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# EVOLUTION OF PROTOSTARS ACCRETING MASS AT VERY HIGH RATES: IS ORION IRc2 A HUGE PROTOSTAR?

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## ABSTRACT

The recent near-infrared spectroscopy of scattered light from Orion IRc2 suggests that the illuminating source at the $K'$ band is either a protostar with a radius $\gtrsim 300\ R_{\odot}$ or a disk with an accretion rate $\approx 10^{-2}\ M_{\odot}\ \mathrm{yr}^{-1}$. To test the former interpretation, we present a simplified stellar model accreting mass at a very high rate, $\approx 10^{-2}\ M_{\odot}\ \mathrm{yr}^{-1}$. We find that the protostar is fully convective at almost all stages of the stellar mass $M \lesssim 15\ M_{\odot}$, and thus a polytrope of index 1.5 is a good approximation of the stellar structure. The maximum radius $\lesssim 30\ R_{\odot}$ is attained at $M \sim 7\ M_{\odot}$. The shell deuterium burning, which would occur afterward, cannot greatly blow up the protostar because the energy released by deuterium burning is small and also because the protostar is already shrinking rapidly. The only remaining possibility to make a huge protostar resides in the rotation of the surface layer almost at its breakup velocity. On the other hand, we find no difficulty in the alternative interpretation that the illuminating source is the accretion disk. In this case we predict that the 2.3 μm CO absorption lines should be observed with a width $\sim 50\ \mathrm{km\ s^{-1}}$ due to the Keplerian motion in the disk. The accretion rate as high as $10^{-2}\ M_{\odot}\mathrm{yr}^{-1}$ is compatible with the velocity dispersion in the Orion KL molecular cloud core. Because the luminosity of IRc2 is dominated by accretion, the protostellar mass is overestimated if the observed luminosity is regarded as intrinsic. Because the $K'$-band luminosity is emitted in the disk region far from the protostellar surface, the total accretion luminosity must be significantly higher than the observed $K'$-band luminosity.

*Subject headings:* stars: evolution — stars: formation — stars: individual (Orion KL IRc2) — stars: pre–main-sequence

## 1. INTRODUCTION

Although the process of low-mass star formation is relatively well understood, not much is known about the formation of massive stars. We have only limited observational information on high-mass star formation mainly because massive protostars are few and evolve rapidly while they are still deeply embedded in dense molecular cloud cores. This makes our chance to witness massive stars in formation very rare. In addition, high-mass star formation is observed in giant molecular clouds, which are much more distant from us than the nearest dark clouds with active low-mass star formation.

The Orion KL Nebula has served as a prototype of high-mass star-forming regions, being the closest (450 pc from the Sun) among such regions. In the standard picture that emerged in the 1980s (Genzel & Stutzki 1989 and references therein), the compact mid-infrared source IRc2 (Rieke et al. 1973) in Orion KL is postulated to be a massive star in formation. It has an estimated bolometric luminosity of $(0.4\text{–}2) \times 10^{5}\ L_{\odot}$ (Wynn-Williams et al. 1984), which gives a mass of about 25 $M_{\odot}$ if it is near the main sequence (Vogel et al. 1985). Molecular line observations have revealed an energetic bipolar outflow of gas (e.g., Erickson et al. 1982; Wright et al. 1983), which excites shocks at its interface with the surrounding molecular gas (Beckwith et al. 1978).

This standard picture of IRc2 is challenged by recent observations. Gezari (1992) revealed a 0″.7 spatial offset of the 10 μm source from the SiO maser and/or radiosource, and Dougados et al. (1993) resolved the infrared source into four knots at 3.8 μm. However, the linear polarization of the 3.8 μm knots leaves room for the standard picture to survive because the knots might not be self-luminous but be illuminated by, for example, the luminosity source associated with the SiO maser (Menten & Reid 1995). Even if the luminosity source is not a single protostar but a group of such objects, a large fraction of the total luminosity might arise from the most massive object. On high–spatial resolution mid-infrared observations of the BN/KL region, Gezari et al. (1998) suggest that IRc2 has a luminosity of only $\sim 10^{3}\ L_{\odot}$ and that the total luminosity of $\sim 10^{5}\ L_{\odot}$ is contributed by several sources very close to IRc2. In this case the object we are going to investigate in this paper is the most luminous object among them. Even in this case we call this object IRc2 in this paper.

A dense disklike cloud of gas and dust roughly orthogonal to the Orion KL outflow axis surrounds the object (e.g., Hasegawa et al. 1984; Wright et al. 1996), and its heavy extinction makes it difficult to observe IRc2 directly at wavelengths shorter than $\sim 4$ μm. No spectroscopic information was hitherto available to reveal the nature of the

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central source except for the emission lines from the gas shocked by the outflow.

A breakthrough was achieved by Morino et al. (1998), who studied the 2 $\mu$m spectrum of the reflection nebula illuminated by the light from IRc2 that escapes through the cavities created by the bipolar outflow. From the discovered CO and metallic absorption lines they derived the effective temperature $T_{\rm eff}$ of the illuminating source to be between 3000 and 5500 K, with the most probable value of 4500 K. They also estimated the $K'$-band absolute magnitude of the illuminating source as $M_{K'} \leq -8.6$ mag from the integrated luminosity of the reflected light. This combination of $T_{\rm eff}$ and $M_{K'}$ enabled them to estimate the source size. If the illuminating $K'$-band radiation arises from the protostar, the radius of its photosphere must be larger than 300 $R_\odot$. In this case, the bolometric luminosity of the protostar is estimated as greater than $4 \times 10^4\, L_\odot$, which is consistent with the estimate from the mid-infrared observations (Wynn-Williams et al. 1984). Alternatively, if this $K'$-band luminosity arises from the accretion disk around the protostar of mass 10–25 $M_\odot$, a region of a similar size in the disk should contribute mainly to the observed $K'$-band spectrum. This, at the same time, requires a mass accretion rate as high as (0.6–1.5) $\times\, 10^{-2}\, M_\odot$ yr$^{-1}$.

