EVIDENCE FOR COLLAPSE IN DARK CLOUDS

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Abstract. Bart Bok speculated back in the 1940's that dark cloud cores (i.e. Bok globules) are sites of star formation. The means for probing the dark cloud cores, molecules, were not discovered until much later. Today, we can finally say Bart Bok was right! Evidence for collapse in dark cloud cores will be discussed in general, along with specific examples of collapse candidates. We also describe methods to search for new candidates and the complications in identifying the infall motion.

1. Introduction

Dark cloud cores were first identified in optical plates as a dark patch of sky surrounded by a more-or-less uniform background of stars, known as Bok globules. Figure 1 shows an optical picture of one such object, Barnard 335 (hereafter B335). Because Bok globules have a roundish shape, it was suggested that they are gravitational bound entities on the way to forming stars (Bok & Reilly 1947; Bok 1948). Optical star-counts and early molecular line studies showed that the globules are centrally condensed and some are unstable against gravitational collapse. The first direct evidence for on-going star formation in globules was the detection of far-infrared continuum emission in B335 (Keene et al. 1983). More general evidence came from the IRAS observations which showed that a significant fraction of globules contain far-infrared point sources (e.g., Beichman et al. 1986).

Isolated globules provide one of the best sites to find evidence for protostellar collapse, a key process of star formation which had long eluded observers. Globules have a relatively simple cloud structure and nearly thermal internal motions, making the collapse motion easier to detect. Here, we briefly describe the signatures of collapse, the best examples of collapsing clouds, and some of the complications in detecting collapse motion.

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Figure 1. The Bok globule B335 is seen as a dark patch of sky devoid of stars. This picture is taken from Palomar Optical Sky Survey.

2. Signatures

It has been recognized from observations that star-forming cloud cores often develop centrally condensed structures (e.g., Arquilla & Goldsmith 1985). Such structures should become unstable first at the cloud center, leading to the popularity of the inside-out collapse model, in which the initial cloud is a singular isothermal sphere with $n \propto r^{-2}$ (Shu 1977). As the inside-out collapse proceeds, the density and velocity at the center of the cloud approach $n \propto r^{-1.5}$ and $v \propto r^{-0.5}$. In fact the same central configuration develops in other collapse models with different initial and boundary conditions (e.g., Larson 1969; Penston 1969). Such an infalling cloud produces unique signatures in the velocity profiles of molecular lines as described below.

The velocity information in molecular clouds is buried in the line profiles — the emission intensity as a function of projected velocity. To decode the spatial velocity, a certain cloud geometry must be assumed. For a collapsing

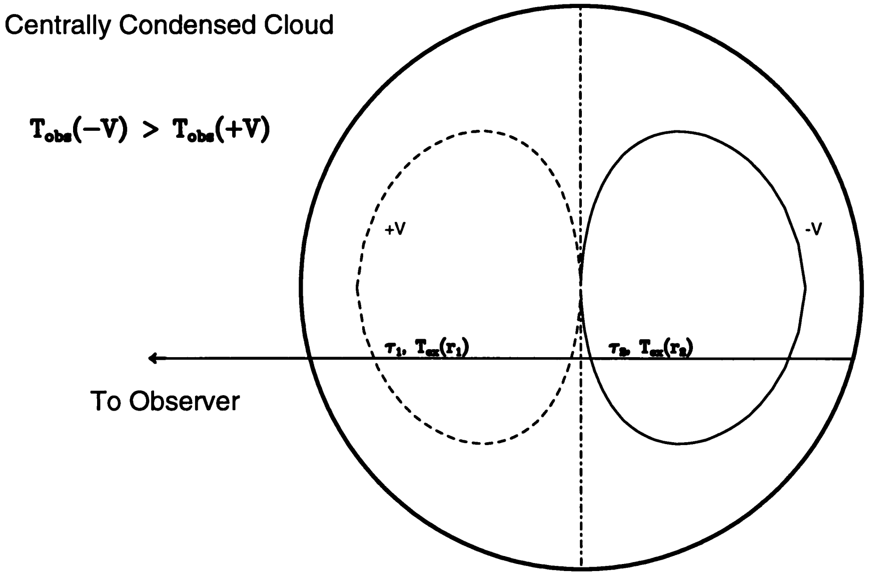

Figure 2. A schematic diagram of a spherical cloud in collapse. This is the case when the infall velocity increases toward cloud center. The oval shaped lines are tracks of constant projected velocity. There are two points along a given line of sight with the same projected velocity.

