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RECENT RESULTS ON STAR FORMATION

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RESUMEN

La nube molecular globular B335 contiene profundamente inmersa en ella una única fuente en el infrarrojo lejano. Nuestras observaciones recientes de H_2CO y de líneas de CS hacia esta fuente dan evidencia cinemática directa de colapso. Tanto la intensidad como forma detallada de los perfiles de la línea concuerdan con aquellos esperados de un colapso de adentro hacia afuera interior a un radio de 0.036 pc. El colapso se inició hace aproximadamente 1.5×10^5 años en tiempos similares al comienzo del flujo emergente. La tasa de acreción de masa es de aproximadamente 10 veces la tasa del flujo emergente, y aproximademente de 0.4 $M_\odot$ deben de haberse acumulado en la estrella y el disco. Debido a que B335 gira muy lentamente, cualquier disco sería aún muy pequeño (cerca de 3 UA). La luminosidad de acreción debe tener la energía adecuada para dar energía a la luminosidad observada. En consecuencia, creemos que B335 es verdaderamente una proto-estrella en colapso. Hemos estudiado seis estrellas Herbig Ae/Be (estrellas de masa-intermedia de la pre-secuencia principal) en el lejano infrarrojo. Las seis habían sido modeladas anteriormente como sistemas que contienen solamente estrellas y discos, pero encontramos emisión extendida en el infrarrojo lejano alrededor de cinco de las seis, lo que implica la presencia de una envolvente, así como de un disco, alrededor de las estrellas.

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 1.5×10^5 yr 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. We have studied six Herbig Ae/Be stars (intermediate-mass pre-main-sequence stars) in the far-infrared. All six had been previously modeled as systems containing only stars and disks, but we find extended far-infrared emission around five of the six, implying the presence of an envelope, as well as a disk, around the stars.

Key words: **ACCRETION, ACCRETION DISKS — ISM: CLOUDS — STARS: FORMATION**

1. INTRODUCTION

During the last decade, a simple, predictive theory for the formation of low-mass stars has been developed Shu 1977; Shu, Adams, & Lizano 1987). In this picture, clouds forming stars of low mass are supported almost ntirely 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 well inside the infall radius ($r_{\rm inf}$) relaxes to $n(r) \propto r^{-1.5}$. This picture has come to be known as "inside-out" collapse.

The picture is modified in the presence of rotation. In calculations of the collapse of a cloud with initially slow rotation, Terebey, Shu, & 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).

While the basic picture has been widely accepted, the observational underpinnings have not been fully secured. In particular, direct observational evidence for collapse is almost entirely lacking. Numerous claims of collapse motions have been made, but most have encountered considerable skepticism (see, e.g., Evans 1991). More importantly, none have applied to the collapse of a region likely to form a single protostar.

The evidence for disks at later stages of the star formation process is stronger. Many T Tauri stars show excess emission extending through the infrared to millimeter wavelengths, which has been attributed to disks (Beckwith et al. 1990). However, disk models which fit the spectral energy distributions of the T Tauri stars with excesses frequently require unorthodox distributions of disk temperature. Both viscous accretion and reprocessing of stellar radiation predict $T_d(r) \propto r^{-0.75}$, whereas flatter power laws (often $r^{-0.5}$) are needed to fit many sources.

Another question involves the range of applicability of the basic theory of low-mass star formation. To address this question, studies of intermediate-mass stars are important. Recent studies have applied the paradigm for low-mass star formation to Herbig Ae/Be stars, intermediate-mass (roughly 1.5-10 $M_\odot$) analogs of T Tauri stars. For example, Hillenbrand et al. (1992) have divided Herbig Ae/Be stars into three groups: one group appears to consist of stars without disks; one group is best modeled with disks around the stars; and the third group requires both disks and envelopes. A natural conclusion would be that these groups represent an evolutionary sequence with the oldest group being the one without stars or envelopes. In addition, Hillenbrand et al. argue that many of the spectra can be fitted with more traditional disk temperature distributions ($T_d(r) \propto r^{-0.75}$) if the emission observed in large beams (typically IRAS data) does not arise in the disk.