In the process of star formation, a very small protostellar core in quasi-static equilibrium forms first, and the core grows gradually by mass inflow from the parental cloud core. The mass inflow rate, or the mass accretion rate $\dot{M}$ of the protostar, is of the order of $C_{\rm eff}^3/G$, where $C_{\rm eff}$ is the effective sound velocity in the cloud core including the turbulent and magnetic effects and $G$ is the gravitational constant (Shu 1977; Stahler, Shu, & Taam 1980). For $C_{\rm eff} = 1.9 \times 10^4$ cm s$^{-1}$, the sound velocity at 10 K, for example, we have the standard accretion rate $0.975 C_{\rm eff}^3/G \approx 1.6 \times 10^{-6}\, M_\odot$ yr$^{-1}$ (Shu 1977). The protostellar radius changes as the mass grows. For protostars growing at a constant rate $\dot{M} = 10^{-5}$ and $10^{-4}\, M_\odot$ yr$^{-1}$, the maximum radius of 8.5 and 16 $R_\odot$ is attained at the protostellar mass $M = 3.9$ and 5.9 $M_\odot$, respectively, slightly after the shell deuterium burning sets in (Palla & Stahler 1992). These maximum radii are much smaller than the protostellar radius of IRc2 estimated by Morino et al. (1998) by assuming that the $K'$-band luminosity comes from the protostar.

According to Nakano, Hasegawa, & Norman (1995), the final stellar mass is determined mostly by the mass of the parental cloud core. Because massive stars form in massive cloud cores that generally have large velocity dispersions (e.g., Tatematsu et al. 1993), protostars must grow much faster than the ordinary rate $\dot{M} \sim 10^{-5}\, M_\odot$ yr$^{-1}$ to become massive stars. With the estimated mass $M \approx 25\, M_\odot$ of the protostar in IRc2 (Vogel et al. 1985) and the kinematical age $1.5 \times 10^3$ yr of the molecular outflow around it (Snell et al. 1984), the accretion rate of the protostar might be as high as $10^{-2}\, M_\odot$ yr$^{-1}$. From the CS ($J$ = 1–0) line width (FWHM) 3.7 km s$^{-1}$ of the Orion KL cloud core (Tatematsu et al. 1993), Nakano et al. (1995) obtained the standard accretion rate $0.975 C_{\rm eff}^3/G \approx 1 \times 10^{-3}\, M_\odot$ yr$^{-1}$. The standard accretion rate is for a similarity solution of dynamical collapse of a spherical cloud which is initially in hydrostatic equilibrium and is constant of time (Shu 1977). However, computer simulations on dynamical contraction of clouds show that the accretion rate is much higher than the standard rate in the early stages of contraction and decreases gradually with time (Foster & Chevalier 1993; Tomisaka 1996). In Tomisaka's (1996) model, for example, 1/20 of the cloud mass falls to the center by the stage where the accretion rate decreases to 10 times the standard value. Nakano et al. (1995) investigated how the outflow from the protostar terminates the accretion by blowing off *a part of* the parental cloud core and found that the star formation efficiency in each cloud core is several percent. This means that the dynamical contraction of a cloud core is terminated in an early stage when only a small fraction of the core mass has contracted, and therefore when the protostar is growing its growth rate is significantly larger than the standard rate. Therefore, the line width of the Orion KL cloud core and the kinematical age of its bipolar outflow consistently suggest the accretion rate $\sim 10^{-2}\, M_\odot$ yr$^{-1}$, which we adopt in this paper.

With such a high mass accretion rate, a protostar might have a very large radius at some stages because the growth time of the protostar, $M/\dot{M}$, must be much smaller than the timescale of energy loss (Kelvin-Helmholtz time), at least when the mass is not very large. Thus, the evolution of protostars accreting mass at such high rates is a challenging problem in star formation. The purpose of this paper is to investigate the evolution of protostars growing at very high rates with a simplified stellar model and to see if the protostars can be as huge at some stages as suggested by Morino et al. (1998). We also discuss the plausibility of the alternative interpretation of Morino et al. (1998) that most of the observed $K'$-band luminosity of IRc2 comes from the accretion disk.

We give the formalism to describe the protostellar evolution in § 2, and show the numerical results in § 3. We investigate the radiation from the accretion disk in § 4. A summary of the paper is given in § 5.

## 2. FORMALISM

To find out the outline of protostellar evolution with a very high mass accretion rate, we adopt a simplified model developed by Nakano et al. (1995) assuming that the homology of the stellar structure does not change much. This approximation is pretty good unless the protostar has some special structure, for example, a shell in which nuclear burning is occurring.

