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SPECTROSCOPIC EVIDENCE FOR INFALL AROUND AN EXTRAORDINARY *IRAS* SOURCE IN OPHIUCHUS

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ABSTRACT

IRAS 16293 – 2422 is an extremely cold infrared source associated with a high velocity molecular outflow in the Rho Ophiuchi molecular cloud. We report millimeter-wave continuum observations and spectral line observations of the $J = 5$–4 and $J = 2$–1 transitions of CS in both common and rare isotopic species toward this source. The continuum energy distribution from 25 to 2700 μm is modeled with dust emission at a single temperature of 39 K and an emissivity law that drops as λ^{-1} longward of 100 μm. The bolometric luminosity is 23 $L_{\odot}$. The CS observations show that the infrared source is embedded in a compact, dense molecular core. The observed $C^{32}S$ line profiles show strong self-absorption. The $C^{32}S$ ($J = 5$–4) line additionally shows a prominent asymmetry which appears best explained by the presence of infalling material in the inner regions of the cloud. We successfully reproduce both the symmetric ($J = 2$–1) and asymmetric ($J = 5$–4) CS emission-line profiles using a spherically symmetric microturbulent cloud model with a steep density gradient and an infalling core. The derived physical parameters agree well with predictions of collapsing protostar models for low-mass stars and suggest that the observed bolometric luminosity of the source may be dominated by energy produced in an accretion shock.

Subject headings: infrared: sources—interstellar: molecules—stars: pre-main-sequence

I. INTRODUCTION

Recently, we have performed a systematic search for molecular outflow activity around a number of infrared sources in the core of the Rho Ophiuchi molecular cloud (Lada, Walker, and Young 1986). ^{12}CO ($J = 2$–1) observations were made toward all sources in the cloud core whose integrated *IRAS* fluxes exceeded 2 $L_{\odot}$ (Young, Lada, and Wilking 1986). In addition a few cold and luminous sources outside the cloud core were also observed. Out of all the sources observed only IRAS 16293 – 2422 (hereafter called IRAS 1629A) had a prominent outflow (Walker *et al.* 1985, 1986). It is located approximately 1° east of the cloud core in one of the "streamer" regions of the cloud. High-resolution ^{12}CO ($J = 2$–1) mapping of this flow suggests that it consists of two separate bipolar outflows which both appear to emanate from the vicinity of the *IRAS* source. The unusual nature of both the outflow and infrared energy distribution of IRAS 1629A motivated us to obtain additional observations which we report here. These observations indicate that IRAS 1629A is a dust-enshrouded object embedded in a dense elongated configuration of molecular gas whose major axis is roughly orthogonal to the direction of the double bipolar outflow. Moreover, our observations appear to provide spectroscopic evidence for significant mass infall motions associated with a young stellar object and suggest that IRAS 1629A is a true protostar, a young stellar object in the process of acquiring mass through the accretion of an infalling envelope.

II. OBSERVATIONS

IRAS 1629A was first detected by *IRAS* in the 25, 60, and 100 μm bands, with color-corrected point source catalog fluxes of 1.59, 271, and 1062 Jy, respectively. The source is unresolved in each of the *IRAS* beams. The unusually steep rise in the flux toward longer wavelengths, and the lack of detectable emission in the 12 μm band in the co-added *IRAS* survey data (i.e., $F_{\nu} < 0.07$ Jy) indicate the source is a very cold, dust-enshrouded object.

Radio continuum observations of this source were obtained at 1.3 mm with the NRAO[1] 12 m radio telescope during 1986 January. The telescope provided spatial resolution of 27″ at 1.3 mm. Observations were obtained with dual channel receivers with instantaneous bandwidths of 600 MHz using a chopping secondary. The chopper throw was 2′. Absolute fluxes were calibrated using Mars and Saturn. The observed flux was found to be 5.7 Jy. The source has also been

[1]The National Radio Astronomy Observatory is operated by Associated Universities, Inc. under contract with the National Science Foundation.

observed in the continuum by Mundy, Wilking, and Myers (1986) who determined a flux of 0.55 Jy at 2.7 mm using the Caltech millimeter wave interferometer.