cloud, it is natural to assume spherical geometry. As the infall velocity is increasing toward the center, points with equal projected velocity form a loop (see Figure 2). Along any given line of sight, there are two points with the same projected velocity. Comparing the red-shifted and blue-shifted emission, we find a non-zero difference (expressed in temperature units):

$$T_B - T_R = (T_2 - T_1)(1 - e^{-\tau_1})(1 - e^{-\tau_2}), \tag{1}$$

where T_1 and τ_1 are the excitation temperature and optical depth, respectively, at the inner points, and T_2 and τ_2 are the corresponding quantities at the outer points. Rotational transition of molecules are excited primarily through collisions, so the excitation temperature is determined by the gas density. For a centrally condensed cloud, we should have $T_2 > T_1$, and consequently $T_B > T_R$, or the velocity profile should be asymmetric with stronger blue-shifted emission. Observing equation (1), we find that the asymmetry $(T_B - T_R)$ should increase with the optical depth of the transition. The blue asymmetry and its dependence on the optical depth are the basic signatures of a collapsing cloud.

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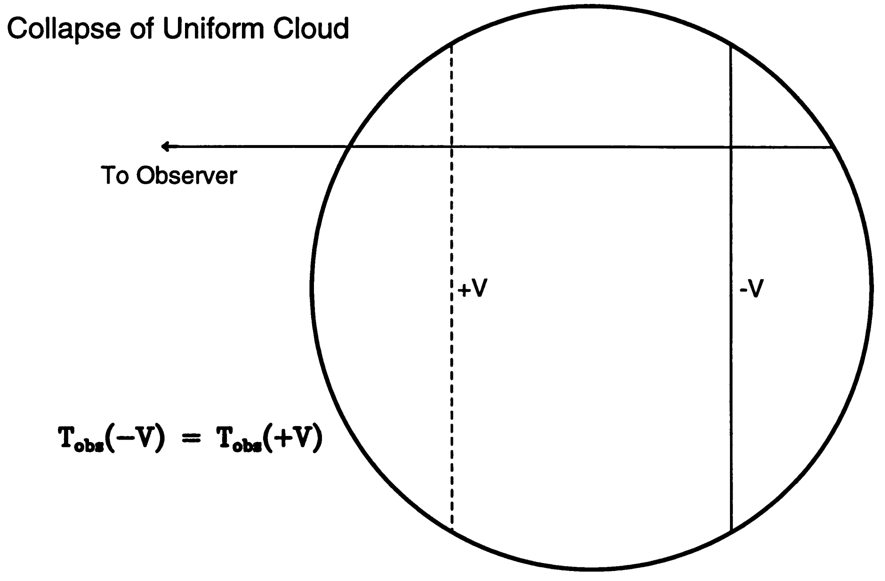

Figure 3. This is the case when infall velocity is proportional to the radius. The tracks of constant velocity are the straight lines and all points along the line of sight have different velocities.

An intuitive way to understand the infall asymmetry is that the observer is facing the hotter side of the blue-shifted hemisphere and the cooler side of the red-shifted hemisphere, so stronger blue-shifted emission is detected. Note that the signature applies only to the inside-out collapse where the infall velocity increases toward the center. Imagine the collapse of an initially uniform cloud, which remains uniform as collapse proceeds. The collapse velocity is proportional to the radius. This is known as the Large Velocity Gradient (LVG) model. In this case, points of equal *projected* velocity form a straight line (or a plane if you think in 3-D) perpendicular to the line of sight (see Figure 3). Along any line of sight through the cloud, there is only one point at a given projected velocity, so all photons reach the observer once emitted. The resulting line profile would undoubtedly be symmetric.