### 2.1. *Energy and Luminosity of the Protostar*

By taking the zero point of the internal energy of the gas at the molecular state of hydrogen and the atomic state of helium, namely, at the state in the parental cloud core, the total energy of the protostar of mass $M$ and radius $R$ can be given by

$$E = -\frac{\beta}{2} a_g \frac{GM^2}{R} + \Psi_I \frac{M}{m_{\rm H}} - f_{\rm D} \Psi_{\rm D} \frac{M}{m_{\rm H}} . \qquad (1)$$

The first term on the right-hand side is the sum of the gravitational, thermal, and radiant energies, where $a_g$ is the coefficient for the gravitational energy; we have $a_g = 3/(5 - N)$ for a polytropic sphere of index $N < 5$ (Chandrasekhar 1939). The coefficient $\beta$ is the mean ratio of the gas pressure to the total pressure in the protostar given by $\beta = 2U_{\rm gas}/(2U_{\rm gas} + U_{\rm rad})$, where $U_{\rm gas}$ and $U_{\rm rad}$ are the total thermal energy of the gas and the total radiation energy, respectively, of the protostar. The second term on the right-hand side is the energy consumed in dissociating and ionizing the gas, where $m_{\rm H}$ is the mass of a hydrogen atom and $\Psi_I$ is the dissociation plus ionization energy per amu and takes a value of about 17 eV for the Population I chemical composition. The last term is the energy released by deuterium burning, where $f_D$ is the fraction of deuterium already burned and $\Psi_D$ is the energy released by deuterium burning per amu. In this paper we adopt the interstellar abundance of deuterium, D/H $= 2.5 \times 10^{-5}$ (Bruston et al. 1981; Geiss & Reeves 1981; Vidal-Madjar & Gry 1984), which gives $\Psi_D \approx 100$ eV.

We have neglected in equation (1) the rotational energy of the protostar. Observations show that many low-mass young stellar objects rotate much slower than their breakup velocities, and the general interpretation for this is that the rotational velocity of the star is kept at a relatively low value through magnetic coupling with the disk around it and loss of angular momentum in a wind (Attridge & Herbst 1992; Bouvier et al. 1993; Edwards et al. 1993; Shu et al. 1994). Although we have few observations on the rotation of massive protostars, we neglect this energy assuming a similar situation as in low-mass young stellar objects. To keep stellar rotation slow, the accretion disk must be separated from the star. For the accretion rate $\dot{M} = 1 \times 10^{-2}\ M_\odot\ \mathrm{yr}^{-1}$ for a star of $M = 3\ M_\odot$ and $R = 20\ R_\odot$, for example, the condition for this (Elsner & Lamb 1977; see also Shu et al. 1994) requires the stellar magnetic field stronger than about 1 kG. This field would not be too strong to be realized. The effect of the rotation will be discussed at the end of § 3.

The energy conservation requires that the total luminosity of the protostar, $L$, satisfy

$$\frac{dE}{dt} = -L - \frac{GM\dot{M}}{R}(1 - f_k) , \quad (2)$$

where $t$ is the time, $\dot{M}$ is the mass accretion rate onto the protostar, and the last term is the energy brought into the protostar per unit time by the accreted matter, most of which must fall through the accretion disk; $f_k$ is the ratio of the kinetic energy per unit mass to the depth of the gravitational potential at the protostellar surface. For instance, the free-fall contraction from infinity gives $f_k = 1$. In equation (2) we have neglected the small internal energy contained in the matter just before it falls to the stellar surface.

The luminosity of a mass-accreting star can be divided into two parts, the luminosity transported from the stellar interior, $L_{\rm int}$, and the luminosity released by the accreted matter, $L_{\rm acc}$:

$$L = L_{\rm int} + L_{\rm acc} . \quad (3)$$

Unless the star has some special structure, for example, with an extended envelope because of the shell nuclear burning and/or with a deep convection zone in the envelope, the intrinsic luminosity $L_{\rm int}$ is equal to the luminosity transported by radiation, $L_{\rm rad}$, and is determined mostly by the stellar mass $M$ almost independent of the stellar radius $R$ (Nakano et al. 1995 and references therein). In most situations we can approximate $L_{\rm int}$ by the luminosity of the zero-age main-sequence star of the same mass, $L_{\rm ms}$, given, for example, by Figure 6 of Nakano et al. (1995). The accretion luminosity can be given by

$$L_{\rm acc} = f_{\rm acc}\, f_k \frac{GM\dot{M}}{R} . \quad (4)$$

Because almost all kinetic energy of the accreted matter is radiated away, $f_{\rm acc} = 1$ has generally been assumed. We take into account the small deviation from this ($f_{\rm acc} < 1$) in the following way because the deviation makes the protostellar radius larger; at least we want to obtain an upper limit to the protostellar radius.

Behind the accretion shock front the gas and the radiation settle gradually into thermal equilibrium. The physical conditions at the point where this equilibrium is attained, which is called the postrelaxation point, are determined by the following relations, which are obtained by extending the relations adopted by Stahler et al. (1980). The gas pressure at the postrelaxation point, $P_p$, is nearly equal to the ram pressure of the accreting matter, or

$$P_p = \frac{\dot{M}}{4\pi}\left(\frac{2f_k GM}{R^5}\right)^{1/2} , \quad (5)$$

unless $f_k \ll 1$. Because some fraction of the dissipated kinetic energy is consumed in dissociating, ionizing, and heating the gas, the temperature $T_p$ at the postrelaxation point must satisfy

$$\dot{M}\left\{f_k \frac{GM}{R} - \frac{X}{m_{\rm H}}(0.5\Psi_{\rm H_2} + x_p \Psi_{\rm H}) - \frac{3kT_p}{2m_{\rm H}}\left[X(1 + x_p) + \frac{Y}{4}\right]\right\} = \frac{16}{3}\pi R^2 \sigma T_p^4 , \quad (6)$$

