SECTION II.6

SMALL-SCALE STRUCTURE AND STAR FORMATION

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Chairmen: F.J. Kerr and R.D. Davies

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A. Blaauw introducing Symposium participants to the historical exhibition about Kapteyn and Van Rhijn CFD

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SMALL-SCALE STRUCTURE AND MOTIONS IN THE INTERSTELLAR GAS

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ABSTRACT: The interstellar medium shows turbulence whose velocity and density spectra are surprisingly like a Kolmogoroff law, in spite of the fact that the turbulence is generated mainly by microscopic explosions, rather than a cascade of energy from larger to smaller scales.

The question of how to describe the small-scale structure and motions in the interstellar medium leads to the question of turbulence. Although there are clearly random variations, it is less clear whether these fit a turbulence spectrum. The fundamental question is whether there is a cascade of kinetic energy from large-scale structures to smaller scales, just as there is in the classical Kolmogoroff problem of dissipation of energy in a viscous fluid. Some of the evidence in favor of such a cascade is compiled by Larson (1981), who draws a diagram similar to fig. 1. Here I take only observations of ^{13}CO, plotting the rms velocities (in this case taken from the line widths) versus the size of the region for many different clouds (points with names given). Recent work by Myers and Benson (1983) using NH_3 observations of very small structures in the Taurus and Ophiuchus clouds is indicated by the oval in the lower left of fig. 1. The random velocity distribution of diffuse clouds has been measured in several ways (reviewed by Crovisier 1978), this distribution is shown by the larger circle at the top right of fig. 1. Internal random velocities of diffuse clouds can be estimated knowing the spin temperature (Dickey et al. 1978, Crovisier 1981). These fall in the smaller circle on fig. 1. Finally recent results from the Columbia survey of CO in the galactic plane (Dame et al. 1983) show a fairly convincing correlation between size and random velocity for molecular clouds and giant-molecular-cloud+HII-region complexes which is indicated by the line of fig. 1. It is interesting that this line has quite a different slope from the data points compiled by Larson, which show velocity increasing roughly with size to the 0.38 power, curiously close to that found in a Kolmogoroff turbulence spectrum (0.33). This would not necessarily be expected, since the interstellar medium is anything but incompressible, and the motions are highly supersonic. On the other hand Dame et al. find slope one for their correlation. An easy way to understand Dame's relation is to use the virial theorem with