3. Observations

The infall signatures described above have long been recognized (e.g. Leung & Brown 1977), but observational searches were unsuccessful until recently. Part of the difficulty was the small size of the infall region (a few 0.01 pc), requiring sub-arcminute beams to resolve it even for the nearest star

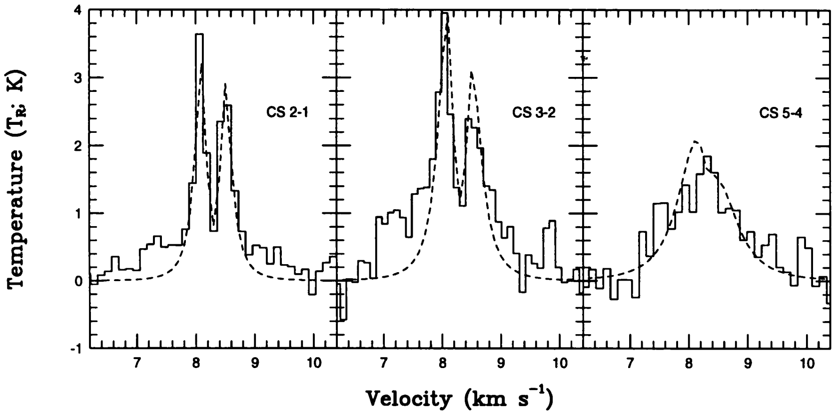

Figure 4. Observed CS line profiles toward the center of B335 (histogram) are plotted along with model fits (dashed lines); adopted from Zhou et al. (1993). The $J = 2 \rightarrow 1$ and $3 \rightarrow 2$ lines show self-absorbed profiles with stronger blue peaks, typical of that expected from an infall region.

forming regions. In addition, the time scale of collapse is about 10^5 years, very short compared to the time scale of several 10^6 years for low-mass star formation. As a result, collapsing objects are rare in the sky.

The signatures for inside-out collapse were first detected by Walker et al. (1986) in IRAS 16293–2422, but the evidence did not gain general acceptance due to the complex structure of the source. Later, Zhou et al. (1993) detected infall signatures in B335, a much simpler source than IRAS 16293–2422. Figure 4 shows the profiles of three CS lines observed toward the center of B335, showing the infall signatures, along with model fits. The evidence in B335 has been taken more seriously and several searches for more collapse candidates have been carried out since then.

Searches for collapse signatures are based on a comparison of line profiles of at least an optically thick and optically thin line. The optically thin line is used to establish the rest velocity of the cloud, while the thick line is examined for infall asymmetry. The first search was made by Wang et al. (1995) toward the sample of 40 isolated globules using lines of H_2CO (thick) and $C^{18}O$ (thin). They found three collapse candidates. Recently, Gregersen et al. (1996) searched 23 class 0 sources in lines of HCO^+ (thick) and $H^{13}CO^+$ (thin) and found six good candidates. A more extensive survey is being conducted by Mardones et al. (1996) toward about 70 sources with the lowest bolometric temperature using lines of H_2CO (thick) and N_2H^+

(thin). The preliminary results are very encouraging and detailed analysis is in progress. Table 1 lists the published collapse candidates in nearby regions of star formation.

TABLE 1. Collapse Candidates

Source Name	References
B335	Zhou et al. 1993; Choi et al. 1995
L1527	Myers et al. 1995; Zhou et al. 1996
IRAS 16293 −2422	Walker et al. 1986; Zhou et al. 1995
L483	Myers et al. 1995
L1251, L1544	Myers et al. 1996
CB 3, CB 54, CB 244	Wang et al. 1995
NGC 1333 IRAS 2	Ward-Thompson et al. 1996
NGC 1333 IRAS 4A/4B	Gregersen et al. 1996
HH25MMS, Serpens SMM4	
IRAS 20050	

4. Complications

So far, we have presented observations which are consistent with detecting infall. Real clouds show motions such as turbulence, rotation, and outflow. Can motions other than infall contrive to mimic the basic signatures described in § 1?