where $x_p$ is the ionization fraction of hydrogen at the postrelaxation point, $\Psi_{\rm H_2} = 4.48$ eV is the dissociation potential of an $H_2$ molecule, $\Psi_{\rm H} = 13.60$ eV is the ionization potential of a hydrogen atom, $k$ is the Boltzmann constant, $\sigma$ is the Stefan-Boltzmann constant, and $X$ and $Y$ are the mass fractions of hydrogen and helium, respectively; we adopt the solar abundance $X = 0.71$ and $Y = 0.27$ (Anders & Grevesse 1989). At this point hydrogen molecules are nearly completely dissociated, the ionization fraction of He is very low, and the radiation pressure is generally quite minor. From equations (5) and (6) together with Saha's ionization formula and the equation of state, we determine $T_p$, $P_p$, $x_p$, and the density $\rho_p$ at the postrelaxation point. With $T_p$ and $x_p$ determined in this way, we have

$$f_{\rm acc} = 1 - \frac{R}{f_k GM m_{\rm H}}\left\{X(0.5\Psi_{\rm H_2} + x_p \Psi_{\rm H}) + \frac{3}{2}kT_p\left[X(1 + x_p) + \frac{Y}{4}\right]\right\} . \quad (7)$$

Except in very early stages the deviation of $f_{\rm acc}$ from 1 is very small because the thermal energy at the center, $kT_c \approx GMm_{\rm H}/R$, is much larger than both the thermal energy $kT_p$ and the energy consumed in dissociation and ionization, $0.5\Psi_{\rm H_2} + x_p \Psi_{\rm H}$, at the postrelaxation point.

The specific entropy at the postrelaxation point is determined from $T_p$, $\rho_p$ (or $P_p$), and $x_p$, and is compared with the specific entropy at the protostellar center. From this comparison we can find out whether overall convection occurs in the protostar or not (see § 3 for the details).

For given $M$, $R$, and $\dot{M}$, we generally determine the total luminosity $L$ in the way described above with $L_{\rm int} \approx L_{\rm ms}$. However, when the effective temperature $T_{\rm eff}$ determined from $R$ and this $L$ is lower than the Hayashi limit, we redetermine the total luminosity according to $L = 4\pi R^2 \sigma T_{\rm H}^4$, where $T_{\rm H}$ is the limiting effective temperature below which no stellar equilibrium configurations exist (Hayashi 1961). We take $T_{\rm H} = 3000$ K in this paper. Because we describe the stellar structure by the total energy $E$, $R$ is fixed for given values of $M$ and $E$, and for a given stellar homology. Therefore, $L$ must be readjusted. In reality, however, because of high $\dot{M}$ such readjustment of $L$ is necessary only for the cases of $f_k \ll 1$ at relatively small stellar mass; only in such a situation $L$ is low, and thus $T_{\rm eff}$ can be low.

### 2.2. *The Evolution Equation*

We assume that the protostellar mass increases with time at a constant rate $\dot{M}$, though the simulations of dynamical contraction (Foster & Chevalier 1993; Tomisaka 1996) show that the accretion rate is high in the early stages and decreases with time as mentioned in § 1. The effect of the changing accretion rate on the evolution will be discussed at the end of § 3. With $M = \dot{M}t$ together with equation (1), equation (2) can be rewritten as

$$\frac{d \log R}{d \log M} = 2 - \frac{2}{a_g \beta}(1 - f_k) + \frac{d \log \beta}{d \log M} - \frac{2R}{a_g \beta G M \dot{M}}(L + L_I - L_{\rm D}) , \quad (8)$$

where

$$L_I = \frac{d}{dt}\left(\Psi_I \frac{M}{m_{\rm H}}\right) = \Psi_I \frac{\dot{M}}{m_{\rm H}} \approx 2.5 \times 10^3 \, L_\odot \frac{\dot{M}}{10^{-2} \, M_\odot \, {\rm yr}^{-1}} , \quad (9)$$

$$L_{\rm D} = \frac{d}{dt}\left(f_{\rm D} \Psi_{\rm D} \frac{M}{m_{\rm H}}\right) . \quad (10)$$

When $T_{\rm eff}$ is higher than the Hayashi limit $T_{\rm H}$, that holds for all the cases shown in this paper, substitution of equations (3) and (4) into equation (8) gives

$$\frac{d \log R}{d \log M} = 2 - \frac{2}{a_g \beta}[1 - f_k(1 - f_{\rm acc})] + \frac{d \log \beta}{d \log M} - \frac{2R}{a_g \beta G M \dot{M}}(L_{\rm int} + L_I - L_{\rm D}) , \quad (11)$$

with $L_{\rm int} \approx L_{\rm ms}$. The uncertainties in $L_{\rm int}$ have little effect on the evolution because we find $L_{\rm int} \ll GM\dot{M}/R \approx L_{\rm acc}/f_k$ at almost all stages of the evolution shown in this paper because of high $\dot{M}$.

### 2.3. *Deuterium Burning*

We assume that deuterium burning occurs only when the central temperature of the protostar, $T_c$, is higher than $1 \times 10^6$ K, which is about the ignition temperature of deuterium. We determine the amount of deuterium burned in each time step in the following way. If this value, or $L_{\rm D}$, were too large, $R$ would increase so much according to equation (8) or (11) that $T_c$ might fall below the ignition temperature. If $L_{\rm D}$ were too small, conversely, $T_c$ might rise and a much larger amount of energy would be released. Therefore, except in the late stages of deuterium burning, $L_{\rm D}$ should be adjusted to keep $T_c$ nearly constant.

