NASA-CR-204926

# IDENTIFICATION OF A COLLAPSING PROTOSTAR *

NEAL J. EVANS II
*Department of Astronomy, The University of Texas at Austin, Austin, Texas, USA*

SHUDONG ZHOU
*Department of Astronomy, University of Illinois, Urbana, Illinois, USA*

and

CARSTEN KÖMPE and C. M. WALMSLEY
*Max-Planck-Institut für Radioastronomie, Bonn, Germany*

**Abstract.** The globular molecular cloud B335 contains a single, deeply embedded, far-infrared source. Our recent observations of $H_2CO$ and CS lines toward this source provide direct kinematic evidence for collapse. Both the intensity and detailed shape of the line profiles match those expected from inside-out collapse inside a radius of 0.036 pc. The collapse began about $1.5 \times 10^5$ years ago, similar to the onset of the outflow. The mass accretion rate is about 10 times the outflow rate, and about 0.4 $M_\odot$ should have now accumulated in the star and disk. Because B335 rotates only very slowly, any disk would still be very small (about 3 AU). The accretion luminosity should be adequate to power the observed luminosity. Consequently, we believe that B335 is indeed a collapsing protostar.

## 1. Introduction

It is by now a commonplace that stars form in collapsing parts of molecular clouds. Theories of both star and planet formation rely on this fundamental picture. It is less well known outside the star formation community that direct observational evidence for collapse is almost entirely lacking. Numerous claims of collapse motions have been made, but most have encountered considerable skepticism. More importantly, none have applied to the collapse of a region likely to form a single protostar (see, e.g., Evans, 1991).

The overwhelming kinematic signature in most regions of star formation is not collapse, but outflow (Lada 1985; Bachiller and Gómez-González, 1993). The outflow is indicated by a variety of tracers, including wide wings on CO and other molecular lines, masers, and Herbig-Haro objects. In a spherical picture of star formation, such outflows would indicate that the collapse phase had already ended in almost every object studied, even those which seem young by other indications.

The ubiquity of evidence for outflow and the nearly total absence of evidence for collapse led Wynn–Williams (1982) to refer to a collapsing protostar as the "holy grail" of star formation studies. As was no doubt true of the legendary grail, there is no shortage of candidates discovered by infrared and submillimeter continuum observations. The problem is one of authentication. A candidate must pass the

* Paper presented at the Conference on *Planetary Systems: Formation, Evolution, and Detection* held 7–10 December, 1992 at CalTech, Pasadena, California, U.S.A.

*Astrophysics and Space Science* **212:** 139–145, 1994.
© 1994 *Kluwer Academic Publishers. Printed in Belgium.*

following tests: first, it must have a kinematic signature of collapse; second, its luminosity must plausibly result from accretion, rather than any nuclear reactions. The latter requirement suggests a focus on objects early in the collapse phase.

During the last decade, three new developments have again raised the possibility of identifying a collapsing protostar. The first of these was inside-out collapse (Shu, 1977; Shu *et al.*, 1987). In their picture, clouds or regions forming stars of low mass are supported almost entirely by thermal pressure. In these conditions, they would first relax to a centrally condensed distribution ($n(r) \propto r^{-2}$) and then initiate collapse from the inside. A wave of infall propagates outward at the effective sound speed, and the density distribution inside the infall radius ($r_{inf}$) relaxes to $n(r) \propto r^{-1.5}$. The implications of this idea for collapse searches are several. Since the collapse occurs first in the inside and occurs at relatively low velocity, we can detect kinematic evidence of collapse in the early, protostellar phases only with the use of high spatial and spectral resolution. Because the collapse begins in the innermost, densest part of the cloud, it will be best revealed by molecular lines that require high density for excitation. These will tend to "see" through the static envelope and probe the collapse region. Finally, since this picture was developed for low-mass star formation, low-mass clouds or regions would be the best candidates. In particular, small, globular molecular clouds of a few solar masses may have only a single collapse center, simplifying the kinematic signature.