H. van Woerden et al. (eds.), The Milky Way Galaxy, 311–317.

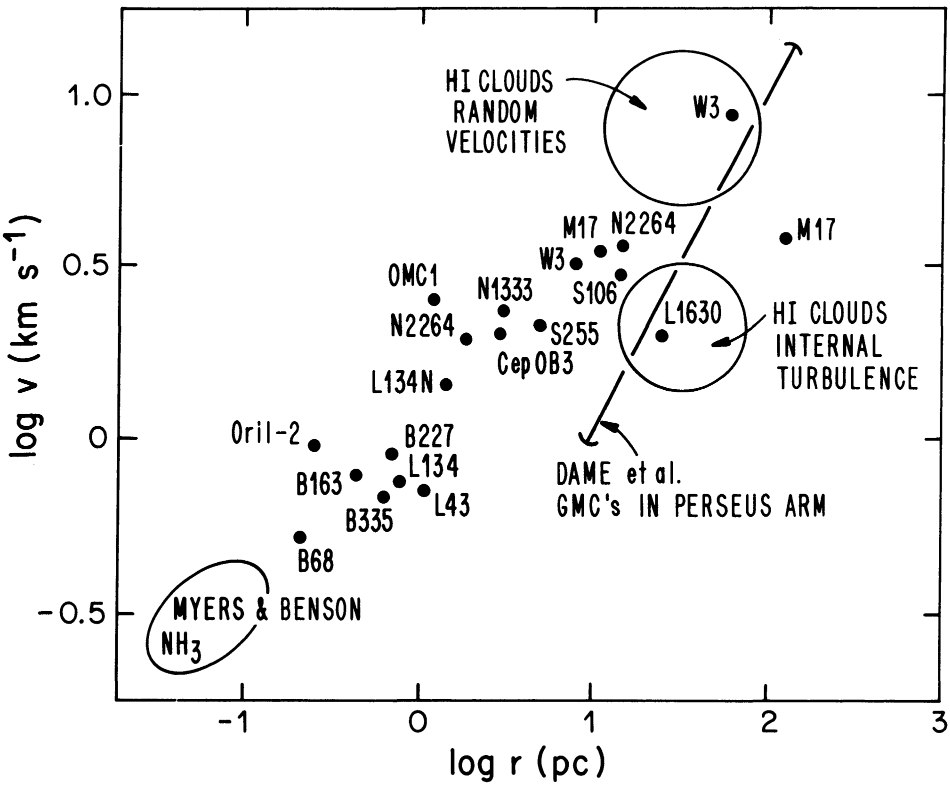

Figure 1. Random velocity vs. size in the interstellar medium.

constant density, which always gives a linear correlation between random velocity and size. The Columbia data suggest density $<n(H_2)> \sim 8$ cm^{-3}, two other densities (0.3 and 300 cm^{-3}) are shown as dashed lines on figure 2. It is interesting that giant HII regions in nearby spiral galaxies (Melnick 1977) also fit nicely with the correlation of Dame et al.; Larson on the other hand would have the density increase with decreasing size, as is shown by density tracers such as NH_3.

The source of the kinetic energy in these motions is not clear. One possibility is galactic differential rotation (eg. Hunter and Fleck 1982). For a flat rotation curve with A = 15 km s^{-1} kpc^{-1}, the shear due to differential rotation is illustrated by the dash-dotted line in the lower right of fig. 2. These velocities are not high enough to explain the random motions observed in the interstellar medium. For galactic rotation to cause the interstellar turbulence requires a moderator, such as spiral shocks or the magnetic field, which can concentrate the shear velocity over a large area and inject violent motions on small scales. An alternative is microscopic injection of kinetic energy by supernovae, as suggested long ago by Spitzer (e.g. 1978). Two possibilities for the expansion of a supernova remnant are traced on the top of fig. 2. These lines are obviously not random motions, they are the bulk motion of an expanding shell; but eventually they will be randomized by collisions