The central temperature is given by

$$T_c = \beta_c \, a_T \frac{\mu m_{\rm H}}{k} \frac{GM}{R} , \quad (12)$$

where $\mu$ is the mean molecular weight of the gas in the protostar and is 0.613 for the chemical composition adopted in this paper, and $a_T$ is a quantity of order unity; for example, we have $a_T = 0.5385$ for a polytrope of index $N = 1.5$ (Chandrasekhar 1939). The ratio of the gas pressure to the total pressure at the center, $\beta_c$, is not equal to the mean value $\beta$ except for a polytrope of $N = 3$, though $\beta_c \approx \beta \approx 1$ for $M \lesssim 10 \, M_\odot$. To keep $T_c$ constant, or $dT_c/dM = 0$, we have from equations (8) and (12)

$$L_{\rm D} = L + L_I + \frac{GM\dot{M}}{R}\left\{1 - f_k - \frac{a_g \beta}{2}\left[1 + \frac{d \log (\beta/\beta_c)}{d \log M}\right]\right\} . \quad (13)$$

When $T_{\rm eff}$ is higher than the Hayashi limit $T_{\rm H}$ as is the case with all the models shown in this paper, we have, by substituting equations (3) and (4) into equation (13),

$$L_{\rm D} = L_{\rm int} + L_I + \frac{GM\dot{M}}{R} \times \left[1 - f_k(1 - f_{\rm acc}) - \frac{a_g \beta}{2}\left(1 + \frac{d \log \beta/\beta_c}{d \log M}\right)\right] , \quad (14)$$

with $L_{\rm int} \approx L_{\rm ms}$. Again, the uncertainties in $L_{\rm int}$ hardly affect $L_{\rm D}$ because $L_{\rm int} \ll GM\dot{M}/R \approx L_{\rm acc}/f_k$ for high $\dot{M}$. From $L_{\rm D}$ we calculate the amount of deuterium left unburned in the protostar.

After the amount of the unburned deuterium becomes less than the amount of deuterium accreted from outside in each time step, we assume steady burning of the accreted deuterium, namely,

$$L_{\rm D} = \Psi_{\rm D} \frac{\dot{M}}{m_{\rm H}} \approx 1.5 \times 10^4 \, L_\odot \frac{\dot{M}}{10^{-2} \, M_\odot \, {\rm yr}^{-1}} , \quad (15)$$

unless otherwise stated. The last expression of this equation is for the interstellar abundance of deuterium, D/H $= 2.5 \times 10^{-5}$ (Bruston et al. 1981; Geiss & Reeves 1981; Vidal-Madjar & Gry 1984). In such a situation, even with this $L_{\rm D}$ the central temperature cannot be kept at $1 \times 10^6$ K and increases gradually with time.

### 2.4. *The Initial Condition*

We determine the initial state for evolution calculation in the following way: Because we are interested at high $M$, we can take the initial protostellar mass not much smaller than 1 $M_\odot$. Because $L_{\rm I} \gg L_{\rm int}$ for high $\dot{M}$ at small mass ($M \lesssim 1 \, M_\odot$) as seen from equation (9), the stellar structure in such a stage is determined mainly by dissociation and ionization of the gas. Because the total energy is negative, we have from equation (1)

$$-\frac{1}{2} a_g \frac{GM^2}{R} + \Psi_{\rm I} \frac{M}{m_{\rm H}} < 0 \quad (16)$$

at small $M$ where $\beta \approx 1$ before deuterium burning sets in, or $f_{\rm D} = 0$. From equations (12) and (16), we have

$$T_c > \frac{a_T}{a_g} \frac{2\mu}{k} \Psi_{\rm I} . \quad (17)$$

This inequality gives a lower limit to $T_c$, for example, $1.4 \times 10^5$ and $1.3 \times 10^5$ K for $N = 1.5$ and 3, respectively, which is not very sensitive to the polytropic index. Because the energy of the matter lost in the accretion disk must amount to a significant fraction of the gravitational energy at the stellar surface, $T_c$ must be considerably higher than the right-hand side of equation (17). Therefore, as a limiting case we take the initial central temperature $T_{ci} = 2 \times 10^5$ K at $M = 0.5\ M_\odot$. We also investigate the case of $T_{ci} = 4 \times 10^5$ K at the same stellar mass. Higher initial $T_c$ gives smaller stellar radius at all stages.

In this paper we investigate the evolution of polytropic protostars of $N = 1.5$ unless otherwise stated and check whether $N \approx 1.5$ is appropriate by comparing the specific entropy at the postrelaxation point with that at the center and also by comparing $L_D$ with $L_{int}$ (see § 3). We take $f_k = \frac{1}{2}$ in numerical computations. Unless $f_k \ll 1$, the radius $R$ is insensitive to $f_k$ as seen from equations (11) and (14) because $f_{acc} \approx 1$, though $L$ and $T_{eff}$ may depend sensitively on $f_k$ especially when $L_{acc} \gg L_{int}$. Even for $f_k \ll 1$, we have confirmed by numerical computations that the results are not much different from those for finite $f_k$ as long as $R$ is concerned, though $L$ and $T_{eff}$ may be significantly smaller. This can also be inferred from equations (11) and (14) because the correction to $L_{int}$ due to the restriction on $T_{eff}$ ($\geq T_H$) is generally small compared with $GM\dot{M}/R$ at high $\dot{M}$.

