TURBULENCE AND COLLAPSE IN STAR-FORMING MOLECULAR CLOUDS

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Abstract. We review developments in our knowledge of interstellar turbulence, and star-forming gravitational collapse. The turbulent motions in interstellar line widths are supersonic, by a factor exceeding ~ 10 on size scales ~ 1 pc, and are progressively smaller on smaller size scales, becoming subsonic by a factor ~ 10 for low-mass dense cores of size ~ 0.1 pc. Line width–size relations $\Delta v \sim R^{1/2}$ in a single line over a wide range of cloud sizes probably reflect little more than virial balance. Line width–size relations over several lines within a cloud vary from low-mass to massive cores, and probably reflect the structure of the density and magnetic field within the cloud. Searches for infall in star-forming clouds rely on line broadening, line asymmetry, spatial variation of the line centroid, and red-shifted absorption. Early claims of infall based on CO lines, coarse angular and spectral resolution, and distant sources were sensitive only to large-scale homologous collapse. More recent observations are sensitive to "inside-out" collapse over sizes 0.01 pc and velocities 0.05 km s^{-1}, and appear consistent with gravitational infall in several well-studied low-mass sources.

1. Introduction

Since radio astronomers first detected interstellar spectral lines, they have tried to apply the physical information derived from the lines to astrophysical problems of the interstellar gas. In this paper we describe work on two of the most fundamental of these problems—the turbulent motions in molecular clouds and the collapse motions associated with star formation.

2. Turbulence

2.1. SUPERSONIC LINE WIDTHS

The earliest radio measurements of interstellar lines of H I (Ewen & Purcell 1951), OH (Weinreb et al. 1963), and CO (Jefferts, Penzias & Wilson 1970) showed that their widths are supersonic—they generally exceed the thermal line width by a significant factor. These observations led to the idea that the supersonic motions arise from large-scale gravitational collapse (Goldreich and Kwan 1974). However, such ubiquitous cloud collapse would imply a star formation rate much higher than the few $M_\odot$ yr^{-1} known from stellar observations (Zuckerman & Evans 1974). A more promising explanation is that the supersonic line widths are magnetic in origin, and correspond to the propagation of magnetohydrodynamic waves (Arons & Max 1975). The ionization of a molecular cloud, with log electron fraction of order -7 to -5, can be maintained by cosmic rays and ultraviolet photons. Even this weak ionization is sufficient to couple the magnetic field and the neutrals together via ion-neutral collisions. If sufficiently excited, the neutral gas will move at a speed close to the wave propagation speed, or the Alfven speed, $v_A = B/(4\pi\rho)^{1/2}$. Here B is the magnetic field strength and ρ is the mass density of neutrals and ions. Typical estimates of v_A are of order 1 km s^{-1}, comparable to observed CO line widths.

2.2. SUBSONIC LINE WIDTHS

After OH and H_2O were discovered, the 1.3 cm $(J, K) = (1,1)$ rotation-inversion line of NH_3 revealed the third radio molecule in the interstellar gas (Cheung et al. 1968). The ability of NH_3 lines to reveal properties of quiescent molecular gas was not realized until nearly a decade later, when sufficiently sensitive maser amplifiers were developed. NH_3 line observations of "dense cores" —opaque spots of high obscuration in dark clouds on the Palomar optical photographs—showed emission localized to $\sim$ 0.1 pc from gas with temperature 10 K, density $\sim 10^4 cm^{-3}$, and FWHM line width $\sim$ 0.3 km s^{-1}. This width is subsonic, i.e., narrower than the thermal width of H_2 gas (0.44 km s^{-1}; Rydbeck et al. 1977; Ho et al. 1977). These subsonic line widths of NH_3 and other heavy molecules, such as HC_3N, were soon found to be widespread in the condensations in nearby dark clouds (Churchwell, Winnewisser & Walmsley 1978; Myers, Ho & Benson 1979; Myers & Benson 1983; Myers 1983). One of the smallest nonthermal components is in L1512, where $\sigma_{NT} = 0.038 \pm 0.005$ km s^{-1}, less than one-tenth of the thermal velocity dispersion σ_T (Fuller & Myers 1993).