The short answer to the question is yes, based on the fact that some sources show both infall asymmetry and anti-infall asymmetry simultaneously. A good example is IRAS 16293 −2422 where Menten et al. (1987) found that the spectrum at the center shows infall asymmetry and half a beam to the south, the spectrum shows anti-infall asymmetry. Other examples include L483, which shows infall asymmetry in the H_2CO line (Myers et al. 1995) and anti-infall asymmetry in the HCO^+ line (Gregersen et al. 1996), and L1157 which shows infall asymmetry in HCO^+ 3-2 line and anti-infall asymmetry in HCO^+ 4-3 line (Gregersen et al. 1996).

The problem, however, appears to be solvable. First, the examples given above are somewhat extreme. There are good cases, such as B335 and L1527, where all observed lines are consistent with the infall model. Second, it is possible to separate the effects of infall from rotation or outflow through careful analysis of molecular line maps and detailed modeling. Figure 5 shows a grid of spectra toward IRAS 16293 −2422 along with a model which includes infall and rotation. We see that both the infall asymmetry at the

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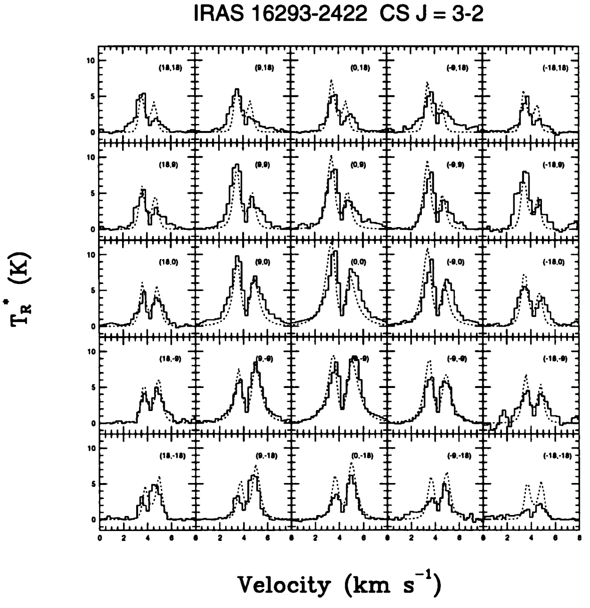

Figure 5. Observed line profiles toward IRAS 16293-2422 (histogram) are plotted with model fits (dashed lines). The data are taken from Menten et al. (1987); model profiles are generated from a model of collapsing cloud with rotation, taken from Zhou (1995).

center and the anti-infall asymmetry to the south are reproduced by the model. In contrast, models with rotation alone would produce a symmetric line profile toward the center position, inconsistent with the observations.

Figure 6 shows the CS 3-2 spectra toward the center and neighboring positions toward B335 along with infall model fits. B335 contains an outflow along the east-west direction. We see strong shoulder emission toward the center and the E-W spectra, but not in the N-S average spectrum. In contrast, the infall asymmetry exhibited in the narrow peaks is seen in all spectra. This is strong evidence that the outflow contributes only to the shoulder emission but not to the narrow peaks.