## 3. RESULTS

Figure 1 shows the change of the protostellar radius $R$ with the growth of the protostellar mass $M$ for several cases of $\dot{M}$ with the polytropic index $N = 1.5$ and $f_k = 0.5$. After deuterium burning begins, $R$ increases almost in proportion to $M$ because the central temperature $T_c$ is kept constant at $1 \times 10^6$ K and because $\beta \approx 1$ at least at $M \lesssim 10\ M_\odot$. When most of the accreted deuterium has burned, $T_c$ begins to increase and the path begins to deviate from the straight line $R \propto M$. Afterward, $L_D$ is given by equation (15), and $R$ increases only slowly, takes a maximum value, and thereafter decreases rather rapidly. For the case of $\dot{M} = 1 \times 10^{-2}\ M_\odot\ \mathrm{yr}^{-1}$ (Fig. 1, *solid lines*), the star takes a maximum radius of 32 and 24 $R_\odot$ at $M \approx 7.0$ and 6.1 $M_\odot$ for the initial condition $T_{ci} = 2 \times 10^5$ and $4 \times 10^5$ K, respectively. For the higher accretion rates $\dot{M} = 10^{-1.5}$ and $10^{-1}\ M_\odot\ \mathrm{yr}^{-1}$, the maximum radii 36 and 39 $R_\odot$, which are attained at $M \approx 8.3$ and 9.2 $M_\odot$, respectively, are only slightly larger than that for the case of $\dot{M} = 1 \times 10^{-2}\ M_\odot\ \mathrm{yr}^{-1}$.

Figure 2 (*top*) compares the specific entropy (per amu) at the postrelaxation point, $s_p$, with that at the center, $s_c$. The entropies were calculated according to the formulae obtained by Nakano, Ohyama, & Hayashi (1968), which include the contribution of radiation field. Although the specific entropy decreases as one goes inside from the postrelaxation point, this decrease is small for very high accretion rates like $\dot{M} \approx 1 \times 10^{-2}\ M_\odot\ \mathrm{yr}^{-1}$, as can be found from Stahler's (1988) result. Therefore, $s_p$ gives a good approximation for the specific entropy in the surface region of the protostar (aside from the effect of the superadiabatic

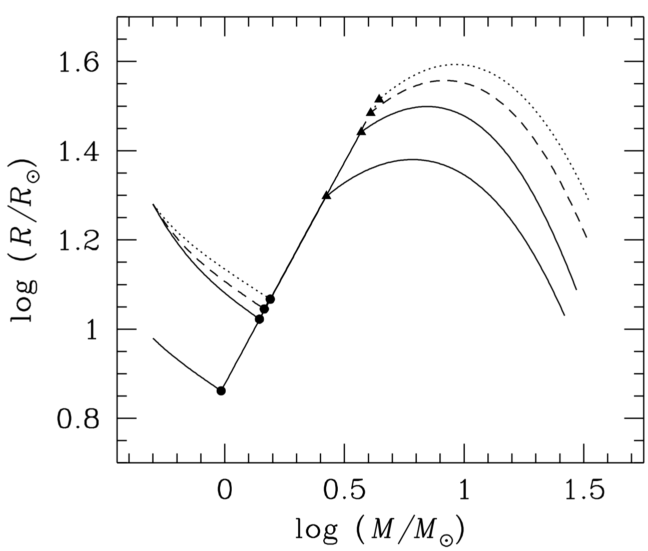


FIG. 1.—Variation of the protostellar radius $R$ with the growth of the protostellar mass $M$. The protostars are assumed to be polytropes of index $N = 1.5$ with $f_k = 0.5$. The solid lines are for the mass accretion rate $\dot{M} = 1 \times 10^{-2}\ M_\odot\ \mathrm{yr}^{-1}$; the top solid line is for the initial central temperature $T_{ci} = 2 \times 10^5$ K at $M = 0.5\ M_\odot$, and the bottom one is for $T_{ci} = 4 \times 10^5$ K at the same mass. The dashed and dotted lines are for $\dot{M} = 10^{-1.5}$ and $10^{-1}\ M_\odot\ \mathrm{yr}^{-1}$, respectively, with the initial condition $T_{ci} = 2 \times 10^5$ K at $M = 0.5\ M_\odot$. At the filled circle on each curve, deuterium begins to burn in the central region, and at the filled triangle almost all accreted deuterium has burned; afterward, deuterium is assumed to burn steadily at the rate given by eq. (15).

