisotropic density field, the density can in fact be isotropic if the medium is dominated by magnetic field pressure. The Cho & Lazarian model results in a velocity field with either Kolmogorov scaling ($E \propto k^{-5/3}$ for Alfvén and slow MHD modes) or close to Kolmogorov scaling ($E \propto k^{-3/2}$ for fast modes).

Kolmogorov behavior is also predicted by the recent intriguing description of the structure of the ISM by Hodge & Deshpande (2005). This model posits that the atomic hydrogen in galaxies is driven by supernova ejecta. In this scenario energy is injected by supernova blast waves and the gas dynamics are governed by momentum conservation; no detailed MHD phenomena are considered. The underlying velocity structure of the ISM that results is described by a single power law that follows Kolmogorov statistics. Measured column density power spectra are nearly always shallower than Kolmogorov, consistent with our results (Fig. 1).

A possible reason for observing shallower than Kolmogorov spectra is given by Goldman (2000), who notes that H I emitting regions are often smaller along the line of sight than their sizes in the plane of the sky (for observational evidence of the cold H I gas being sheetlike, see Heiles & Troland 2003). This is consistent with the the ISM being shaped on large scales by supernova explosions. In such a medium, the observed power spectrum will have a break at a spatial frequency that depends on the line of sight thickness of the emitting medium, and the low k spectral index will be shallower than the high k index by unity (Miville-Deschênes, Lagache, & Puget 2002). We find 4 out of 5 regions in our sample with dual power laws in the x-direction have indices separated by about unity. Two regions, G105.6 + 4.0 and G254.4 − 9.0, have a high k index that is close to the Kolmogorov value. We conclude that our data are consistent with a sheetlike medium with the underlying density and velocity statistics being Kolmogorov and isotropic.

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