2.3. LINE WIDTHS AND MAP SIZES

As dense cores were mapped in different lines, it became apparent that the size of a map varies from line to line, from ~ 0.1 pc for NH_3 to ~ 1 pc for CO. This was understood as a consequence of decreasing critical density for excitation $n_{\rm cr}$, since from NH_3 to CO $n_{\rm cr}$ declines from $\sim 10^4 {\rm cm}^{-3}$ to $\sim 100 {\rm cm}^{-3}$, taking radiative trapping into account. In addition, the width Δv of the line generally increases with a measure of its map size R, such as the geometric mean of the maximum and minimum FWHM diameters. This increase can be described as $\Delta v \sim R^p$, with $p = 0.3$–0.5 (Ho et al. 1977; Martin & Barrett 1978; Myers et al. 1978; Snell 1981). When only a few examples were known, this "line width–size relation" was interpreted in terms of large-scale sytematic motion in TMC-2 in Taurus (Ho et al. 1977), and in terms of radial inward motion which is slower than free-fall, in L1688 in Ophiuchus (Myers et al. 1978).

By the early 1980s nearly 100 clouds within a few kpc of the Sun had been mapped in the 2.7 mm $J = 1$–0 line of ^{13}CO. Compiling the information in these ^{13}CO maps, and in maps of NH_3 and H_2CO lines, Larson (1981) showed that the increase of line width with map size is a distinct trend, not only for the few lines which could be observed in a cloud, but also for the many clouds recently mapped in the ^{13}CO line. Larson's linear fit through a log-log plot of Δv v. L, where L is the largest map dimension, has slope 0.38. Larson also showed that the mean density n in a map tends to decrease with increasing map size as L^{-1}, suggesting that the observed clouds have constant column density of a few $\times 10^{21} {\rm cm}^{-2}$ within scatter of nearly a factor of 10. With similar large scatter, Larson showed that his cloud data are also consistent with "virial equilibrium," where the cloud mass M, the line width Δv, and the map size R follow $\Delta v^2 \sim GM/R$, with G the gravitational constant.

These "Larson's Laws" $\Delta v \sim R^p$, and $n \sim R^{-q}$, with $p \sim 0.4$ and $q \sim 1$, can be understood to follow from two independent relations. One is generally accepted to be virial equilibrium, but the physical basis of the second is still uncertain. Larson (1981) proposed that the second relation is the Kolmogoroff turbulent energy cascade from large to small scales, which for the "inertial range" of size scales, where no dissipation occurs, would yield $\Delta v \sim R^{1/3}$. More recent line width–size studies for large samples tend to find p closer to 0.5 (e.g., Falgarone & Puget 1986; Falgarone, et al. 1992).

The line width–size relation from cloud to cloud in a line is much more distinct than from line to line in a cloud. Two surveys of the Galactic plane in the ^{12}CO line showed $\Delta v \sim R^{0.5}$ (Dame et al. 1986; Solomon et al. 1987), and a compilation of various observations from cloud to cloud, including those used by Larson (1981), also showed $\Delta v \sim R^{0.5}$ over three decades in R (Myers & Goodman 1988). In contrast, the line width–size relations from line to line in a cloud shows slopes and intercepts differing according to the cloud, and also to the mass of the star characteristic of the cloud (Fuller & Myers 1992; Myers & Fuller 1993; Caselli & Myers 1995).

2.4. LINE WIDTH–SIZE RELATION FROM CLOUD TO CLOUD IN A LINE

The line width–size relation from cloud to cloud in a line, with $\Delta v \sim R^{0.5}$, has a simple explanation based on virial equilibrium and the relatively small variation of the observed column density N compared to the relative variation of the cloud size R (Larson 1981, Myers 1990). To illustrate this point, consider a uniform cloud of radius R, mean column density N, velocity dispersion σ, mean molecular mass m, and ratio of kinetic and gravitational energy density $\mathbf{K/G}$. Then it follows that

$$\sigma^2 = (2\pi Gm/5)\ (K/G)\ NR \qquad (1)$$

Eq. (1) shows that $\sigma \sim R^{1/2}$ if most clouds in the sample are close to virial equilibrium ($\mathbf{K/G} \approx 1$) and if the relative range of R is much larger than the relative range of N. This suggests that the line width-size relation from cloud to cloud in a line, with a large range in cloud sizes R, is little more than a statement of virial equilibrium. In a survey of clouds at a wide range of distances, R can range over several decades. The relatively small range of N, less than one decade, can arise for several reasons, including sample selection, instrumental sensitivity, or, if the magnetic field strength B is close to its equipartition value, a small range in B from cloud to cloud (Myers & Goodman 1988a).