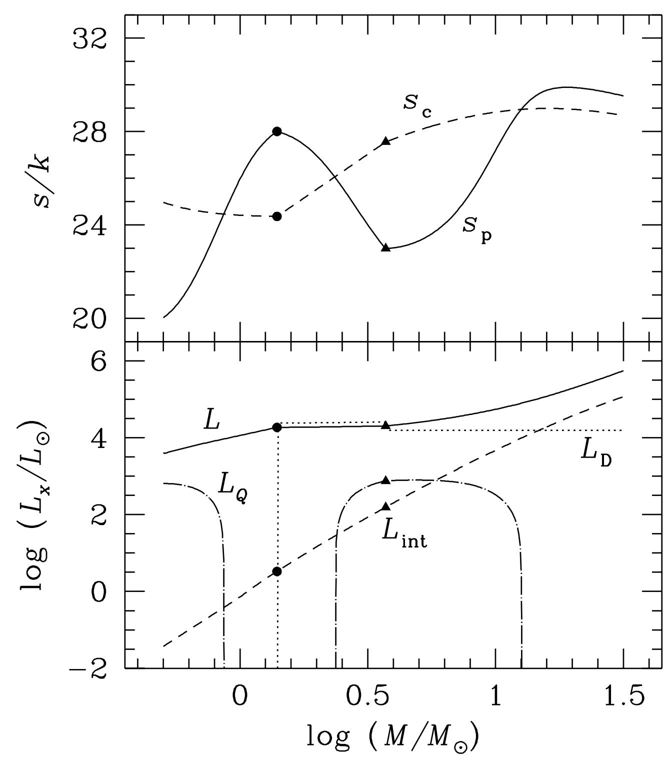


FIG. 2.—Variation of some quantities with the growth of the protostellar mass $M$ for a polytropic protostar of $N = 1.5$ with $\dot{M} = 1 \times 10^{-2}\ M_\odot\ \mathrm{yr}^{-1}$ and $f_k = 0.5$ for the initial condition $T_{ci} = 2 \times 10^5$ K at $M = 0.5\ M_\odot$. *Top*: Specific entropies (amu$^{-1}$) at the postrelaxation point $s_p$ (*solid line*) and at the center $s_c$ (*dashed line*) divided by the Boltzmann constant $k$. *Bottom*: Various luminosities; the solid line represents the total luminosity $L$; the dashed line is the luminosity transported from the stellar interior, $L_{int}$, which is equal to the luminosity transported by radiation, $L_{rad}$, in this case; the dotted line is the energy released by deuterium burning per unit time, $L_D$; and the dot-dashed line is $L_Q$ given by eq. (18). At the filled circle on each curve, deuterium begins to burn in the central region, and at the filled triangle almost all accreted deuterium has burned; afterward, deuterium is assumed to burn steadily at the rate given by eq. (15).

zone and the effect of heat transport from inside; see below), and then the difference $s_p - s_c$ has information on whether convection occurs in most parts of the star. Decrease of entropy just inside the postrelaxation point mentioned above makes the prevention of convection more difficult.

A necessary condition for inhibition of convection in the star is that the specific entropy in the surface region is larger than that at the center. In reality, however, there may exist a superadiabatic zone near the stellar surface because of the low efficiency of convective energy transport caused by low temperature and low density, and the specific entropy just inside this zone might be somewhat larger than $s_p$, and thus larger than $s_c$, and as a result the convection might be inhibited except in the thin surface layer. However, the gap of the entropy, $(s_c - s_p)/k =$ several, seen in some mass ranges in Figure 2 must be too large to be conquered by the superadiabatic zone. The specific entropy in the surface region may also be enhanced above $s_c$ by radiative heat transport from the stellar interior. A necessary condition for preventing overall convection in the star by this mechanism may be roughly given by

$$L_{\rm rad} > \frac{\dot{M}}{m_{\rm H}} (s_{\rm c} - s_p) T_p \equiv L_Q \; , \qquad (18)$$

though the actual condition must be much more severe because only a small fraction of $L_{\rm rad}$ will be deposited in the surface region and the rest must be reemitted outward. As seen from Figure 2 (*bottom*), $L_{\rm int}$ $(=L_{\rm rad}$ in this case) is far below $L_Q$, and convection inevitably occurs at $M \lesssim 0.86\, M_\odot$.

At $M \approx 1.4$ $M_\odot$ deuterium burning sets in. Because $L_{\rm D} \gg L_{\rm int}(=L_{\rm rad})$, the energy released by deuterium burning in the central region cannot be redistributed in the star without convection. This situation lasts up to $M \approx 15$ $M_\odot$, where $L_{\rm int}$ catches up $L_{\rm D}$. Thus, in almost all stages of $M \lesssim 15$ $M_\odot$ the protostar is fully convective, and the polytrope of $N = 1.5$ is a good approximation to the structure.

If the overall convection disappears at, for example, $M \approx 15$ $M_\odot$, deuterium burning stops because the accreted deuterium is not transported to the central region. Ceasing the deuterium burning has the effect of decreasing stellar radius more rapidly. On the other hand, because $s_p > s_c$ in this stage as seen in Figure 2, the effective polytropic index may become larger than 1.5. This has an effect of decelerating the decrease of the stellar radius. However, expansion of the protostar is not expected because large $L_{\rm int}$ already makes the protostar shrink rapidly. In reality, expansion of the protostar after the cessation of core deuterium burning does not occur in the cases of moderate accretion rates $\dot{M} = 10^{-5}$–$10^{-4}$ $M_\odot$ yr$^{-1}$ (Palla & Stahler 1992).

As the protostellar mass grows, the temperature at the bottom of the deuterium-containing envelope rises, and at last shell deuterium burning sets in when it rises to the ignition temperature. Shell nuclear burning generally has an effect of expanding the stellar envelope; by shell hydrogen burning, for example, the star becomes a red giant. However, in the case of deuterium burning, which can release only very small energies, expansion of the envelope is quite modest. For the cases of $\dot{M} = 10^{-5}$–$10^{-4}$ $M_\odot$ yr$^{-1}$, the shell deuterium burning enhances the stellar radius only by a factor of 2 (Palla & Stahler 1992). The energy released by deuterium burning, $\Psi_{\rm D} \approx 100$ eV amu$^{-1}$, is only half the thermal energy of the gas, $3kT/2\mu$, at the ignition temperature $1 \times 10^6$ K; by deuterium burning the thermal energy of the envelope would increase at most by a factor of 1.5 even if almost all deuterium were burned instantaneously. Thus, it is understandable that the stellar radius increases only by a factor of 2 by shell deuterium burning in the cases of $\dot{M} = 10^{-5}$–$10^{-4}$ $M_\odot$ yr$^{-1}$. Similarly, in the cases of $\dot{M} \sim 1 \times 10^{-2}$ $M_\odot$ yr$^{-1}$, we cannot expect that shell deuterium burning can expand the protostar far above 100 $R_\odot$.