CS observations of the central region surrounding IRAS 1629A were made in the $J = 5$–4 and $J = 2$–1 transitions with the 12 m telescope during 1985 March and July and 1986 April. A map of the $J = 5$–4 transition of $C^{32}S$ was obtained for the central region from observations at 24 points separated by 15″ intervals. Single long integration measurements toward the center of the source were also made in the $J = 5$–4 and $J = 2$–1 transitions of $C^{32}S$ and $C^{34}S$. The $J = 2$–1 and $J = 5$–4 $C^{32}S$ lines were observed at 97.980968 GHz and 244.935686 GHz, respectively. The corresponding isotopic $C^{34}S$ $J = 2$–1 and $J = 5$–4 lines were observed at 96.412982 GHz and 241.016176 GHz. These frequencies are accurate to within 0.05 km s^{-1} (Lovas 1986). The data were calibrated using the standard chopper wheel technique (Ulich and Haas 1976). As an additional calibration check, M17SW was observed in both the $J = 2$–1 and $J = 5$–4 transitions of $C^{32}S$. The corresponding values of T_R^* were within 12% of those obtained by Snell *et al.* (1984).

III. RESULTS

In Figure 1 the source energy distribution from 12 μm to 2700 μm is displayed. The data are fitted with a blackbody curve modified by an emissivity $\varepsilon \propto \lambda^{-1}$, where $T = 39$ K, and $\tau(100\ \mu m) = 0.7$. Integration under the curve gives a bolometric luminosity of 23 $L_\odot$. The source diameter of 9″ implied by our fit is consistent with interferometric observations of the source at 2.7 mm (Mundy, Wilking, and Myers 1986).

Figure 2 shows our integrated intensity map of $C^{32}S$ ($J = 5$–4) emission in the region around the infrared source. The CS emitting region is elongated with its major axis running northwest to southeast, roughly orthogonal to the axes of the two bipolar flows emanating from the region (Walker *et al.* 1985, 1986). The half-power width of the CS emission region is about 30″ (or 0.02 pc). The CS emission peaks very close to the position of the *IRAS* source. This close coincidence suggests that the infrared object is extremely young. If, for example, the infrared source had a velocity only 1 km s^{-1} different from the CS gas in the plane of the sky, it would take only 10^4 yr for the infrared object to become displaced from the CS emission peak by 15″.

Figure 3 shows long-integration $C^{32}S$ and $C^{34}S$ spectra obtained at the position of the infrared source in the $J = 2$–1 and $J = 5$–4 transitions respectively. The $J = 2$–1 line of $C^{32}S$ is strong and double-peaked while the corresponding isotopic transition appears (within the noise) to be a single-peaked line whose center velocity bisects the double peaked $J = 2$–1 line. The single Gaussian nature of this isotopic profile has been confirmed by a much higher signal-to-noise ratio spectrum of the source obtained recently by John Bally (1986, personal communication). These observations indicate that the double-peaked nature of the $J = 2$–1 $C^{32}S$ emission line is a result of self-absorption in the source profile, rather than multiple velocity components in the gas. Similarly, Figure 3 (*right*) shows that the main isotope in the $J = 5$–4 transition is also double-peaked, while the rarer $C^{34}S$

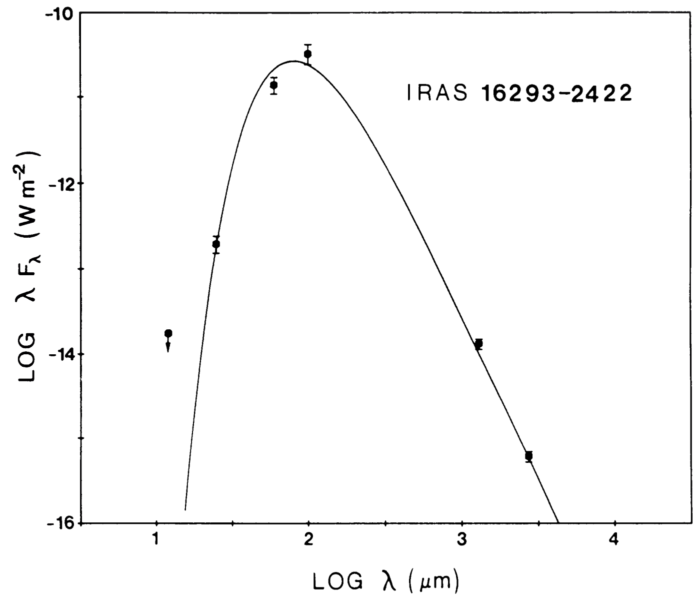

FIG. 1.—Spectrum of IRAS 1629A from 12 to 2700 μm. The solid curve is a fit of the form $(1 - e^{-\tau})B)(\lambda, 39\ K)$, where $\tau \propto \lambda^{-1}$ and $\tau(100\ \mu m) = 0.7$. The 2700 μm point is from Mundy, Wilking, and Myers (1986).

