IRAS 01202+6133: A POSSIBLE CASE OF PROTOSTELLAR COLLAPSE TRIGGERED BY A SMALL H II REGION

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Received 2012 June 28; accepted 2012 September 7; published 2012 October 11

ABSTRACT

We present an analysis of HCO+ (J = 3 → 2) and H13CO+ (J = 3 → 2) observations of the massive (M \sim 20 M⊙) submillimeter/IR source IRAS 01202+6133 located on the periphery of the H II region KR 120 (Sh 2-187). The HCO+ line profile has a classic blue-asymmetric shape with the optically thin H13CO+ line peaking at the position expected if the HCO+ line arises from a combination of self-absorption and infall motion. We have modified existing analytic radiative transfer models to allow for the fitting of submillimeter/millimeter line profiles that have both self-absorption features and optically thin wings and applied these models to our HCO+ spectrum of IRAS 01202+6133. We conclude that it is a young Class I young stellar object with a substantial envelope undergoing slow infall and having some outflow motions. The young age of the H II region rules out a “collect and collapse” scenario. While we cannot eliminate the possibility that IRAS 01202+6133 formed spontaneously at its current location, considering its early evolutionary state and its proximity to the H II region, we think that the formation of IRAS 01202+6133 was triggered by the expansion of KR 120 (Sh 2-187).

Key words: H ii regions – ISM: kinematics and dynamics – ISM: molecules – line: profiles – stars: formation

Online-only material: color figures

1. INTRODUCTION

The molecular gas surrounding an H II region is thought to be a place where star formation can be induced. Such triggered star formation can arise from the overpressurization of existing density enhancements (Thompson et al. 2004) or through the collapse of swept up layers of material (Elmegreen 1998; Deharveng et al. 2003). This paper presents an analysis of submillimeter spectroscopic observations of the Class I young stellar object (YSO) IRAS 01202+6133 which is located on the periphery of the relatively nearby (d = 1.44 ± 0.26 kpc) H II region KR 120 (Sh 2-187; Arvidsson & Kerton 2011; Kalas & Reich 1980; Sharpless 1959). As shown in Figure 1, the proximity alone of this massive (M = 21 ± 9 M⊙), luminous (L \sim 5600 L⊙) YSO to the H II region makes it a strong candidate for an example of triggered star formation. The submillimeter spectra presented here strengthen this scenario as they clearly show that infall is occurring as would be expected for a very young YSO. We believe that IRAS 01202+6133 is one of the clearest examples to date of an H II region triggering the formation of another massive star.

Our observations are described in Section 2. In Section 3, we review the analytic models of Myers et al. (1996) and DeVries & Myers (2005), and develop new varieties of these models that allow for both infall and outflow motions. Physical properties of the YSO derived using these models are presented and discussed in Section 4, followed by our conclusions in Section 5.

2. OBSERVATIONS

In order to explore the kinematics of IRAS 01202+6133, we obtained observations of the commonly used (e.g., Sun & Gao 2009) optically thick infall tracer molecule HCO+ (J = 3 → 2; 267.6 GHz) and its optically thin isotopologue H13CO+ (J = 3 → 2; 260.3 GHz) at the James Clerk Maxwell Telescope (JCMT) in the 06B semester. Single pointing observations (beam size \sim 20′′ FWHM) were made using the A3 receiver and ACSIS back end with a frequency resolution of 61 kHz (0.068 km s\(^{-1}\)) and an integration time of \sim 40 minutes for each line. The reduced spectra are shown in Figure 2. Both have a noise level of \sim 0.1 K resulting in a peak S/N \sim 30 for the HCO+ spectrum and \sim 3 for the weaker H13CO+ spectrum.

If there was no infall motion associated with IRAS 01202+6133, then we would expect the HCO+ spectrum to be a single self-absorbed profile with symmetric red and blue peaks around a local minimum at some systematic velocity. Following Myers et al. (1996), in the case of infall, there will be density and excitation temperature (T ex) differences between the central regions and the outer parts of the molecular core. Blueshifted emission from the rear of the core is not strongly absorbed because it passes through the central (high T ex) region then through a highly Doppler shifted front portion of the core. In contrast, the redshifted emission from the front of the core is absorbed by surrounding gas that is at both a comparable velocity and similar (low) T ex. The overall effect of the infall motion is to create a “blue-asymmetric” line profile, where the self-absorption line is asymmetric with a stronger blue peak. Such a line profile could also form from multiple unrelated emission components being aligned along the line of sight or from rotational motion, but in both cases we would expect to see a similar profile in the optically thin line. The fact that our H13CO+ spectrum peaks up at the same velocity as the minimum in the HCO+ spectrum makes us confident that we are looking at a single self-absorbed line profile with the asymmetry arising from infall motions.