Despite the optimistic cases shown above, one must admit that many sources may possess complicated structures to mimic infall signatures without infall motions. The question is whether the infall interpretation of the blue asymmetry is valid in general. One can approach this question statistically by noting that motions other than infall tend to share a common characteristic—overall they produce at least as much red-shifted emission as blue-shifted. For turbulence, rotation, and outflow, there should be an

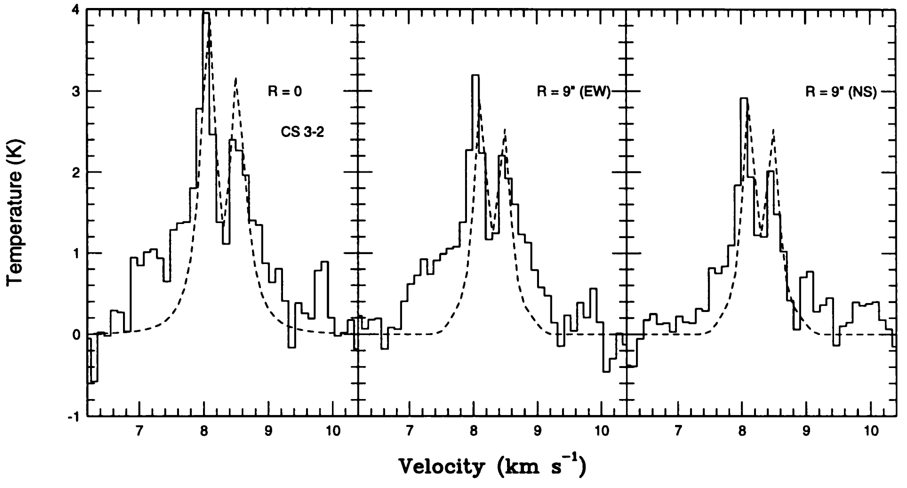

Figure 6. Plotted are the CS $J = 3 \rightarrow 2$ spectra at the center and the average spectra 9″ to the east-west and north-south (solid lines). A spherical infall model is also shown (dashed lines). Excess wing emission is seen toward the center and along the E-W direction, but not along the N-S direction. This spatial distribution indicates that the wing emission is from the outflow, which lies along the E-W direction. In contrast, infall asymmetry is seen in all positions.

equal amount of blue-shifted and red-shifted emission; for spherical expansion, there should be more red-shifted than blue-shifted emission, the opposite of infall. Therefore, the infall signature can be proven statistically if surveys of likely infall candidates show an excess of blue-shifted emission. Recent surveys indeed show such an excess. In the sample of Gregersen et al. (1996), there are 7 sources with infall asymmetry and 2 sources with anti-infall asymmetry among sources showing double-peaked line profiles; the probability is only 7% that the source population shows an equal amount of blue-shifted and red-shifted emission. Mardones et al. (1996) also found an excess of blue-shifted emission in their sample at a confidence level of about 90%.

In summary, infall motions in nearby dark clouds can now be probed through molecular line profiles. While a variety of motions may contribute to the observed line shape, it is possible to separate infall motions from rotation and outflow at least in a few simple cases. Moreover, signatures of infall also show up statistically, arguing against models in which the infall asymmetry arises by chance from random motions.

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Discussion

Wootten: How well do these observations fit Shu's models of inside-out-collapse. Is there unanimity?
Zhou: No. Some cores show an over-density over the singular isothermal sphere, others deviate significantly from spherical symmetry.

Mangum: Was the projection effect for outflow velocity statistics taken into account in the Mardones comparison to infall velocities?
Zhou: No, this work was only a basic comparison to see if outflow can be mistaken as infall.

Shu: As a control sample, one might choose a set of starless cores to see whether the asymmetry is absent. Has this been done?
Zhou: This has been done by Y. Wang and collaborators toward Bok globules (see his ApJ paper in 1995). No asymmetry was found in the control sample. However, the Myers group at CfA did find a possible infall candidate in L1544 which has no infrared emission.

Slysh: The dip in the profile can be produced not only by collapse, but also by a temperature gradient in the cloud, with a cold outer layer absorbing emission from the inside. There are CO spectra showing this effect, as well as CS spectra in the poster of Val'tts & Larionov.
Zhou: Infall profiles can be understood as a form of foreground absorption as described. One difference is that in the infall case, the velocity of the optically thin line should align with the absorption dip rather than the background component. There is a detailed discussion in our ApJ paper in 1993.