Star formation: basic physics

Lectures 3/4 supplementary images
Daniel Price

Dense “cores” in Taurus

Owen et al. (see 465, 816)
A C$^{18}$O SURVEY OF DENSE CLOUD CORES IN TAURUS: CORE PROPERTIES

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ABSTRACT

This paper discusses observational results of physical properties of dense cores in the Taurus complex. The observations were carried out in the C$^{18}$O ($J = 1$–0) line at a linear resolution of 0.1 pc with the 4 m millimeter radio telescope at Nagoya University. Based on the previous $^{12}$CO observations of Mizuno et al. (1995) as a guide map, we obtained 7200 spectra (8 deg$^{-2}$) at a $2'$ grid spacing, corresponding to more than 90% of the area whose molecular column density is greater than $3.5 \times 10^{17}$ cm$^{-2}$. The total molecular mass of the C$^{18}$O cloud is estimated to be 2900 M$_{\odot}$, which is 43% of the mass of the $^{12}$CO cloud. About 97% of the C$^{18}$O spectra have an optical depth smaller than 0.5, and the C$^{18}$O emission is optically thin over almost all the region at a size scale down to $\sim 0.1$ pc. The basic structure of the C$^{18}$O cloud is clumpy. We identified 40 dense cores of $n(H_2) \sim 10^4$ cm$^{-2}$, whose mass ranges from 1 to 80 M$_{\odot}$. The average physical parameters of the C$^{18}$O cores are as follows: radius 0.23 pc, line width 0.49 km s$^{-1}$, column density $6.9 \times 10^{21}$ cm$^{-2}$, and mass 23 M$_{\odot}$. The mass spectrum of the cores, $dN/dM$ versus $M$, is fitted by a power law with an index of $-0.9 \pm 0.2$, which is significantly smaller than those of the previous surveys. Most of the cores are spatially elongated; the average aspect ratio is 1.8, and the direction of the major axis of the cores tends to be perpendicular to the typical direction of the optical polarization vectors. An analysis of correlations among the physical quantities of the cores indicates that the line width has a positive correlation with the mass and the column density, but not with the size. Most of the cores are roughly gravitationally bound and at least approximately in virial equilibrium.

Subject headings: ISM: clouds — ISM: individual (Taurus Cloud Complex) — ISM: molecules — ISM: structure — radio lines: ISM

1. INTRODUCTION

A dense molecular cloud core is considered to be a site of star formation. Molecular gas will contract gravitationally at some regions within a molecular cloud to form dense core leading to star formation and dissipation of the mass region (Elias 1978; Cohen & Kui 1979; Jones & Herbig 1979; Herbig & Bell 1988), and the complex is one of the most typical low-mass star-forming regions. The mass of the PMS stars is around 0.7 M$_{\odot}$ (Cohen & Kui 1979; Herbig & Bell 1988). The Taurus region is not affected by external

Fig. 1.—Positions of the cores selected are indicated on the C$^{18}$O integrated intensity map. The solid lines show the observed area. The lowest contour level and interval are 0.42 and 0.42 K km s$^{-1}$, respectively.
CMF was a factor of cluster embedded in the Orion Nebula (ALL07). However, the shape was very similar to that of the stellar IMF for field star origin of the stellar IMF. In our earlier study of the Pipe CMF 4), the CMF after modification of the individual core masses in each other. This was interpreted to indicate that the stellar IMF may not be relevant since CO does not trace the dense core mass function (DCMF) in a number of nearby molecular cloud complexes. For cores with masses in the range of about 4 million stars in the background of the complex. Approximately 160 individual cores are identified within the cloud and are marked by an open circle proportional to the core radius. Most of these cores appear as distinct, well separated entities.

3.1. Core Stability: From CMF to IMF

As thermally dominated, dense cores in pressure equilibrium with the surrounding cloud material, the Pipe cores are perhaps most appropriately modeled as Bonnor-Ebert spheres (e.g., Johnston et al. 2000; Alves, Lada & Lada 2001). Bonnor-Ebert spheres are pressure truncated isothermal spheres in hydrostatic and pressure equilibrium with their surroundings. Bonnor (1956) and Ebert (1955) investigated the stability of such pressure-confined isothermal spheres and showed that under a specific condition each object becomes unstable. This condition corresponds to the critical Bonnor-Ebert (BE) mass given by:

$$m_{BE} = 1.83 \left( \frac{\rho_0}{10^{-20} \text{ cm}^{-3}} \right)^{-1.5} \frac{\text{M}_\odot}{10^2}.$$  (1)

where $\rho_0$ is the mean volume density of the core. Above this mass cores are out of equilibrium and prone to fragmentation and/or collapse. Below this mass cores are in equilibrium states, primarily stable equilibrium states. For the mean density of the Pipe cloud (7.3 × 10^{-20} cm^{-3}), this critical mass is about 2 M\odot. In figure 9 we plot the ratio of core mass to critical BE mass, $m/m_{BE}$ (calculated individually for each core) against core mass. The two quantities form a tight relation which crosses the critical threshold ($m = m_{BE}$) at a mass of $\approx 2 \times 3 \times 10^{-2} \text{M}_\odot$. This is also the mass at which the cores appear to become gravitationally bound (figure 4)