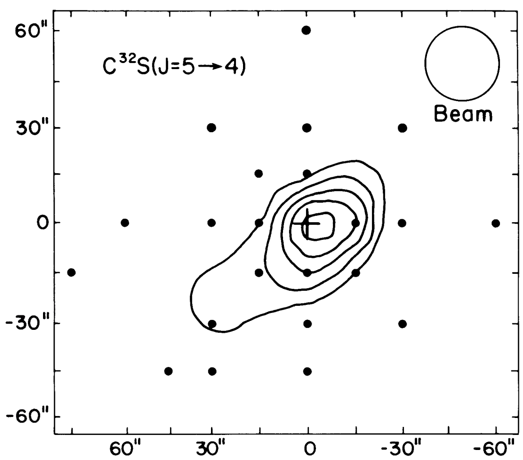

FIG. 2.—Integrated intensity $C^{32}S$ ($J = 5$–4) map of the central region of IRAS 1629A. The observed positions are indicated by filled circles, and the position of the IR source by a cross. The center position of the map is $\alpha(1950) = 16^h29^m20\rlap{.}^s9$, $\delta(1950) = -24°22'13''$. The contours are evenly spaced at intervals of 1 K km s^{-1} starting with the 3.5 K km s^{-1} contour.

isotope is, within the noise, well represented by a single Gaussian shape. Clearly deep self-absorption is present in the $J = 5$–4 transition as well. Unlike the $J = 2$–1 transition, however, the main line in the $J = 5$–4 transition is asymmetric in the sense that the two emission peaks are of unequal amplitude.

IV. INTERPRETATION: EVIDENCE FOR INFALL

The presence of deep self-absorption in both the $J = 5$–4 and $J = 2$–1 transitions of $C^{32}S$ indicates that the absorbing