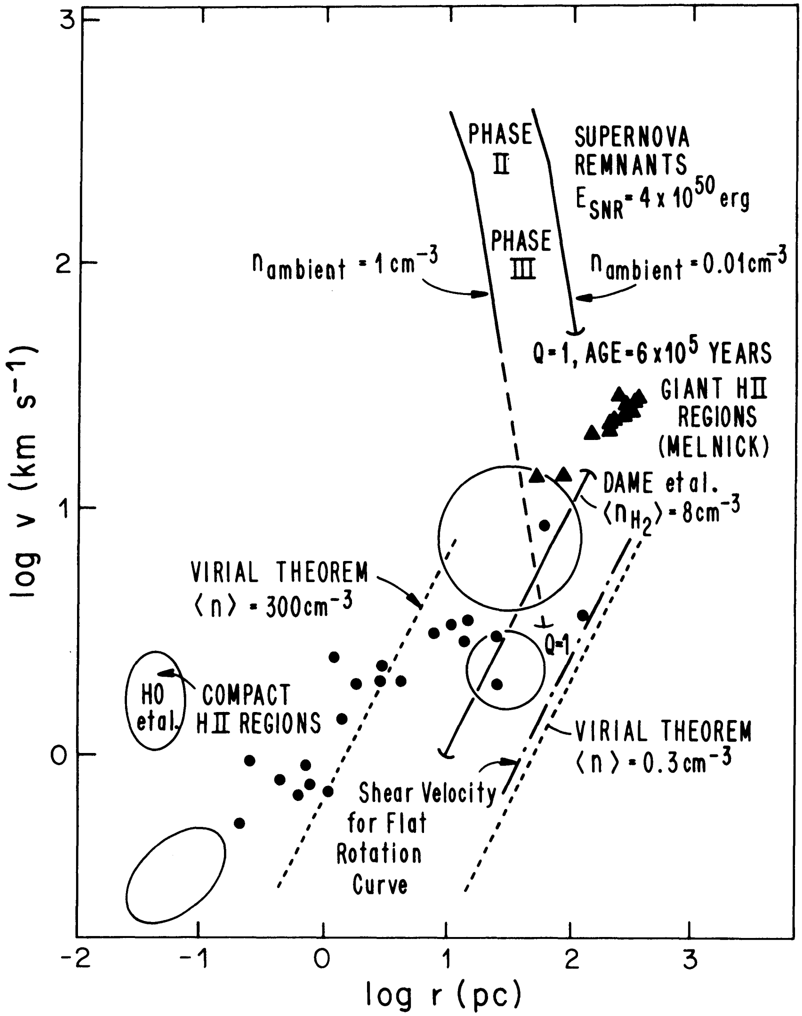

Figure 2. Simple theoretical explanations for fig. 1.

among nearby shells, just as rain drops falling on a pool of water cause at first ordered expanding rings which are soon converted to random motions by collisions with others. The age at which this randomization occurs is given by the porosity parameter Q (Cox and Smith 1974, McKee and Ostriker 1977); the velocity and size of the shell when Q = 1 predicts where on fig. 2 the turbulent motion is injected by this process. Unfortunately we do not understand how the system of clouds relaxes, since cloud collisions are so inelastic (Hausman 1981, Scalo and Pumphrey 1982). This problem is also central to understanding the cloud mass spectrum (Cowie 1980).

In dense molecular clouds other microscopic sources of turbulence are important. One theory which has abundant observational support is

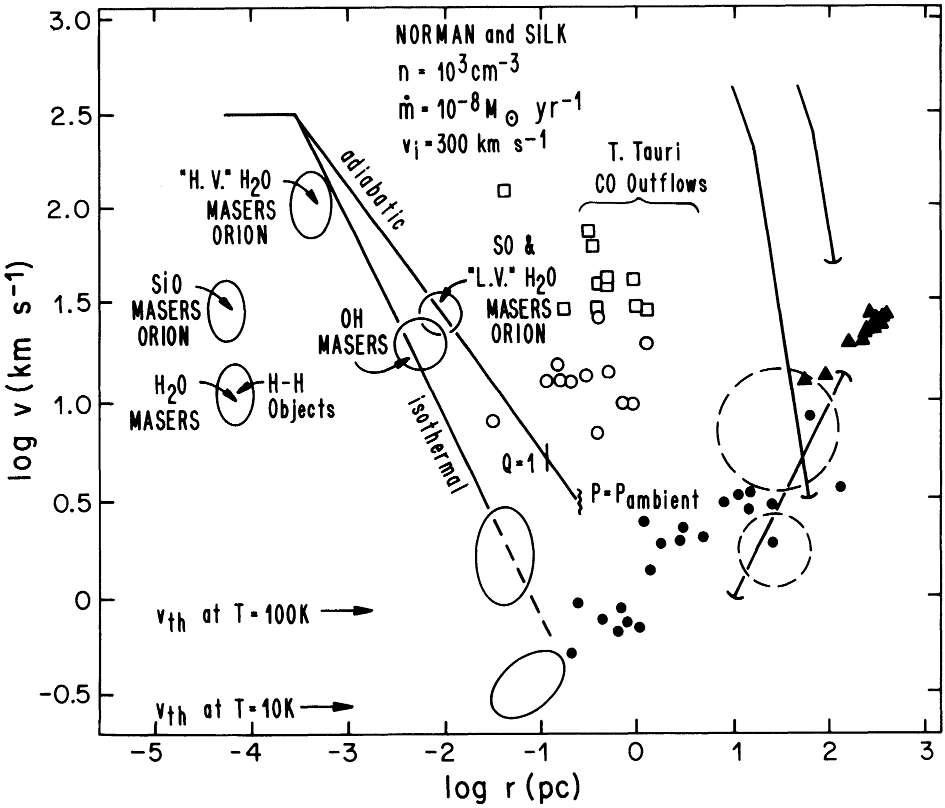

Figure 3. Figure 1 extended to star-formation regions.