3. ANALYTIC RADIATIVE TRANSFER MODELING

Myers et al. (1996) and DeVries & Myers (2005) developed basic one-dimensional (1D) analytic radiative transfer models to derive kinematic data from the millimeter/submillimeter spectra of star-forming molecular cores. In this section, we first review these models and then present modified versions that better model cases where there is simultaneous infall and outflow motions.
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All of the models are based on the general solution to the 1D radiative transfer equation for a homogeneous medium with total optical depth $\tau_0$,

$$T_B = T_i e^{-\tau_0} + \int_0^{\tau_0} J(T)e^{-\tau}d\tau, \quad (1)$$

where $T_B$ is the brightness temperature of the outgoing radiation, $T_i$ is the brightness temperature of any incoming radiation, $J(T) \equiv T_0/[\exp(T_0/T) - 1]$, and $T_0 \equiv hv/k$, where $v$ is the frequency of the transition and $T$ is the temperature.

If $J(T)$ is a linear function of $\tau$, then Equation (1) can be integrated to obtain

$$T_B = T_i e^{-\tau_0} + (J_2 - J_1) \frac{1 - e^{-\tau_0}}{\tau_0} + J_1 - J_2 e^{-\tau_0}, \quad (2)$$

where $J_1$ and $J_2$ are the values of $J(T)$ at the two ends of the path with optical depth $\tau_0$. All of the models presented in this section are based on Equation (2) with variations due to how $J(T)$ varies with $\tau$ in detail.

3.1. Two-layer Model

The two-layer model of Myers et al. (1996) has “front” and “rear” constant $T_{ex}$ layers moving toward each other each at an infall velocity, $v_{in}$ (see Figure 1 of DeVries & Myers 2005).

The line brightness temperature of the two-layer model is

$$\Delta T_B = J(T_f)[1 - e^{-\tau_f}] + J(T_r)[1 - e^{-\tau_r}]e^{-\tau/2} - J(T_b)[1 - e^{-\tau_f}]e^{-\tau/2}, \quad (3)$$

where $T_f$ and $T_r$ are the front and rear excitation temperatures and $T_b$ is the background temperature. The optical depths of each layer, $\tau_f$ and $\tau_r$, are given by

$$\tau_f = \tau_0 \exp \left[-(v - v_{LSR} - v_{in})^2/2\sigma^2\right], \quad (4a)$$

where $\tau_0$ is the line center optical depth, $v_{LSR}$ is an average line-of-sight velocity of the system, and $\sigma$ is the velocity dispersion of the observed molecule.

For a given choice of $T_b$ (usually $T_b = 2.7$ K), the two-layer model has six adjustable parameters: $T_f$, $T_r$, $v_{LSR}$, $v_{in}$, and $\sigma$. By making some assumptions about the expected density and temperature structure in an infalling core, Myers et al. (1996) was able to reduce the number of parameters in the two-layer model to five, replacing $T_r$ and $T_f$ by a kinetic temperature, $T_k$. This version of the model also used the non-thermal velocity dispersion as an input, $\sigma_{NT} \equiv (\sigma^2 - kT_k/m_{obs})^{1/2}$, where $m_{obs}$ is the mass of the observed molecule. Here, we present the
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Figure 3. Basic model results. The figure shows how the basic two-layer model (left) and hill model (right) are unable to fit the extended wings seen in the HCO+ spectrum. In these plots, the systematic velocity of the cloud ($V_{\text{LSR}} = -13.7$ km s$^{-1}$) has been removed.

Figure 4. Modified radiative transfer models. In order to fit the extended wings seen in the HCO+ spectrum, we added a central low optical depth “outflow” region to the existing two-layer and hill models. The diagrams schematically show the run of temperature with optical depth in the 2L-O model (left) and Hill-O model (right).

Formulas used to calculate the model parameters and refer the reader to Myers et al. (1996) for their derivation.