In this paper, we describe two recent observational results which bear on the theoretical picture. One involves detection of the kinematic signature of collapse in a region forming low-mass stars and a detailed comparison to the theoretical predictions (Zhou et al. 1993). The second concerns the status of the Herbig Ae/Be stars studied by Hillenbrand et al. (1992).

2. COLLAPSE

The overwhelming kinematic signature in most regions of star formation is not collapse, but outflow (Lada 1985; Bachiller & Gómez-González 1992), 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.

For these reasons, a collapsing protostar has been viewed as the "holy grail" of star formation studies (see, e.g., Wynn-Williams 1982). As is true of other "holy grails", like black holes or planets around other stars, there is no shortage of candidates, discovered by infrared and submillimeter continuum observations. The problem is one of authentication. A candidate must pass the 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.

Rotation breaks the spherical symmetry, so that collapse and outflow can coexist. Since many outflows are bipolar, it is natural to think of collapse in the plane perpendicular to the outflow direction. In searching for collapse, we need not reject clouds with outflows, but we must avoid tracers like CO, which are dominated by outflow.

The inside-out theory of collapse has several implications for searches for collapse. Since the collapse occurs first in the inside and 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 lines 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 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.

With this perspective, Zhou (1992) modeled the evolution of line profiles during an inside-out collapse, ocussing on lines of molecules which require high densities for excitation. The primary result of that study s that the best line to employ for collapse searches is one requiring fairly high densities to excite, but which also has a line opacity of order 1. The modest opacity produces a distinctive kinematic signature of collapse, n 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 nfall radius ($r_{\rm inf}$), making the whole theory eminently testable.

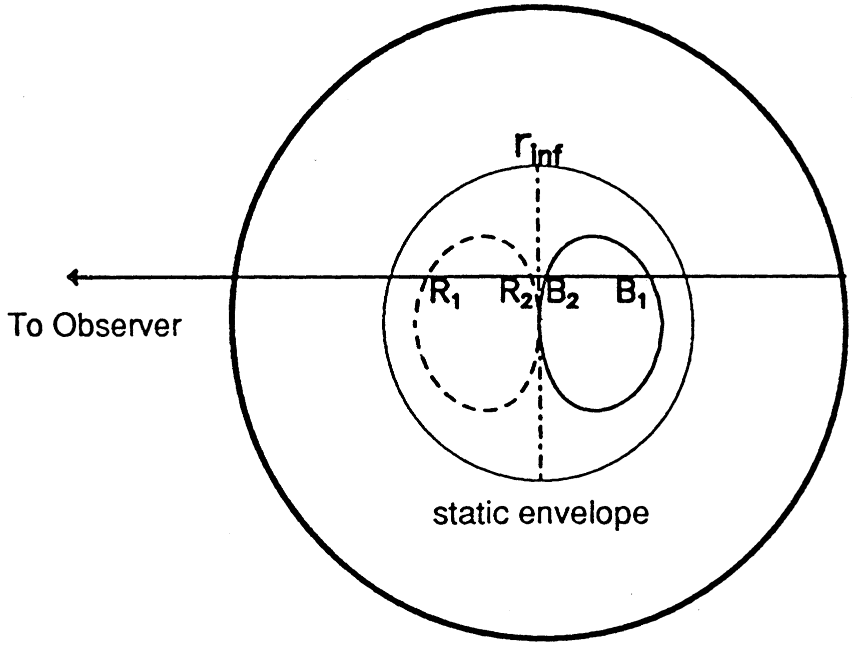

Fig. 1

A schematic diagram of a cloud experiencing inside-out collapse inside the inner circle (labeled $r_{\rm inf}$). 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.