The second important development was the abandonment of spherical symmetry. In non-spherical geometries, collapse and outflow can coexist. Since many outflows are bipolar, it is natural to think of allowing collapse in the plane perpendicular to the outflow direction. Theoretically, non-spherical geometries in the innermost regions of the collapse are a natural consequence of rotation. In calculations of the collapse of a cloud with initially slow rotation, Terebey, Shu, and Casson (1984) found that the geometry becomes quite non-spherical and a disk is likely to form inside the centrifugal radius (where the infall speed equals the rotation speed). The outflow would then be perpendicular to the plane of the disk. Since the disk is the likely site of planet formation, it is very important to check this picture observationally. The relevance of this idea to searches for collapse is that we need not reject clouds with outflows, but we must use tracers which are not dominated by outflow.

With the perspective of the first two developments, it is easy to see why observational evidence of collapse has remained elusive. Almost all simulations of line profiles from collapsing clouds (e.g., Anglada *et al.*, 1987) and most searches for kinematic evidence concentrated on CO, a molecule which is abundant and easily excited. These properties meant that CO emission probed mostly the outer regions of clouds and that it was especially prominent in outflows. Clearly, simulations of line profiles and observational efforts needed to focus on different molecular lines.

The third important development grew out of this last realization. Zhou (1992) modeled the evolution of line profiles during an inside-out collapse, focusing on lines of molecules which require high densities for excitation. The primary result

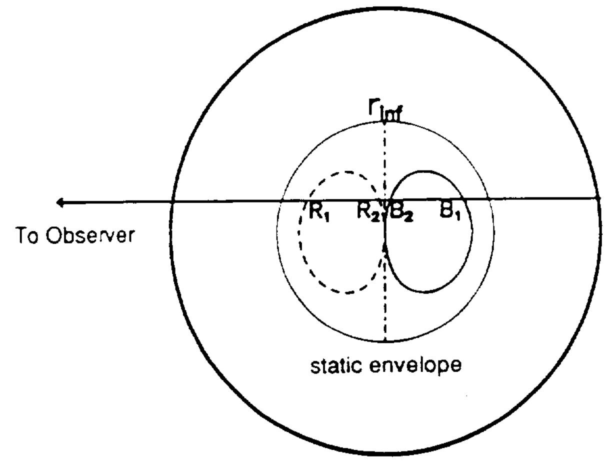


Fig. 1. A schematic diagram of a cloud experiencing inside-out collapse inside the inner circle (labeled $r_{inf}$). The ovals are the locus of points with the same velocity projected on the line of sight to the observer. For a density sensitive line and the density field of collapse, $B_2$ and $R_2$ produce stronger emission than $B_1$ and $R_1$. Since $R_1$ lies in front of $R_2$, and has the same projected velocity, $R_1$ obscures $R_2$, whereas the strong emission from $B_2$ is unobscured by $B_1$.

of that study is that the best line to employ for collapse searches is one requiring fairly high densities to excite, but which also has opacity of order 1. The modest opacity produces a distinctive kinematic signature of collapse, in which the profile appears self-absorbed (having a central minimum between two peaks), and the blue-shifted peak is brighter than the red-shifted peak. The self-absorption and the line width should decrease away from the center of the collapse or when observed with lower resolution. Finally, if several lines with different critical density are observed, the line width should increase with increasing critical density. These properties thus define a distinctive signature of inside-out collapse. In addition to predicting the general shapes of the lines, the inside-out collapse model, together with Zhou's radiative transport calculations, provides a prediction for the intensities and detailed shape of the lines, as a function of the time since collapse began, or equivalently the infall radius ($r_{inf}$), making the whole theory eminently testable.