2.5. LINE WIDTH–SIZE RELATIONS FROM LINE TO LINE IN A CLOUD

On the other hand, the line width–size relation from line to line in a cloud varies substantially from one cloud to the next, and contains more physical information about the cloud structure than does eq. (1). Observations among "low-mass" cores in Taurus, Ophiuchus, Cygnus, and Cepheus are summarized by Fuller & Myers (1992; FM) and Myers & Fuller (1992, 1993). Observations of both low-mass cores, as in FM, and "massive" cores in Orion A and B are discussed by Caselli & Myers (1995; CM). These observations indicate that low-mass cores have narrower lines, which increase more rapidly with size scale than do massive cores. Thus low-mass cores have a transition from a nonthermally-dominated exterior to a thermally-dominated interior at a radius ~ 0.1 pc, while massive cores remain nonthermally dominated for all observed scales. Figure 1 summarizes observations of line width–size relations for low-mass and massive cores.

Figure 1. Line width–size relations between the nonthermal component of the line width and the map radius for (a) 18 massive cores in Orion, and (b) 8 low-mass cores in Perseus, Taurus, Orion, Ophiuchus, and Cepheus. Dashed lines labelled Δv_{T} represent the thermal part of the line width of the molecule of mean mass, assuming temperature 18 K (massive cores), or 10 K (low-mass cores). Massive cores have broader lines and a slower rate of increase of line width with size than do low-mass cores (Caselli & Myers 1995).

"TNT" models of hydrostatic equilibrium, including thermal motions due to uniform kinetic temperature, and nonthermal motions which increase as a power law of radius, match the line width–size relations of low-mass and massive cores, and predict typical column densities of ~ 3 and $20 \times 10^{21}\mathrm{cm}^{-2}$, in good agreement with observations (CM). In these models the density profile of the typical low-mass core gradually changes from $n \sim r^{-2.0}$ to $n \sim r^{-1.1}$, with equal contributions to the velocity dispersion from thermal and nonthermal motions at $r = 0.1$ pc. In contrast, the typical massive core maintains a density profile $n \sim r^{-1.6}$ over all observed scales.

The internal structure of the CM cores has also been modelled as a self-gravitating, pressure-bounded "pure logotrope" with equation of state

$$P = P_c[1 + A \ \ln(\rho/\rho_c)] \tag{2}$$

where P and ρ are the kinetic pressure and the mass density, the subscript c denotes values at the center, and A is a constant determined from fitting to the CM data to be 0.18 (McLaughlin & Pudritz 1996). In this model, low-mass cores have flatter density structure than massive cores, which are closer to critical stability against collapse. This model provides a good fit to the line width–size relations and provides a uniform framework in which to model both low-mass and massive cores.

The TNT and logotropic models fit the observed line width–size data well, but do not specify the physical basis of the nonthermal motions. The coupling of the magnetic field to the neutrals seems necessary to maintain the amplitude of the observed nonthermal motions, and estimates of ionization in molecular cloud cores suggest that ion-neutral coupling is sufficient to support MHD waves, even in the densest cores (Myers & Khersonsky 1995). Further, the relatively shallow dependence of the kinetic pressure on radius, $P \sim r^s$, with $0 < s < 1$, from the line width–size relations, combined with the evidence for similarity of magnetic and kinetic energy density in some clouds (Myers & Goodman 1988b), suggest that the magnetic field must also vary very slowly with radius in dense cores.

Magnetic support of molecular clouds, and its relation to the line width–size relations, are the subject of many recent theoretical discussions, including those of Henriksen (1991); McKee et al. (1993); Fatuzzo & Adams (1993); McKee & Zweibel (1995); Zweibel & McKee (1995); Fleck (1996); and Gammie & Ostriker (1996). Gammie & Ostriker (1996) use numerical simulations to investigate a system where nonlinear MHD waves propagate, interact, and decay. They find that the turbulent spectrum of velocities approaches that expected for $\Delta v \sim R^{1/2}$. If the line width–size relations originate in nonlinear MHD turbulence, it will take substantial computational power to simulate these phenomena for a compressible, self-gravitating medium in three dimensions.

3. Kinematic Studies of Infall

3.1. EARLY ATTEMPTS 1974 – 1992

In the same year that Goldreich and Kwan (1974) proposed the homologous collapse of GMCs, Loren, et al. (1974) observed spatially concentrated CO line broadening toward R CrA , LkHα 198, and Mon R2 which they interpreted as indicating infall. This spatial concentration would soon have another, more convincing explanation, in terms of molecular outflow.