B335 is in many ways an ideal candidate for collapse. The cloud is a small, isolated globule (Barnard 1927) at a distance of 250 pc. This general class of objects was suggested to be the site of star formation by Bok & Reilly (1947). It has very little turbulence, making it likely that Shu's picture of a thermally supported cloud is relevant. The infrared source (Keene et al. 1983) is deeply embedded, being detected only at $\lambda > 60$ μm, indicative of an early phase in the collapse process. Several authors have suggested it as a possible protostar (Keene et al. 1983; Gee et al. 1985; Chandler et al. 1990). However, the only kinematic signature previously known was that of an outflow. 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 ($\Delta J = 0$) H_2CO line using the VLA (Zhou et al. 1990). Detailed modeling of these observations showed that a density gradient consistent with an inside-out collapse ($n(r) \propto r^{-\alpha}$, with $\alpha = 2.0$ in the outer parts and 1.5 inside a radius of about 0.03 pc) 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 central region. Viewed with sufficient resolution, these lines might also show the kinematic signature of collapse.

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 $r_{\rm inf} = 0.036$ pc, with H_2CO favoring slightly smaller radii and CS favoring slightly larger radii. The resulting model profiles are compared with the observations in Fig. 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 3.6×10^{-9} and the best-fit CS abundance is 3.2×10^{-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.

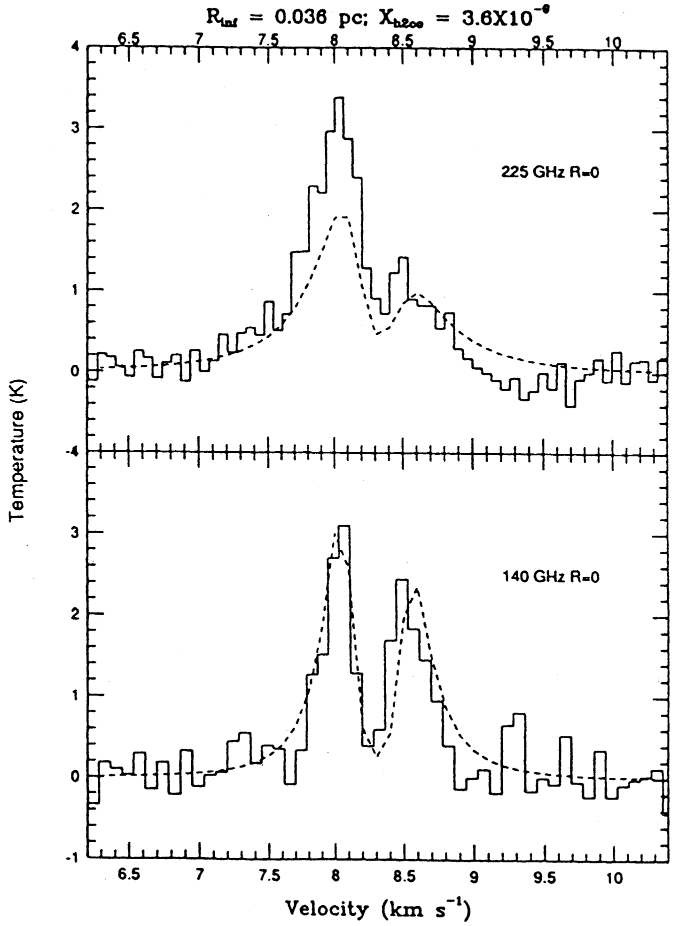

Fig. 2

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 $r_{\rm inf} = 0.036$ pc.

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).

Assuming that the collapse interpretation is correct, one can then use the inside-out collapse model to compute other quantities of interest. With $r_{\rm inf} = 0.036$ pc and an effective sound speed (including a small turbulent contribution) of 0.23 km s^{-1}, the time since collapse began is 1.5×10^5 yr, equal within uncertainties to the age of the outflow, indicating that outflow must have begun very early in the collapse. The mass accretion rate would be 2.8×10^{-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 so small that the size of a disk should be only 3 AU (0.01″). 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 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.