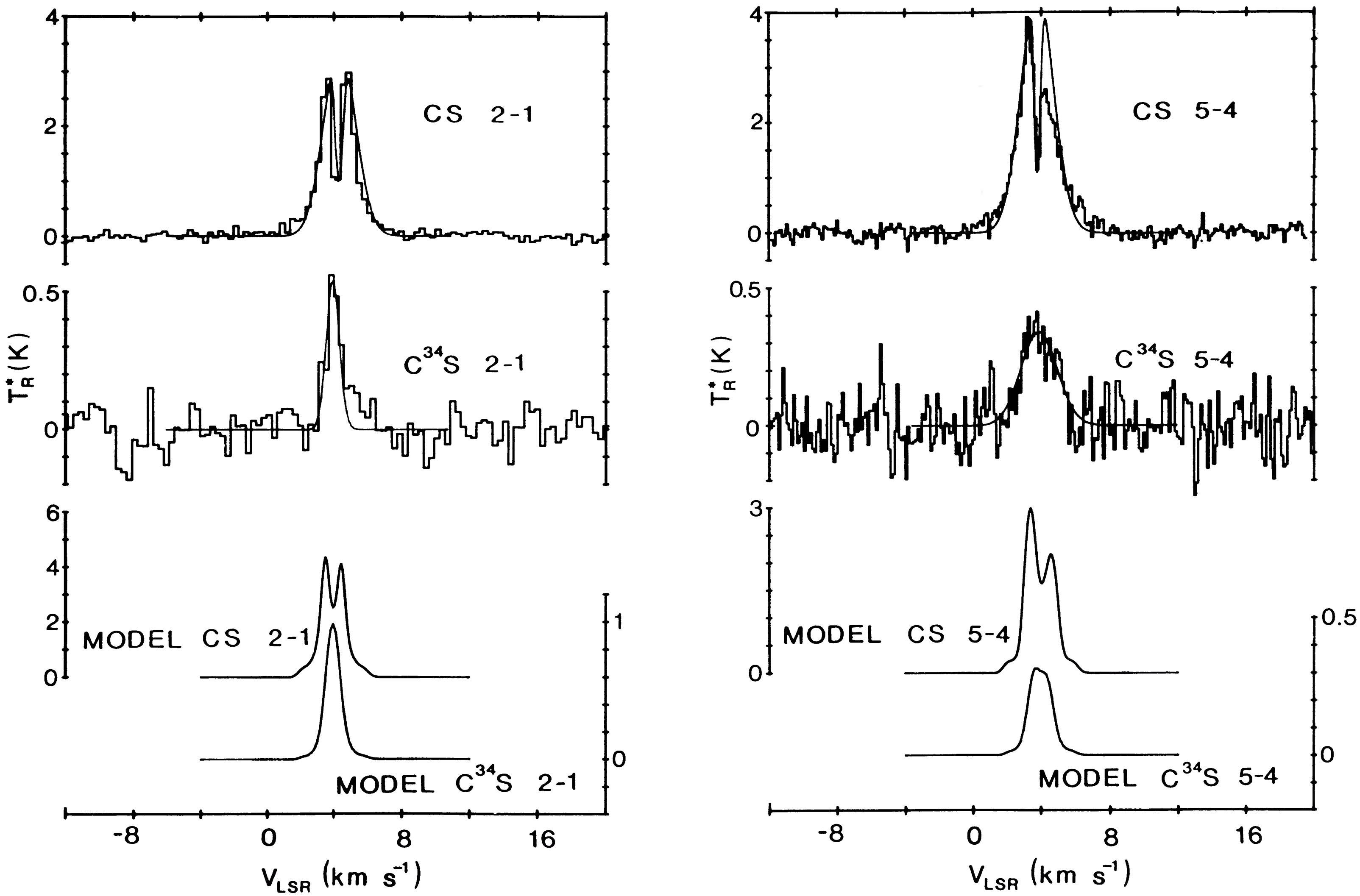

FIG. 3.—$C^{32}S$ and $C^{34}S$ spectra (*histogram*) observed toward IRAS 1629A in the $J = 2$–1 (*left*) and $J = 5$–4 (*right*) transitions. Each spectrum is fitted with one or more Gaussians (*smooth lines*; see text). Plotted below the observed spectra are the corresponding synthetic profiles generated by a microturbulent cloud model, with a steep density gradient and an infalling core. To compensate for the effect of the telescope error patterns, the model $J = 5$–4 and $J = 2$–1 profiles were multiplied by 0.5 and 0.9, respectively.

gas is characterized by large opacities. To make a rough estimate of the optical depth in the center of the self-absorption dip we have fitted the observed profiles with the convolution of two Gaussian functions, one to match the emission profile and one to model the absorption dip. The resulting synthetic profiles are displayed in Figure 3 superposed on the data. The line center absorption optical depths required to fit the data were equal to 1.5 in both transitions. Examination of Figure 3 (*left*) shows that this simple fit represents the shape of the observed $J = 2\text{–}1$ $C^{32}S$ profile quite well. However, the synthetic $J = 5\text{–}4$ profile lacks the very marked asymmetry of the two emission peaks present in the data.

The high opacities inferred from the presence of deep self-absorption in both the $J = 2\text{–}1$ and $J = 5\text{–}4$ transitions coupled with the lack of any significant velocity structure in the $C^{34}S$ lines suggest the asymmetric shape of the $C^{32}S$ $J = 5\text{–}4$ line is due to opacity effects in an infalling region of the cloud core, rather than to emission from distinct cloud components at different velocities and with different excitation conditions.

To see how systematic infall will produce an asymmetry in an optically thick line, consider a spherical cloud with an excitation temperature decreasing with radius and a constant microturbulent velocity field. In the absence of systematic gas motions, the emergent line profile will have a symmetric, double-peaked shape. The most important effect of systematic gas velocities which are comparable to or less than the microturbulent velocities will be to distort the monochromatic optical depth scales and thereby alter the absorption coefficient and emergent line profiles (Leung and Brown 1977). In particular, equation (2) of Leung and Brown (1977) shows that the presence of a small infall velocity will produce smaller optical depths for photons on the blue side of the line profile and increased opacity on the red side of the line, resulting in emission on the blue side of the profile coming from deeper in the cloud than emission on the red side. The intensity on the blue side of the emergent line will be greater than that on the red side if the excitation temperature decreases from the cloud center. The converse is true for an expanding cloud. The observed asymmetry in the $J = 5\text{–}4$ profile could thus be produced by a contracting cloud with a radially decreasing excitation temperature.[2]

Three considerations lead to the conclusion that the CS excitation temperature decreases outward from IRAS 1629A. First, the extents of the $C^{18}O$, CS ($J = 2\text{–}1$) and CS ($J = 5\text{–}4$) emission regions are progressively smaller (Walker *et al.* 1986) indicating a relatively steep density fall-off from the source. Second, the derived dust temperature for the inner dust core of 39 K is higher than the gas kinetic temperature derived from CO observations (about 24 K) which sample the outer parts of the cloud. Finally, the deep dip in the $J = 2\text{–}1$ profile could only be produced with a radially decreasing excitation temperature in a static microturbulent cloud since a radially increasing excitation temperature would produce a single, symmetric peak. Therefore, we conclude that the asymmetry in the $J = 5\text{–}4$ profile is produced by infalling optically thick gas.