## 2. The Candidate

Our candidate for collapse is an isolated, roundish globule called B335, located at a distance of 250 pc. It was probably discovered by Barnard (1927); at least it takes its name from his photographic atlas. The term globule was given to this class of objects by Bok and Reilly (1947), who also suggested that they may represent objects "... just preceding the formation of a star." Their suggestion was verified by Keene *et al.* (1983), who discovered a far-infrared source in B335, which they suggested "may prove to be ... low luminosity protostar." Two later papers presenting data on the submillimeter continuum emission (Gee *et al.*, 1985 and Chandler *et al.*, 1990) actually used the term protostar in the title, but both with question marks. The main source of the uncertainty was that outflow, not collapse, was indicated by CO observations.

B335 is in many ways an ideal candidate for collapse. The cloud is small and has very little turbulence, making it likely that Shu's picture of a thermally supported cloud is relevant. The infrared source is deeply embedded, being detected only at $\lambda > 60$ $\mu$m, indicative of an early phase in the collapse process. The outflow is nearly in the plane of the sky, oriented east–west, with an opening angle of about 45° (Hirano *et al.*, 1988; Cabrit *et al.*, 1988). These properties make it possible to avoid the outflow to some extent by mapping north–south.

Our work on this object began with a map of the 6-cm $H_2CO$ line using the VLA (Zhou *et al.*, 1990). This line, a transition between two states of a K-doublet ($J_{K_{-1}K_1} = 1_{11} - 1_{10}$) appears in absorption against the cosmic background radiation because of a collisional pumping effect which cools its excitation temperature below 2.7 K (Townes and Cheung, 1969). Since the cosmic background temperature is extremely uniform, it provides a smoothly distributed background lamp, meaning that any structure in the observations arises in the cloud. We observed an apparent ring of absorption, with a hole centered near the infrared source and the location of peak emission in other molecular tracers. The explanation for this effect is that the collisional pump works optimally in a range of densities from about $10^3$ to $10^4$ cm$^{-3}$; above about $10^6$ cm$^{-3}$, the collisions drive the line into emission, but there is a range of densities where the line has an excitation temperature close enough to that of the background radiation that neither emission nor absorption will be seen. We interpreted the ring as the effect of a density gradient in the source. Detailed modeling showed that a density gradient consistent with an inside-out collapse ($n(r) \propto r^{-\alpha}$, with $\alpha = 2.0$ outside a radius of about 0.03 pc and and 1.5 inside that radius) gave the best fit to the data. This model then predicted that the $\Delta J = 1$ transitions of $H_2CO$ would appear in emission from the region of the "hole" in the absorption ring. Viewed with sufficient resolution, these lines might also show the kinematic signature of collapse.

## 3. The Evidence

To obtain the requisite resolution, the IRAM 30-m telescope was used to observe simultaneously two $\Delta J = 1$ lines of $H_2CO$: the $J_{K_{-1}K_1} = 2_{12} - 1_{11}$ line (140 GHz) and the $J_{K_{-1}K_1} = 3_{12} - 2_{11}$ line (225 GHz). The lines toward the peak of the map, coincident within uncertainties with the infrared source and a radio continuum source (Anglada *et al.*, 1992), match the predictions for an inside-out collapse remarkably well (Zhou *et al.*, 1993). The shapes of the lines provide strong evidence for collapse. Zhou *et al.* (1993) also observed three lines of CS

($J = 2 - 1$, $3 - 2$, and $5 - 4$), and these lines also indicate collapse, although they are more affected by the outflow than are the $H_2CO$ lines. Both molecules can be used to determine the parameters of the infall by varying the infall radius and molecular abundance to find the best fit to the observed profiles. The overall best fit is obtained for $r_{inf} = 0.036$ pc, with $H_2CO$ favoring slightly smaller radii and CS favoring slightly larger radii. The resulting model profiles are compared with the observations in Figure 2 (note that the model profiles differ slightly from those in Zhou *et al.*, 1993, because we have corrected an error in the modeling program).

The best-fit abundance of $H_2CO$ is $3.6 \times 10^{-9}$ and the best-fit CS abundance is $3.2 \times 10^{-9}$, consistent with many other determinations, but much more constrained than previous measurements. The CS lines, especially the $3 - 2$ line, are more affected by the outflow than are the $H_2CO$ lines, but spectra at positions to the north and south (perpendicular to the outflow axis) are relatively free of outflow emission and match predictions of the model well.