that of Norman and Silk (1980), which discusses the effects of winds from pre-main-sequence stars on the dense clouds in which they form. This theory was originally motivated by Hα observations of T Tauri stars; recently there have been detections of such winds using many molecular tracers, especially CO. The CO detections are shown as circles (Edwards and Snell 1983) and crosses (Bally and Lada 1983) on fig. 3, which is once again the same velocity vs. size plot as above, but with a still smaller scale. Again these are not random velocities but ordered expansion which will be randomized by collisions with other shells. It is this collision process which causes the interstellar bullets which drive a rapid agglomeration process leading to star formation. Infrared observations of star-formation regions such as Chameleon (Hyland et al. 1982) and Ophiuchus (Wilking and Lada 1983) show just about the density of pre-main-sequence stars required by the Norman and Silk model (Beckwith et al. 1983). Theoretical predictions for the expansion of such T Tauri shells are illustrated on fig. 3. As for supernova shells, the expansion begins as ordered motion on the upper left, then converts to random motions somewhere near the lower right end of the diagonal lines, where Q $\sim$ 1. It is interesting that the highest-velocity molecular outflows detected (e.g. Orion) are considerably stronger than predicted

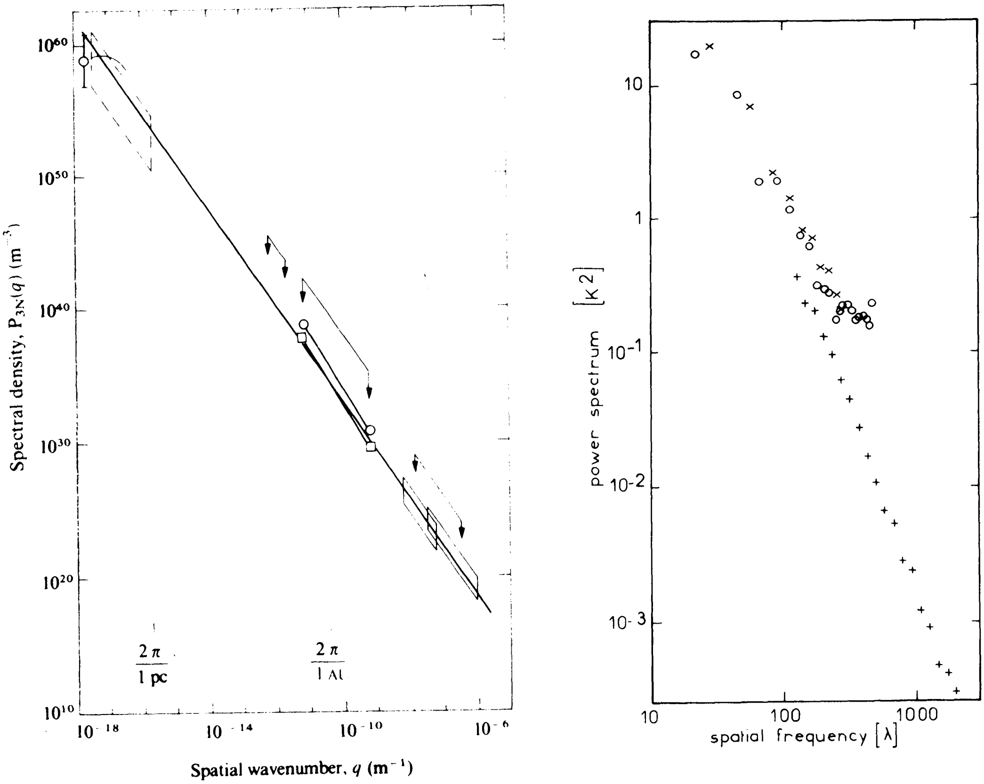

Figure 4. Recent measurements of the interstellar turbulence spectrum.

by ordinary T Tauri winds. Also shown on fig. 3 are observations of various masers which trace expanding shells around stars at smaller radii (eg. Genzel et al. 1982) and the recent aperture-synthesis study of SO in Orion (Plambeck et al. 1982). These scatter over various expansion velocities and sizes down to a few AU, but the evidence is fairly clear that stellar winds can generate the turbulent velocities needed to support dense molecular-cloud cores and globules.