The results presented above may have interesting ramifications for understanding the origin of the stellar IMF. In our earlier study of the Pipe CMF we showed that its overall shape was very similar to that of the stellar IMF for field stars and for the young Trapezium clusters embedded in the Orion Nebula (ALL07). However, the two functions (i.e., CMF and IMF) differed in their characteristic masses. The characteristic mass and mass scale of the IMF was a factor of $\sim 3$ higher than those of the stellar IMF which were very similar to each other. This was interpreted to indicate that the stellar IMF directly originates from the CMF after modification of the individual core masses in the CMF by a uniform star fragmentation would appear to have subsonic turbulence to an observer. This is inconsistent with our observations of the Pipe cloud where $\sim 70\%$ of the cores are characterized by subsonic turbulence (c.f. figure 2). Another important constraint provided by our observations is the fact that the cores are pressure-confined entities and in pressure equilibrium with an external pressure source, most likely provided by the weight of the Pipe cloud itself. As we discuss below, this constraint provides a potential critical insight into the origin of the core masses and the IMF.

Fig. 1. Dust extinction map of the Pipe nebula molecular complex from Lombardi et al. (2006). This map was constructed from near-infrared observations of about 4 million stars in the background of the complex. Approximately 160 individual cores are identified within the cloud and are marked by an open circle proportional to the core radius. Most of these cores appear as distinct, well separated entities.

Fig. 9. The ratio of core mass to Bonnor-Ebert critical mass for each individual core plotted against core mass. The entire core population appears to be characterized by a single critical BE mass of $\approx 2 \text{M}_\odot$. Cores with masses in excess of the critical mass are likely out of equilibrium and destined to form stars. There is also a large population of cores that are presently in equilibrium states. Most of these are likely in stable equilibrium states and thus are unlikely to collapse to form stars unless further perturbed via an increase in the external pressure, loss of internal pressure support (e.g., cooling), or a combination of both effects.
Figure 4. Normalised logarithmic radial flux density profiles of pre-
stellar cores L1544 and B133 (elliptically averaged). The profile is flat
in the centre and steepens towards the edge in each case. This is typical
of pre-stellar cores and has been modelled in several ways.

The latter interpretation of density structure in terms of Bonnor-Ebert
profiles is interesting, because it might imply that the cores are in some form of
pressure equilibrium. However, this result may be misleading. Some recent work
has shown that even highly non-equilibrium cores can demonstrate a Bonnor-
Ebert form of profile (e.g. Ballesteros-Paredes et al. 2003).


FIG. 4. Radial column density profile of the prestellar core
L1689B derived from combined infrared absorption and
1.3-mm continuum emission maps. Crosses show the observed
values with the corresponding statistical errors, while the total
uncertainties in the method are indicated by the dashed lines.
For comparison, the solid line denotes the best-fitting Bonnor-
Ebert sphere and the dotted line the column density profile of
a singular isothermal sphere. The observed profile is well re-
produced by an unstable Bonnor-Ebert sphere with a density
contrast of ~50. See Bacmann et al. (2000) for further details.
Theoretical deconstruction