Zhou *et al.* (1993) considered alternative models for B335, including increased turbulence toward the center, rotation, spherical expansion, and outflow. None of these can explain the line profiles. The only alternative model which comes close to matching the observations requires a foreground cloud absorbing the emission from the background cloud, which contains the infrared source. This picture requires a very low velocity dispersion in the foreground gas ($\Delta v_f = 0.15$ km s$^{-1}$) for which there is no supporting evidence. In addition, the CS lines are not well-fitted in this model unless the central velocity of the background component shifts with $J$. The foreground absorption model is highly contrived and thus quite unlikely. While certainty is probably unattainable, simplicity certainly favors the conclusion that B335 is undergoing inside-out collapse, with density and velocity fields given by Shu *et al.* (1987).

## 4. Conclusions

Assuming that the collapse interpretation is correct, one can then use the inside-out collapse model to compute other quantities of interest. With $r_{inf} = 0.036$ pc and an effective sound speed (including a small turbulent contribution) of 0.23 km s$^{-1}$, the time since collapse began is $1.5 \times 10^5$ yr, similar to the (quite uncertain) age of the outflow, indicating that outflow may have begun very early in the collapse. The mass accretion rate would be $2.8 \times 10^{-6}$ $M_\odot$ yr$^{-1}$, about 10 times the mass loss rate in the outflow. The total mass accumulated in the star and disk would be 0.4 $M_\odot$, while the total reservoir from which material could eventually accrete is about 12 $M_\odot$. The B335 cloud rotates only very slowly, with $\Omega = 1.4 \times 10^{-14}$ s$^{-1}$ (Frerking *et al.*, 1987). Consequently, the centrifugal radius is only 3 AU. Deviations from spherical symmetry would thus occur on much smaller scales than our resolution and hence be negligible in our modeling.

Finally, we can ask whether B335 satisfies the other criterion for a collapsing protostar: luminosity derived from accretion. Given the mass accretion rate derived

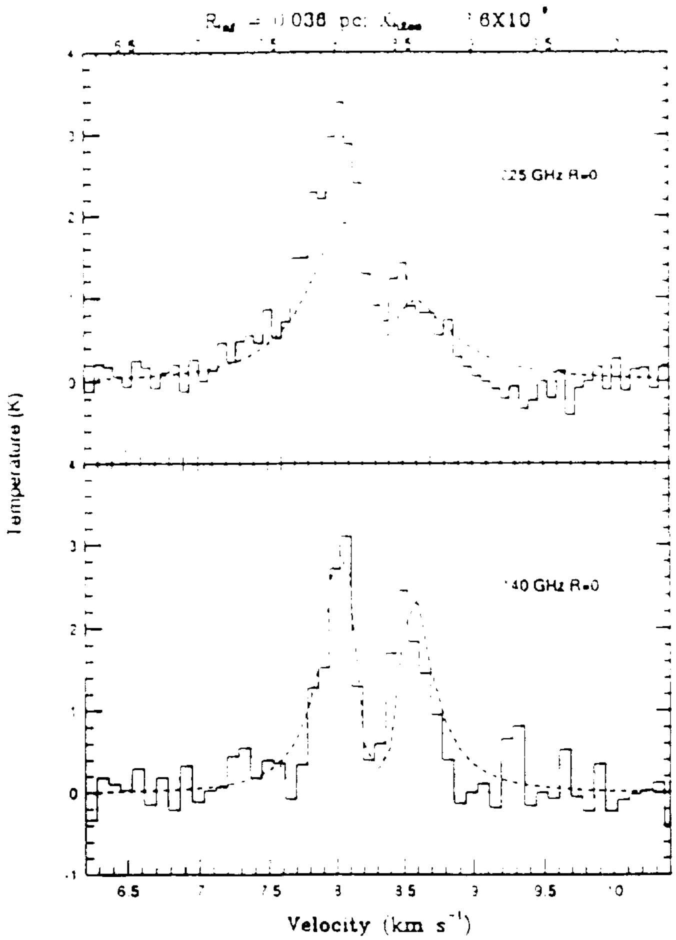


Fig. 2. The observed spectra toward the center of B335 are shown as solid histograms. The dashed lines are model line profiles predicted by an inside-out collapse model with $r_{inf}$ = 0.036 pc.