3. DISKS AROUND INTERMEDIATE MASS STARS

While B335 is the only collapse candidate with strong kinematic evidence, the basic theory finds support in several other sources. The far-infrared data on L1551 IRS5 (Butner et al. 1990) are consistent with an infalling envelope with a density gradient characteristic of collapse ($n(r) \propto r^{-1.5}$) and with the specific predictions by Adams, Lada, & Shu (1987) for an inside-out collapse. In addition, there is strong evidence for a substantial disk around L1551 IRS5 (Keene & Masson 1990; Butner, Natta, & Evans 1993).

Since the picture of Shu and co-workers seems to work well for B335 and (in less detail) for other low-mass stars, it is interesting to see if it can be applied to more massive stars. In particular, the general scenario has been applied to Herbig Ae/Be stars, a group of intermediate mass (1.5–10 $M_\odot$) stars analogous to T Tauri stars in their evolutionary state. Since the spectral energy distributions of T Tauri stars from visible light to millimeter wavelengths can be fitted with models of stars and disks (Beckwith et al. 1990), a similar approach was used to model the spectral energy distributions of Herbig Ae/Be stars (Hillenbrand et al. 1992).

Hillenbrand et al. studied 47 Herbig Ae/Be stars and found three classes of spectral energy distributions: Group III stars (6 stars) had little or no infrared excess and could be modeled simply as diskless stars; Group I sources (30 stars) could be modeled as a star plus a disk with $T_d(r) \propto r^{-0.75}$, as expected for either reprocessing of stellar light or viscous accretion; Group II sources (11 stars) required an envelope in addition to the star and disk to match their spectral energy distributions. However, Hillenbrand et al. noted that many of the Group I sources displayed far-infrared emission, measured with IRAS, considerably greater than predicted from their models with stars and disks only. Since the beam of IRAS was quite large, the far-infrared emission could be coming from a different source or could be rather diffuse emission not directly associated with the object.

To clarify the origin of the far-infrared emission, we obtained far-infrared data for six of the Group I stars, using the KAO, which achieves a spatial resolution of 20–30″ at 50–100 μm (Di Francesco et al. 1993). We found that the far-infrared emission peaks on the stellar position to the accuracy of our positional measurements. While some stars show secondary peaks, the primary contribution to the IRAS fluxes appears to be dust associated with the Herbig Ae/Be stars themselves. In addition, the emission is resolved in five of the six objects, with AB Aur being the only exception. Typical sizes for the emission regions are 30–90″.

To see whether the observed far-infrared emission can come from a disk, we have modeled the emission from disks. To give disks the benefit of the doubt, we have chosen all parameters in such a way as to maximize the extent of the far-infrared emission. For example, we assumed the disks to be face on and optically thick in the far-infrared and allowed the disks to have an intrinsic luminosity equal to that of the entire star-disk system. Since the emission from a disk depends on the temperature gradient in the disk, we have modeled disks with the flattest temperature gradient suggested for young objects ($T_d(r) \propto r^{-0.5}$). Nonetheless, we find that the temperature falls below that required to maintain the 100 μm emission in the Rayleigh-Jeans limit (T_{RJ})

at radii of a few arcsec or less. Since the intensity drops sharply for radii where the temperature has dropped below T_{RJ}, emission from disks cannot account for the extended far-infrared emission that we see.

We attribute the resolved far-infrared emission to a circumstellar envelope, perhaps a remnant of the original infalling envelope that formed the star. Since envelopes had already been inferred for the Group II stars (Natta et al. 1993), this result suggests that the two groups may be less distinct than previously thought. In addition, previous models of these systems with only stars and disks should be reevaluated. Consistent models with stars, disks, and envelopes are needed to extract information from the spectral energy distribution, as well as to assess mass accretion rates and the evolutionary status of objects.