The symmetric nature of the $J = 2\text{–}1$ $C^{32}S$ line indicates that the infalling gas is not observable in this transition. Since the $J = 2\text{–}1$ transition probes gas of relatively lower excitation and since the beam at the $J = 2\text{–}1$ frequency is a factor of 2 larger than that of the $J = 5\text{–}4$ transition, this suggests that the outermost layers of the cloud are not participating in infall. This limits the size of the infall region to less than about 6×10^{16} cm in diameter. As we will argue below, this provides a compelling argument for identification of IRAS 1629A as a true protostar, that is, a young stellar object in the process of assembling the mass it will contain when it ultimately reaches the main sequence.

It is useful to consider in more detail whether such a collapsing cloud can produce the spectral signature we have observed for IRAS 1629A. To do this we have attempted to model the CS line profiles using a Monte Carlo microturbulent radiative transfer code originally developed by Bernes (1979). We assume a spherically symmetric cloud with a steep radial density gradient and a kinetic temperature which decreases linearly from $T = 40$ K at the center to 20 K at the edge. The density profile we adopted was a simple power law, with

$$n = n_0, \qquad r \le r_0$$

$$n = n_0 (r/r_0)^{-2}, \qquad r > r_0. \tag{1}$$

A constant microturbulent velocity field was included throughout the entire cloud. Collision rates from Green and Chapman (1978) were used. To simultaneously produce an asymmetric $J = 5\text{–}4$ profile and minimize asymmetries in the $J = 2\text{–}1$ profile the addition of a systematic infall velocity field of the form:

$$v = v_0 (r/r_0)^{-1/2}, \qquad r \le r_1$$

$$v = 0, \qquad r > r_1 \tag{2}$$

was necessary. An $r^{-1/2}$ velocity field is what is expected for free fall collapse; however, the results are only weakly dependent on the slope of the velocity law. Strictly speaking, the density should vary as $r^{-1.5}$ in the region of infall to be consistent with our assumed velocity field; however, for the sake of simplicity we used a constant power law for the density throughout the whole cloud. To directly compare model profiles with the observed spectra the model was numerically convolved with a 30″ Gaussian beam function for the $J = 5\text{–}4$ transition and a 60″ beam for the $J = 2\text{–}1$ line, assuming that the source was centered in each beam. Models were run with varying values of n_0, r_0, v_0, r_1, $\Delta v_{\rm turb}$, and the CS abundance $X_{\rm CS}$. The turbulent velocity is constrained to $\Delta v_{\rm turb} = 0.4$ km s^{-1} by the widths of the lines. The degree of asymmetry in the 5–4 and 2–1 lines is very sensitive to the density profile of the models. The best fitting model had $n_0 = 1.0 \times 10^6$ cm^{-3}, $r_0 = 10^{16}$ cm, $v_0 = 0.8$ km/s, $r_1 = 4.7 \times 10^{16}$ cm, and $X_{\rm CS} = 1.7 \times 10^{-8}$. Although the density does not increase above 10^6 cm^{-3} in the inner part of the cloud due to computational constraints, we expect a more

[2]Asymmetries in the line shape can also be produced with an excitation temperature that increases with radius in an expanding or contracting cloud. However, unlike a cloud with a radially decreasing excitation temperature and the observed spectra, the resulting emergent line profiles are single-peaked rather than double-peaked.

realistic model with increasing central density would only have the effect of broadening the wings of the model profiles. The results are shown in Figure 3. Profiles were generated for both the $C^{32}S$ and $C^{34}S$ isotopes in the two transitions, assuming a terrestrial isotopic abundance. The synthetic profiles match the shapes, widths, and intensities of both $J = 5$–4 isotopes remarkably well. The observed absorption dip in the main line, however, appears much deeper than in the model. The model $J = 2$–1 profiles are stronger than observed. The synthetic $C^{32}S$ $J = 2$–1 line is considerably more symmetric than the corresponding $J = 5$–4 line but not as symmetric as the observed profile. Nonetheless the qualitative agreement of the models and the data is excellent. The depth of the observed $J = 5$–4 absorption, the high degree of symmetry of $J = 2$–1 profile, and the lower intensities of the observed $J = 2$–1 lines could be modeled, in principle, by incorporating a shallower density gradient in the outermost parts of the cloud. A nonconstant density law is suggested from CO observations, but in the interest of simplicity was not included in the present calculations. The spherical symmetry of the model is another simplification that, of course, ceases to be valid for the innermost regions. Nevertheless, the good agreement with the observed line profiles suggests that the adopted infall model is a good approximation of the CS emitting regions.

