RevMexAA (Serie de Conferencias), **3**, 289–291 (1995)

TURBULENCE IN THE ISM

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RESUMEN

Se discute la formación de nubes interestelares por compresión turbulenta. La dimensión fractal 2D de los límites de las nubes pueden estar relacionados con la función de distribución de las masas de las condensaciones proyectadas dentro de las nubes, $n(M) \propto M^{-1.7}$. La distribución de masas tridimensional de las condensaciones y la función de masas estelares pueden estar relacionadas con la dimensión fractal 3D de las nubes, lo que da $n(M) \propto M^{-2.2}$. La formación de nubes a menudo empieza en gran escala con una inestabilidad lineal cuyo remanente es una bien definida longitud de Jeans para la separación entre los complejos moleculares gigantes a lo largo de los brazos espirales. El crecimiento posterior de la inestabilidad produce turbulencia y estructura fractal debido a los movimientos alimentados por autogravedad.

ABSTRACT

The formation of interstellar clouds by turbulence compression is discussed. The 2D fractal dimension of cloud boundaries may be related to the distribution function of projected clump masses within the clouds, $n(M) \propto M^{-1.7}$. The three-dimensional mass distribution of clumps, and the stellar mass function as well, may be related to the 3D fractal dimension of clouds, which gives $n(M) \propto M^{-2.2}$. Cloud formation often begins on a large scale with a linear instability whose remnant is a well-defined Jeans length for the separation between giant cloud complexes along spiral arms. Subsequent growth of the instability produces turbulence and fractal structure because of motions fed by self-gravity.

Key words: **IMS: CLOUDS — IMS: STRUCTURE — TURBULENCE**

1. INTRODUCTION

Interstellar clouds were discovered in the late 1930's and early 1940's by their narrow line absorption of stellar spectra. Early work by Dunham (1937), Adams (1941), and others determined some of their basic properties. The two phase model began in 1965 when Clark (1965) found H I in emission that was not visible in absorption; this was taken as evidence for a warm, low-density phase of H I. These observations were soon explained in terms of a thermal instability by Field, Goldsmith, & Habing (1969). This model required a penetrating source of ionization and heating, such as cosmic rays or X-rays, so that the gas could remain mostly neutral. When *Copernicus* observations failed to observe the predicted highly ionized states from these radiation sources (Mezaros 1973), the thermal instability model had to be abandoned as the main mechanism for cloud formation. The next series of models proposed that clouds formed by localized expansions around stars or other high pressure sources. This began with Hills (1972) and ended with McKee & Ostriker (1977).

Today a more comprehensive explanation for cloudy structure seems to be that most of it arises from a combination of two effects: gravitational instabilities and highly pressurized motions, all followed by supersonic, sub-Alfvenic turbulence and the associated compression to very small scales. The importance of turbulence follows from the power-law scalings between size, mass, density, and velocity (Larson 1981) and from the fractal structure of cloud edges (Beech 1987; Falgarone, Phillips, & Walker 1991).

2. TURBULENCE

The non-linearity of the equations of hydrodynamics causes high amplitude structures to change their shape in a way that continuously broadens the wave spectrum to include smaller and smaller scales. The way in which this steepening occurs is not understood and may in fact have many different forms depending on the initial conditions. A single wave train merely steepens into a shock front and then damps at the leading edge, whereas a complex pattern of motions can drive a cascade of energy dissipation and sharp gradients that take on a fractal structure.

The mass spectrum for clumps in clouds, and perhaps even for whole clouds, can be the result of projection effects in a fractal hierarchy of structures. If the fractal dimension of a structure is D, then the number of self-similar structures, with sizes λ that are larger than L, is given by (Mandelbrot 1982):

$$N(\lambda > L) \propto L^{-D}. \quad (1)$$

This implies that the differential number distribution of regions with sizes between L and $L + dL$ is $n(L)dL = (dN/dL)dL \propto L^{-D-1}dL$. If the mass enclosed within a region of size L is $\propto L^{\kappa}$, then the differential mass function for cloudy substructure is

$$n(M)dM \propto M^{-(D+\kappa)/\kappa}. \quad (2)$$

Observations suggest $D = 1.4$ (Falgarone et al. 1991) and $\kappa = 2$ (Larson 1981), in which case $n(M) \propto M^{-1.7}$, which is in the observed range for both cloud and clump spectra (Solomon et al. 1987; Dickey & Garwood 1989; Blitz 1993). Thus many of the clumps that are seen in molecular cloud maps can result from the same fractal turbulence that is seen at the cloud edges.

An important consideration here is that $D = 1.4$ for projected cloud boundaries, and therefore that $n(M) \propto M^{-1.7}$ only in projection. Many of the clumps that enter into this observation of a clump mass distribution could be blends of several clumps at different positions along the line of sight. If cloud clumps could be observed in their true three dimensions, then the mass distribution function could be steeper. To calculate this, we should use the 3D fractal dimension, which is $D + 1 = 2.4$. This would produce a mass distribution function $n(M) \propto M^{-2.2}$, which is closer to the stellar mass function than the projected clump mass function. Perhaps the stellar mass function is a remnant of the true mass function of clumps, as distinct from the projected mass function.

Whole giant molecular clouds can also result from fractal turbulence if they are small parts of even larger clouds, as suggested by Elmegreen & Elmegreen (1983, 1987). The largest clouds presumably form by gravitational instabilities in the ambient gas. These instabilities begin in the linear hydrodynamic regime and have a well-defined length scale without obvious fractal structure. The ambient gas loses its fractal structure on the scale of kiloparsecs because of differential rotation and other mixing in the Galaxy. As the instability develops into the non-linear regime (presumably because self-gravity feeds energy into supersonic motions), the non-linear aspects of the equation of motion begin to produce fractal structure on smaller scales. It is conceivable that most structures smaller than 2π times the galactic scale height are fractal and turbulent, and most structures larger than this are not.

The observation that $\kappa \approx 2$ may result from turbulence too, because, for approximate pressure equilibrium, $\rho \propto v^{-2}$, whereas for turbulence, $v \propto L^{0.5}$ or so, thus $\rho \propto L^{-1}$ and $M \propto L^2$.

Another property of turbulence is that many of the small-scale structures should be short-lived. The lifetime should scale with size L as $L/v \propto L^{0.5}$. Only if self-gravity is important on the small scale should a piece survive very long. Elmegreen (1993) suggested that self-gravity is important in turbulence-compressed regions only inside virialized clouds. In diffuse clouds, turbulence-compressed regions should be transient. Perhaps this is why only virialized clouds form stars.

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