The excitation temperature of each layer is determined using the following equations:

$$\frac{T_f}{T_k} = \frac{T_k + (4T_0/\beta \langle n_f \rangle)/n_{\text{max}}}{T_k + (4T_0/\beta \langle n_f \rangle)/n_{\text{max}}}, \quad (5a)$$

$$\frac{T_r}{T_k} = \frac{T_k + (4T_0/\beta \langle n_r \rangle)/n_{\text{max}}}{T_k + (4T_0/\beta \langle n_r \rangle)/n_{\text{max}}}, \quad (5b)$$

where $\beta = (1 - \exp(-\tau_0))/\tau_0$, and $\langle n_f \rangle/n_{\text{max}}$ and $\langle n_r \rangle/n_{\text{max}}$ are given by

$$\frac{\langle n_f \rangle}{n_{\text{max}}} = (1 - e^{-\tau_0})^{-1} \left[ \frac{6}{\tau_0^3} - e^{-\tau_0} \left( 1 + \frac{3}{\tau_0} + \frac{6}{\tau_0^2} + \frac{6}{\tau_0^3} \right) \right], \quad (6a)$$

$$\frac{\langle n_r \rangle}{n_{\text{max}}} = (1 - e^{-\tau_0})^{-1} \left[ 1 - \frac{3}{\tau_0} + \frac{6}{\tau_0^2} - \frac{6}{\tau_0^3} (1 - e^{-\tau_0}) \right]. \quad (6b)$$

3.2. Hill Model

In the “hill” model of DeVries & Myers (2005), $J(T)$ increases linearly from the $T_0$ to $T_p$ over a front optical depth ($\tau_f$), and then decreases from $T_p$ to $T_0$ over a rear optical depth ($\tau_r$). The shape of a $J(T)$ plot against $\tau$ gives the model its name (see Figure 1 of DeVries & Myers 2005). As with the two-layer model, the front and rear sections, each with a line center optical depth ($\tau_0$), are moving toward each other with an infall velocity $v_{\text{in}}$, and have a velocity dispersion $\sigma$.

The line brightness temperature of the hill model is given by

$$\Delta T_B = [J(T_p) - J(T_0)] \left[ \frac{1 - e^{-\tau_f} - e^{-\tau_r} (1 - e^{-\tau_r})}{\tau_f} \right]$$

$$+ [J(T_0) - J(T_p)] \left( 1 - e^{-\tau_f - \tau_r} \right). \quad (7)$$

For a given choice of $T_0$, the hill model has six adjustable parameters: $T_0$, $T_p$, $\tau_0$, $v_{\text{LSR}}$, $v_{\text{in}}$, and $\sigma$. Equations (4a) and (4b) are used to determine $\tau_f$ and $\tau_r$.

3.3. Analytical Models with Outflow

While the two-layer and the hill models are able to reproduce the central portion of the observed blue-asymmetric line profile, they are not able to model the extended wings of the line profile observed beyond $\sim \pm 2$ km s$^{-1}$ (see Figure 3). In order to correctly model the entire line, we follow the approach used in the Myers et al. (1996) analysis of L 1527 and incorporate a central outflow region into both the two-layer and hill models. The resulting variation of $T_{\text{ex}}$ with $\tau$ is shown schematically in Figure 4 (cf. Figure 1 of DeVries & Myers 2005).

3.3.1. Two-layer Model with Central Outflow (2L-O Model)

With the addition of a central outflow region to the two-layer model, the line brightness temperature (Equation (3))

$^1$ The equation in DeVries & Myers (2005) is typeset incorrectly in the Astrophysical Journal. The correct version is found in the arXiv version (DeVries & Myers 2004).
exactly match the model H2CO (appropriate. becomes Figure 5.

As a test of our version of the 2L-O model, we were able to obtain accurate estimates of infall velocities (rms error 0.01 km s$^{-1}$) from two-peak profiles, in contrast with two-layer model, it has some trouble matching the line widths and the trough structure. The best-fit parameters are given in Table 1 and the systematic velocity of the YSO has been removed from this plot.

$$\Delta T_B = J(T_f)[1 - e^{-\tau_f}] + J(T_{out})[1 - e^{-\tau_{out}}] e^{-\tau_f}$$

$$+ J(T_i)[1 - e^{-\tau_i}] e^{-\tau_i - \tau_{out}} - J(T_p)[1 - e^{-\tau_i - \tau_{out} - \tau_{out}}],$$

(8)

where $\tau_{out}$ and $T_{out}$ are the optical depth and excitation temperature of the outflow.

The only additional parameters needed in the 2L-O model are $\tau_{out}$ and $\sigma_{out}$, the line center optical depth and the velocity dispersion of the outflow region. Both are used to calculate $\tau_{out}$ using

$$\tau_{out} = \tau_{0, out} \exp \left[-(v - v_{LSR})^2/2\sigma_{out}^2\right].$$

(9)

In our model, we set $T_{out}$ equal to the average of $T_r$ and $T_f$ calculated using $\tau_{out,0}$ in Equations (5a), (5b), (6a), and (6b) as appropriate.

As a test of our version of the 2L-O model, we were able to exactly match the model H$_2$CO ($J = 2 \rightarrow 1$) profile of L 1527 shown in Figure 3 of Myers et al. (1996) using the outflow and model parameters given in the figure caption.