above, the accretion luminosity would equal the observed luminosity of 3 $L_{\odot}$ as long as the radius of the star is about 6 $R_{\odot}$, consistent with theoretical expectations (Stahler *et al.*, 1980). All the facts are consistent with the interpretation of B335 as a collapsing protostar — the holy grail of star formation.

**Acknowledgements**

This work was supported by NSF Grants AST88-15801 and 90-17710, by NASA grant NAGW-2323, by a grant from the W. M. Keck Foundation, and by a grant from the Texas Advanced Research Program to the University of Texas.

## References


Anglada, G. Rodríguez, L. F., Cantó, J., Estalella, R. and López, R. 1987, *Astron. Astrophys.* **186**, 280.

Anglada, G. Rodríguez, L. F., Cantó, J., Estalella, R. and Torrelles, J.M.: 1992, *Astrophys. J.* **395**, 494.

Bachiller, R. and Gómez-González, J.: 1993, *Astron. Astrophys. Rev.* 3, 257.

Barnard, E.E.: 1927, in: E.B. Frost and M. R. Calvert (eds.), *A Photographic Atlas of Selected Regions of the Milky Way*, Carnegie Institution of Washington.

Bok, B.J. and Reilly, E.F.: 1947, *Astrophys. J.* **105**, 255.

Cabrit, S., Goldsmith, P.F. and Snell, R.L.: 1988, *Astrophys. J.* **334**, 196.

Chandler, C.J., Gear, W.K., Sandell, G., Hayashi, S., Duncan, W.D., Griffin, M.J. and Hazell, A.S.: 1990, *Monthly Not. Roy. Astr. Soc.* **243**, 230.

Evans II, N.J.: 1991, Star formation: Observations, in: D.L. Lambert (ed.), *Frontiers of Stellar Evolution*, San Francisco, Astronomical Society of the Pacific, p. 45.

Frerking, M.A., Langer, W.D. and Wilson, R. W.: 1987, *Astrophys. J.* **313**, 320.

Gee, G., Griffen, M.J., Cunningham, C.T., Emerson, J.P., Ade, P.A.R. and Caroff, L.J.: 1985, *Monthly Not. Roy. Astr. Soc.* **215**, 15P.

Hirano, N., Kameya, O., Nakayama, M. and Takakubo, K.: 1988, *Astrophys. J. Letters* **327**, L69.

Keene, J. *et al.*: 1983, *Astrophys. J. Letters* **274**, L43.

Lada, C.J.: 1985, *Ann. Rev. Astron. Astrophys.* **23**, 267.

Shu, F.H.: 1977, *Astrophys. J.* **214**, 488.

Shu, F.H., Adams, F.C. and Lizano, S.: 1987, *Ann. Rev. Astron. Astrophys.* **25**, 23.

Stahler, S.W., Shu, F.H. and Taam, R.E.: 1980, *Astrophys. J.* **241**, 637.

Terebey, S., Shu, F.H. and Cassen, P.: 1984, *Astrophys. J.* **284**, 529.

Townes, C.H. and Cheung, A. C.: 1969, *Astrophys. J. Letters* **157**, L103.

Wynn-Williams, C.G.: 1982, *Ann. Rev. Astron. Astrophys.* **20**, 587.

Zhou, S.: 1992, *Astrophys. J.* **394**, 204.

Zhou, S., Evans II, N.J., Butner, H.M., Kutner, M.L., Leung, C. M. and Mundy, L.G.: 1990, *Astrophys. J.* **363**, 168.

Zhou, S., Evans II, N.J., Kömpe, C. and Walmsley, C.M.: 1993, *Astrophys. J.* 404, 232.