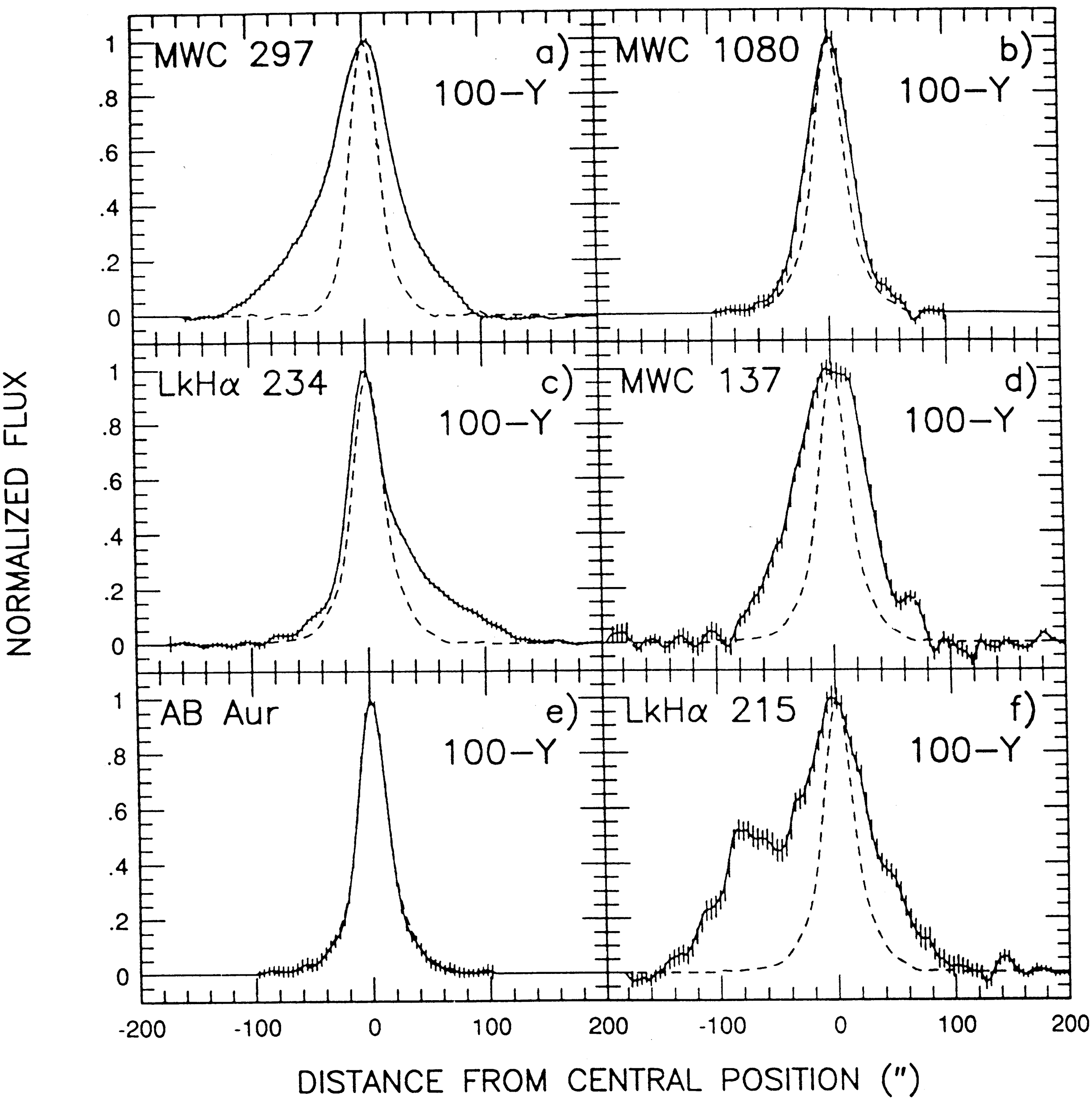

Fig. 3

Scans of 6 sources at 100 μm, compared to scans of unresolved sources (dashed lines). Erro: bars represent the standard deviation of the mean for data averaged over the resolution element

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