This is the picture of small-scale motions which has been emerging over the last several years. There are problems with this picture. Figures like 1 - 3 illustrate inhomogeneities, they do not describe a statistically homogeneous process. It is not fair to compare the random motion measured in, say, the Kleinmann-Low region with the random motion measured over the entire Orion molecular cloud, and draw a spectrum between these points. The small-scale measurement should describe a region typical of any small volume chosen at random within the larger region. Obviously the OMC is not filled with K-L's! To construct a turbulence spectrum properly we should weight all points equally.

Two alternative means can be used to describe turbulent motions: the correlation function or the power spectrum. A nice example of both treatments applied to the motions of interstellar clouds is given by Kaplan (1966). A problem with Kaplan's analysis is that correlation in density (i.e. clouds) imposes a correlation in velocity. To study the turbulence spectrum we must first understand the density spatial power spectrum. This has been attempted for various phases of the interstellar medium, but with only preliminary results. One example, shown on the left on figure 4, is for the ionized gas which causes the pulsar scintillations (Armstrong et al. 1981). Various kinds of observations combine to suggest a power-law spectrum over a very broad range of sizes, from many parsecs to much less than an AU. The slope of this power law is surprisingly close to 11/3, which in this notation corresponds to the Kolmogoroff spectrum. This may have implications for the velocity spectrum as well, since the density and velocity spectra are often the same in astrophysical plasmas (Neugebauer et al. 1978). Another tracer to use to measure the power spectrum of small-scale fluctuations in the interstellar medium is the 21-cm emission. Studies of this have been done by Crovisier and Dickey (1983). On the right of fig. 4 is a spectrum from the former work, showing the spatial power spectrum as measured by four different telescopes. Here again we see a power law, with slope in the range 2.5 to 3, i.e. somewhat flatter than Kolmogoroff. More studies of this spectrum using other tracers of the interstellar medium (e.g. inside molecular clouds) would be of great interest.

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DISCUSSION

B.G. Elmegreen: An important clue to the origin of the largest clouds, and to the initiation of star formation on the largest scales, comes from the observation that these clouds have the Jeans mass, and that their separations are the Jeans length, as measured in the ambient interstellar medium. Also, some of the hierarchy of scales you attribute to a turbulent cascade may instead be the result of self-gravitational fragmentation. This process may not operate down to scales as small as single stars, but it could account for the larger-scale clumpy structure seen in some clouds.

Dickey: You can play with the Jeans mass here, as Larson does, for example. Constant density gives lines parallel to that of Dame et al. in Figures 1-3; to follow both the Jeans mass and the virial theorem Larson changes the density as a function of size. I don't think we have very good observational indicators of the masses of individual clouds on small scales, so I have not talked about mass. But yes, if you assign masses to these clouds based on the virial theorem, you get an initial mass function. However, if you don't believe there is a cascade of turbulence down the virial-theorem lines, then I don't see how the "machine" runs.

Elmegreen: Well there are other ways to cascade, there is simple gravitational fragmentation.

Dickey: Yes, that is supposed to take over on the smallest scales. Gravitational fragmentation peels small clouds off the log(v)-log(r) line. That probably works, but the evidence to date is not entirely convincing.

Centre: Dickey between Iwanowska (left), G.D. van Albada and Liszt. Front row: De Zeeuw, second row: Pismis and Wramdemark. Fourth row: Hermsen, Bloemen and Fujimoto. Further behind: Yuan and Terzides; Israel and Van der Laan; Jackson.

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