3.3.2. Hill Model with Central Outflow (Hill-O Model)

The brightness temperature of the hill model with a central outflow is

$$\Delta T_B = (J_p - J_0) \left[ \frac{1 - e^{-\tau_f}}{\tau_f} - \frac{(1 - e^{-\tau_i}) e^{-\tau_i - \tau_{out}}}{\tau_i} \right]$$

$$+ (J_0 - J_0)(1 - e^{-\tau_i - \tau_{out} - \tau_{out}}),$$

(10)

where $\tau_{out}$ is the optical depth of outflow. Since we set the excitation temperature of the outflow equal to $T_p$ (see Figure 4), the only additional parameters are $\tau_{0, out}$ and $\sigma_{out}$. As in the 2L-O model, $\tau_{out}$ is calculated using Equation (9).

4. RESULTS AND DISCUSSION

4.1. YSO Properties

We applied the 2L-O and the Hill-O models to our observed HCO$^+$ spectrum (see Figures 5 and 6, respectively). The best-fit parameters are given in Tables 1 and 2. Uncertainties were derived using a Monte Carlo method; an initial best fit of the model was obtained, then random noise at the same level as the observed line profile was added to the best fit and the resulting simulated line profile was then fit, generating a new set of parameters. The standard deviation of spectral line parameters after 1000 repeats was combined with the mean fit uncertainties to produce the final error estimates.

As noted by Myers et al. (1996), the two-layer model tends to output profiles that have narrower peaks and flatter central troughs than observations, and both of these characteristics can be seen in the 2L-O best-fit model shown in Figure 5. In contrast, the Hill-O model does a much better job in fitting the observed peak widths and the structure of the central absorption trough.

DeVries & Myers (2005) showed that hill style models were able to obtain accurate estimates of infall velocities (rms error 0.01 km s$^{-1}$) from two-peak profiles, in contrast with two-layer
models, which tended to underestimate the infall velocity by factors of $\sim 2$. Consistent with this finding, we see that the best-fit 2L-O $V_{\text{in}}$ is a factor of $3.5$ lower than the Hill-O value. While we adopt the numerical results of the Hill-O model for IRAS 01202+6133, we note that regardless of the exact numeric values, both the 2L-O and Hill-O results are consistent with an object with a substantial envelope ($\tau_0 \sim 10$) undergoing slow infall ($V_{\text{in}} \ll \sigma$).

4.2. Formation Scenarios

There are two basic scenarios for the formation of IRAS 01202+6133, either its formation was triggered by the action of the expanding H II region or it formed spontaneously and its proximity to the H II region is coincidental.

To gauge the likelihood of the first scenario, we can first look at the various time scales associated with the YSO-H II region system. The canonical duration of the Class I stage of YSO evolution is of the order of $10^5$ years (Ward-Thompson 2002). The fact that IRAS 01202+6133 still has a substantial envelope and exhibits slow infall suggests that it is still a fairly young Class I YSO. The presence of outflow motions does not constrain the age as they are known to be associated with even the very earliest stages of YSO evolution (André et al. 1993). Assuming that any Class 0 stage would be very rapid ($\sim 10^4$ years), we conclude that the age of the YSO is $\tau_{\text{YSO}} \lesssim 10^5$ years.

KR 120 is a fairly young H II region. On balance though, we prefer the triggered scenario as it naturally explains the close spatial association of the H II region and the very young Class I YSO.

5. CONCLUSIONS

1. Our analysis of the HCO$^+$ ($J = 3 \rightarrow 2; 267.6$ GHz) and H$^{13}$CO$^+$ ($J = 3 \rightarrow 2; 260.3$ GHz) spectra of the submillimeter/IR source IRAS 01202+6133 shows that the blue-asymmetric HCO$^+$ line profile is almost certainly due to infall motions.

2. We have modified the analytic radiative transfer models of Myers et al. (1996) and DeVries & Myers (2005) to allow for fitting of submillimeter/millimeter line profiles that have both self-absorption features and optically thin wings. We applied these models to our HCO$^+$ submillimeter spectrum of IRAS 01202+6133 and conclude that it is a young Class I YSO with a substantial envelope undergoing slow infall.

3. Based on its young evolutionary state ($\tau_{\text{YSO}} < \tau_{\text{HII}}$) and its proximity to the H II region KR 120 (Sh 2-187), we think that the formation of IRAS 01202+6133 was triggered by the expansion of the H II region. However, due to the young age of the H II region, a “collect and collapse” scenario is ruled out.

We thank Dr. Lewis B. G. Knee for his assistance with the processing of the JCMT data.

Facility: JCMT

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