Six myths on the virial theorem for interstellar clouds

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ABSTRACT

The interstellar medium is highly dynamic and turbulent. However, little or no attention has been paid in the literature to the implications that this fact has on the validity of at least six common assumptions on the virial theorem (VT), which are as follows. (i) The only role of turbulent motions within a cloud is to provide support against collapse; (ii) the surface terms are negligible compared to the volumetric ones; (iii) the gravitational term is a binding source for the clouds since it can be approximated by the gravitational energy; (iv) the sign of the second time-derivative of the moment of inertia determines whether the cloud is contracting \( (I < 0) \) or expanding \( (I > 0) \); (v) interstellar clouds are in virial equilibrium (VE) and (vi) Larson’s relations (mean density–size and velocity dispersion–size) are the observational proof that clouds are in VE. However, turbulent, supersonic interstellar clouds cannot fulfill these assumptions because turbulent fragmentation will induce flux of mass, moment and energy between the clouds and their environment, and will favour local collapse while it may also disrupt the clouds within a dynamical time-scale. It is argued that although the observational and numerical evidence suggests that interstellar clouds are not in VE, the so-called ‘virial mass’ estimations, which should actually be called ‘energy-equipartition mass’ estimations, are good order of magnitude estimations of the actual mass of the clouds just because observational surveys will tend to detect interstellar clouds appearing to be close to energy equipartition. Similarly, order of magnitude estimations of the energy content of the clouds is reasonable. However, since clouds are actually out of VE, as suggested by asymmetrical line profiles, they should be transient entities. These results are compatible with observationally based estimations for rapid star formation, and call into question the models for the star formation efficiency based on clouds being in VE.
DYNAMIC CORES IN HYDROSTATIC DISGUISE
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ABSTRACT
We discuss the column density profiles of “cores” in three-dimensional smoothed particle hydrodynamics (SPH) numerical simulations of turbulent molecular clouds. The SPH scheme allows us to perform a high spatial resolution analysis of the density maxima (cores) at scales between ~0.003 and 0.3 pc. We analyze simulations in three different physical conditions: large-scale driving (LSD), small-scale driving (SSD), and random Gaussian initial conditions without driving (GC), each one at two different time steps: just before self-gravity is turned on (t0) and when gravity has been operating such that 5% of the total mass in the box has been accreted into cores (t1). For this data set, we perform Bonnor-Ebert fits to the column density profiles of cores found by a clump-finding algorithm. We find that, for the particular fitting procedure we use, 65% of the cores can be matched to Bonnor-Ebert (BE) profiles, and of these, 47% correspond to stable equilibrium configurations with $\Omega_{\text{max}} < 6.5$, even though the cores analyzed in the simulations are not in equilibrium but instead are dynamically evolving. The temperatures obtained with the fitting procedure vary between 5 and 60 K (in spite of the simulations being isothermal, with $T = 11.3$ K), with the peak of the distribution being at $T = 11$ K and most clumps having fitted temperatures between 5 and 30 K. Central densities obtained with the BE fit tend to be smaller than the actual central densities of the cores. We also find that for the LSD and GC cases, there are more BE-like cores at $t_0$ than at $t_1$ with $\Omega_{\text{max}} \leq 20$, while in the case of SSD, there are more such cores at $t_1$ than at $t_0$. We interpret this as a consequence of the stronger turbulence present in the cores of run SSD, which prevents good BE fits in the absence of gravity, and delays collapse in its presence. Finally, in some cases we find substantial superposition effects when we analyze the projection of the density structures, even though the scales over which we project are small (~0.18 pc). As a consequence, different projections of the same core may give very different values of the BE fits. Finally, we briefly discuss recent results claiming that Bok globule B68 is in hydrostatic equilibrium, stressing that they imply that this core is unstable by a wide margin. We conclude that fitting BE profiles to observed cores is not an unambiguous test of hydrostatic equilibrium and that fit-estimated parameters such as mass, central density, density contrast, temperature, or radial profile of the BE sphere may differ significantly from the actual values in the cores.

Subject headings: ISM: clouds — ISM: kinematics and dynamics — stars: formation — turbulence

THE VIRIAL BALANCE OF CLUMPS AND CORES IN MOLECULAR CLOUDS
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ABSTRACT
We study the instantaneous virial balance of CCs in numerical models of MCs. The models represent a range of magnetic field strengths in MCs from subcritical to nonmagnetic regimes. We identify CCs at different density thresholds and calculate, for each object, the terms that enter the EVT. A CC is gravitationally bound when the gravitational term in the EVT is larger than the amount for the system to be virialized, which is more stringent than the condition that it be large enough to make the total volume energy negative. We also calculate other quantities used to indicate the state of gravitational boundedness: Jeans number $J$ mass-to-magnetic flux ratio $\mu$, and viral parameter $\alpha$. Our results suggest the following: (1) CCs are dynamical out-of-equilibrium structures. (2) The surface energies are of the same order as their volume counterparts. (3) CCs are either in the process of being compressed or dispersed by the velocity field. Yet, not all CCs that have a compressive net kinetic energy are gravitationally bound. (4) There is no one-to-one correspondence between the states of gravitational boundedness as described by the virial analysis or by the other indicators. In general, in the virial analysis, only the inner regions of the objects are gravitationally bound, whereas $J$, $\alpha$, $\mu$, and $\nu$ estimates tend to show that they are more bound at the lowest threshold levels and more magnetically supercritical. (5) We observe, in the nonmagnetic simulation, the existence of a bound core with structural and dynamical properties that resemble those of Barnard 68. This suggests that such cores can form in a larger MC and then be confined by the warm gas of a newly formed, nearby H II region.

Subject headings: ISM: clouds — ISM: globules — ISM: kinematics and dynamics — stars: formation — turbulence

Online material: color figures