A more specific diagnostic of infall compares optically thick and thin line profiles. In an infalling system with centrally elevated excitation temperature, the peak of the thicker profile is skewed to the blue, with a self-absorption dip for sufficiently large optical depth (Hummer & Rybicki 1968; Lucas 1976, Snell & Loren 1977; Leung & Brown 1977; Leung 1978; Zhou 1992, Walker, Narayanan, & Boss 1994). Model profiles demonstrate this effect, with more pronounced self-reversals for inward-increasing velocity laws (e.g., $v \sim r^{-1/2}$) than for homologous collapse ($v \sim r$). Such skewing was observed in Mon R2 by Loren et al. (1974), and further examples, including self-reversal, were reported in ρ Oph A by Encrenaz, Falgarone, & Lucas (1975); in NGC 1333 by Loren (1976); and in seven other regions, primarily of massive star formation, by Loren et al. (1981) and by Phillips et al. (1981). All of these regions showed self-reversal of their CO line emission, but in about half the cases the brighter peak was skewed to the blue, and in half to the red. The variety and complexity of the CO line profiles was more impressive than the case for infall. Similarly, asymmetrical ^{13}CO lines in the starless dark clouds TMC2 and L134N were modelled in terms of inward motions (Myers 1980), but further maps of the ^{13}CO line showed a complex pattern which was difficult to interpret.

In 1977 an important physical model of the collapse process was developed, starting not from uniform gas, but instead from centrally concentrated gas–a structure which would be expected in an isothermal, self-gravitating cloud (Shu 1977). This initial condition was a much more realistic approximation to the recent observations than maps of higher-density tracer lines, such as NH_3 and HC_3N, which have smaller extent than do maps of lower-density tracer lines, such as ^{13}CO and ^{12}CO. The self-gravitating isothermal sphere was also well-known theoretically (Chandrasekhar 1939). In the form of a singular isothermal sphere (SIS)—infinitely extended and infinitely dense at the center—it is simpler to model than the pressure-bounded sphere (Bonnor 1956; Ebert 1955), since the SIS has only one parameter—the kinetic temperature. Furthermore, Shu's similarity solution to the infall problem gave an important physical insight into the possible nature of star-forming collapse.

The mass shells of a collapsing SIS do not all fall in together, as in homologous collapse, but in sequence, from the inside out. Each collapsing shell removes the pressure support for the next, so the instantaneous locus where infall starts is an "expansion wave" moving outward at the sound speed. Inside-out collapse presents a much harder detection problem than does uniform collapse. The collapsing region moves slowly, with the infall speed close to the sound speed (0.19 km s^{-1} for gas at 10 K), and is small, extending outward only to a few hundredths of a pc in order to form a star of 1 $M_\odot$.

The first spectroscopic evidence for infall toward a previously unknown IRAS source was based on CS 5–4 and 2–1 observations toward IRAS 16293−2422 in the L1689 cloud in Ophiuchus (Walker et al. 1986). The asymmetrical CS 5–4 profile, with deep self-absorption, and the more symmetrical CS 2–1, C^{34}S 5–4, and C^{34}S 2–1 profiles were well-fit by infall models with inward-increasing velocity law $v \sim r^{-1/2}$, the asymptotic form of the inside-out collapse model. However, this infall interpretation was challenged by Menten et al. (1987), who mapped the CS 3–2 emission with resolution (17″) finer than that of Walker et al. (1986; 27″). Menten et al. found that the sense of asymmetry reverses from infall-like to outflow-like in about one-quarter of the map positions. They concluded the absorption and emission come from physically independent regions, and the shift in line asymmetry is due to rotation. Further complications arose as new observations indicated the "source" has two peaks at 6 and 2 cm, separated by ~ 750 AU (Wootten 1989), and has four CO outflow lobes (Mizuno et al. 1990).

Indications of large-scale collapse in regions of massive star formation have been reported, via red-shifted absorption against the continuum emission from H II regions, for W49 in the HCO^+ line by Welch et al. (1987), and for G10.6-0.4 in the NH_3 line (Keto, Ho, & Haschick 1987; Keto 1990). In these cases the relatively large spatial scales suggest that the infall is not necessarily associated with the formation of a single star, but instead represents gas falling toward a massive cluster of stars.