If IRAS 1629A is a protostar as we suggest, then our observations in conjunction with our modeling enable estimates of important physical properties of the system. The scaling of equation (2) necessary to fit our observations (i.e., r_1 and v_0) yields a mass of the central protostar of order $v_0^2 r_0/(2G)$ or about 0.24 $M_\odot$. It is unlikely that r_1 is much larger than we assumed since the models predict a prominent asymmetry in the $J = 2$–1 profiles for larger values of r_1. However, slightly higher infall velocities could be consistent with the observations and a central core mass as large as 0.5 $M_\odot$ may well be possible. In our model the mass of the infall region is 0.1 $M_\odot$. Combining this with the adopted size scale and velocity gradient of the infalling envelope, we estimate a mass and infall rate, the expected accretion luminosity (i.e., $L = GM\dot{M}/r$) would equal the observed bolometric luminosity of IRAS 1629A for $r = 2 \times 10^{11}$ cm, or about 3 $R_\odot$, which is typical of the size scale expected for the hydrostatic core of an accreting protostar (Stahler, Shu, and Taam 1980). Therefore, the observed luminosity of IRAS 1629A could be entirely produced by accretion.

On the basis of theoretical considerations it has been long suspected that the collapse of a protostellar cloud core proceeds in a highly nonhomologous, inside-out manner (e.g., Larson 1973). Shu (1977) demonstrated that the collapse of an isothermal cloud core, initially near hydrostatic equilibrium, proceeds in a self-similar manner and produces an outward expansion wave of infall, at the head of which the central regions fall freely from the isothermal outer envelope. The expansion wave collapse moves outward through the cloud at the speed of sound a and takes approximately 3×10^4 yr to reach a radial size of order 3×10^{16} cm for a cloud temperature of 20 K. The mass infall rate predicted for such an isothermal cloud is $\dot{M} = 0.975 a^3/G$ or 5×10^{-6} $M_\odot$ yr^{-1}. The parameters used in our simple models to fit the observed spectra are remarkably close to those expected for a collapsing isothermal cloud and support the interpretation of infall that we have adopted to explain our observations.

Finally, we point out that outflow and infall are observed simultaneously for IRAS 1629A. Moreover, our models and data suggest that this source is an extremely young protostellar object with an age on the order of a few times 10^4 yr. It is interesting that this age is of the same order as the dynamical age of the associated outflow (Walker *et al.* 1986) suggesting that the outflow stage of stellar evolution begins not long after the initiation of the accretion phase.

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REFERENCES

Bernes, C. 1979, *Astr. Ap.*, **73**, 67.
Green, S., and Chapman, S. 1978, *Ap. J. Suppl.*, **37**, 167.
Lada, C. J, Walker, C. K., and Young, E. T. 1986 in preparation.
Larson, R. B. 1973, *Ann. Rev. Astr. Ap.*, **11**, 219.
Leung, C. H., and Brown, R. L. 1977, *Ap. J. (Letters)*, **214**, L73.
Lovas, F. J. 1986, *J. Phys. Chem. Ref. Data.*, **15**, 251.
Mundy, L. G., Wilking, B. A., and Myers, S. 1986. in preparation.
Shu, F. H. 1977, *Ap. J.*, **214**, 488.
Snell, R. L., Mundy, L. G., Goldsmith, P. F., Evans, N. J., II, and Erickson, N. R. 1984, *Ap. J.*, **276**, 625.
Stahler, S. W., Shu, F. H., and Taam, R. 1980, *Ap. J.*, **241**, 637.
Ulich, B. L., and Haas, R. W. 1976, *Ap. J. Suppl.*, **30**, 247.
Walker, C. K., Lada, C. J., Young, E., Margulis, M., and Wilking, B. A. 1985, *Bull. AAS* **17**, 835.
______. 1986, in preparation.
Young, E. T., Lada, C. J., and Wilking, B. A. 1986, *Ap. J. (Letters)* **304**, L78.

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