3.2. RECENT ATTEMPTS 1993 – 1996

The most detailed case, with the fewest objections, has been made for infall of the gas near the far infrared source in the isolated globule B335, observed in high-density tracer lines of CS and H_2CO (Zhou et al. 1993). There the effects of rotation and outflow appear much smaller than in IRAS 16293-2422, and the thick and thin profiles maintain their infall-asymmetry relationship over the map. Monte Carlo models of the line profiles, assuming the velocity and density laws of inside-out collapse, indicate an expansion wave radius of 0.03 pc, collapse age of 1×10^5 yr, mass infall rate of $3 \times 10^{-6} M_\odot yr^{-1}$, and a stellar mass of 0.4 $M_\odot$ (Choi et al. 1995).

Similar evidence for infall has been presented for L1527 in Taurus (Mardones et al. 1994; Zhou et al. 1994; Myers et al. 1995), and several other protostellar candidates are under intensive study. These relatively few sources cannot show the general prevalence of infall in young stellar objects, since in such few cases the line properties could arise from peculiarities in source structure and outflow motions.

Several efforts are underway to overcome the limitations of small-number statistics, of confusion from outflows, and of slow infall speeds. If infall candidates are well-selected to be at similar distances and are truly collapsing, surveys of such objects, made with sufficient resolution and sensistivity, should reveal a statistical excess of sources with infall asymmetry, since outflows should mask this effect in at most half of the cases. Surveys have been undertaken in lines of H_2CO and $C^{18}O$ (Wang et al. 1995), H_2CO, CS, C_3H_2, and N_2H^+ (Mardones et al. 1996), and HCO^+ and $H^{13}CO^+$ (Gregerson et al. 1996).

The slow infall speeds deduced from filled-aperture observations are masked by the random motions of the ambient dense core gas, complicating the detection problem. Interferometric observations so far have focussed on the relatively bright lines of CO and its isotopes, which are sensitive to densities $\sim 10^{3-4} cm^{-3}$. With tracer lines such as 1mm H_2CO, sensitive to density greater by a factor > 10, and with sufficient sensitivity, it should be possible to detect "infall wings" on small scales at high density, just as one detects "outflow wings" on large scales at lower density. At sufficiently short wavelengths, in the submillimeter, the continuum brightness temperature of the protostar should exceed the excitation temperature of the infalling gas. Then submillimeter interferometers should reveal red-shifted absorption against the protostar.

As techniques for observing infall have improved, so too have the tools for diagnosing and modelling infall systems. The velocity centroid of an optically thick line from an infall system becomes bluer as the map position approaches the center of infall, whereas for rotation the centroid becomes bluer on one side of the map and redder on the other (Adelson & Leung 1988; Walker, Narayanan, & Boss 1994). Monte Carlo codes have improved to the point where one need not use the large-velocity-gradient approximation for radiative transfer in situations where the expected gradients are small (Choi et al. 1995). A simplified analytic model of infall determines the characteristic infall speed of the gas forming the observed line via fitting of the line profile, and for two-peak lines via a formula depending only on observables (Myers et al. 1996).

3.3. OUTLOOK

This survey of old and new searches for infall raises the question whether the newer claims of infall evidence are also destined for refutation, once more detailed observations are made. To address this point, we note important changes in the way the more recent data have been taken. The recent observations of B335, L1527, and similar sources are made with much finer linear resolution (~ 0.01 pc) and spectral resolution (~ 0.05 km s^{-1}) than previous searches, and have been made using lines requiring much higher densities ($> 10^5$cm^{-3} for H_2CO rather than $\sim 10^3$cm^{-3} for ^{13}CO) for excitation. These changes have become possible largely because of the improvements in resolution and sensitivity of large millimeter-wavelength telescopes. Figure 2 illustrates this point with three versions of the $2_{12} - 1_{01}$ line of C_3H_2 at 85 GHz from the inside-out infall candidate protostar in L1527. With fine spectral resolution but coarse angular resolution (top), or with fine angular resolution but coarse spectral resolution (bottom), the two-peak infall signature is absent. Only with the combination of both fine spectral resolution and fine angular resolution is the infall signature visible.

These improvements suggest that the quantitative study of the kinematics of gravitational collapse is now underway, and that in the near future we may expect dramatic improvements in our knowledge of how stars form.

Figure 2. Spectra of the 85 GHz $J_{K-K+} = 2_{12} \rightarrow 1_{01}$ line of C_3H_2 in the star-forming core L1527, observed with differing angular and spectral resolutions, at the AT&T 7 m telescope by R. W. Wilson, and at the Haystack Observatory 37 m telescope (Myers et al. 1995). Only with the combination of both fine angular resolution (FWHM 25$''$) and fine spectral resolution (0.05 km s^{-1}) is the two-peak signature of infall motions evident.

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