For the case of $T_{\rm ci} = 4 \times 10^5$ K (Fig. 1, *bottom solid line*), we have reached the same conclusion as above though $s_p - s_c$ is slightly larger. The core deuterium burning sets in at a lower mass $M = 0.97\, M_\odot$ with a larger gap between $L_{\rm D}$ and $L_{\rm int}$ compared with the case of $T_{\rm ci} = 2 \times 10^5$ K, and $L_{\rm D} > L_{\rm int}$ lasts up to $M \approx 15$ $M_\odot$. We have also investigated the evolution of a polytropic protostar of $N = 3$ accreting mass at a rate $\dot{M} = 10^{-2}$ $M_\odot$ yr$^{-1}$ with the initial condition $T_{\rm ci} = 2 \times 10^5$ K at $M = 0.5$ $M_\odot$ for $f_k = 0.5$, and found that $(s_c - s_p)/k$ takes a value between 4 and 10 at $M \lesssim 38$ $M_\odot$. Such a large difference is because larger $N$ makes the stellar radius somewhat larger, and thus the kinetic energy of the matter just landing onto the stellar surface is smaller, and as a result $s_p$ is smaller. Such a large gap in the entropy means that prevention of convection is quite difficult in all stages and that the protostar must rearrange its structure to a polytrope of $N \approx 1.5$. This also supports our assumption $N = 1.5$ adopted above.

The situation is quite similar for the cases of higher mass accretion rates shown in Figure 1. Deuterium burning sets in at $M = 1.5$ and 1.6 $M_\odot$, and $L_{\rm D} > L_{\rm int}$ lasts up to $M \approx 22$ and 36 $M_\odot$ for $\dot{M} = 10^{-1.5}$ and $10^{-1}$ $M_\odot$ yr$^{-1}$, respectively. Thus the protostar is fully convective in almost all stages of $L_{\rm D} > L_{\rm int}$, and the polytrope of $N \approx 1.5$ is again a good approximation to the structure.

The initial central temperature $T_{\rm ci} = 2 \times 10^5$ K at $M = 0.5$ $M_\odot$ adopted above is almost a lower limit. For higher $T_{\rm ci}$ the protostar has a smaller radius at all stages. Therefore, the results obtained above mean that the protostar cannot have a radius larger than about 100 $R_\odot$ even if the accretion rate is as high as $10^{-1}$ $M_\odot$ yr$^{-1}$ unless it has an extraordinary structure, as will be discussed below.

We have assumed that the protostar grows at a constant mass accretion rate. However, computer simulations on dynamical contraction of clouds show that the accretion rate is high in the early stages and decreases gradually with time (Foster & Chevalier 1993; Tomisaka 1996). Even if the protostar in IRc2 grew at a rate $\dot{M} \approx 10^{-1}$ $M_\odot$ yr$^{-1}$ in its earliest stage and slowed down its growth later on, its radius at each stage cannot be larger than that for the case of constant accretion rate with $10^{-1}$ $M_\odot$ yr$^{-1}$ shown by the dotted line in Figure 1. Thus, it is not necessary to change our conclusion obtained above that the protostar in IRc2 cannot have radius larger than about 100 $R_\odot$ unless it has an extraordinary structure.

The only remaining possibility to make a huge protostar would reside in the rapid rotation of the protostar. Although the total rotational energy of the protostar must be significantly smaller than the gravitational energy, the centrifugal force must have great effect on the structure of the envelope if the stellar surface rotates almost at its breakup velocity near the equator. The envelope of such a star might be highly deformed, though most of the mass must distribute almost spherically (e.g., Bodenheimer 1971). In such a situation the envelope cannot be approximated by a simple polytrope and could be highly extended. Such a possibility could not be excluded if magnetic coupling of the protostar with the surrounding disk and angular momentum loss in a wind were not efficient in contrast to the cases of low-mass protostars.

## 4. RADIATION FROM THE ACCRETION DISK

We discuss the alternative interpretation proposed by Morino et al. (1998) that a significant fraction of the $K'$-band luminosity of IRc2 comes from the accretion disk around the protostar. Assuming that heating of the disk by the radiation from the protostar is negligible and that the disk is opaque to thermal radiation, we find that the local effective temperature of the steady accretion disk is given by

$$T_{\rm eff}(r) = \left(\frac{3GM\dot{M}}{8\pi\sigma r^3}\right)^{1/4} \quad (19)$$

at a distance $r$ far from the protostellar surface (Lynden-Bell & Pringle 1974). Conversely, the observed $K'$-band luminosity with the effective temperature $T_{\rm eff}(\approx 4500$ K) must come mostly from the annular region centered at

$$r(T_{\rm eff}) \approx 234\ R_\odot \left(\frac{M}{10\ M_\odot}\frac{\dot{M}}{0.01\ M_\odot\ {\rm yr}^{-1}}\right)^{1/3} \times \left(\frac{4500\ {\rm K}}{T_{\rm eff}}\right)^{4/3} . \quad (20)$$

With the temperature distribution given by equation (19), we calculate the $K'$-band magnitude of the disk to have

$$M_{K'}^{(\rm d)} = -9.27 - \frac{5}{3}\log\left(\frac{M}{10\ M_\odot}\frac{\dot{M}}{0.01\ M_\odot\ {\rm yr}^{-1}}\right), \quad (21)$$

assuming that the temperature at the inner edge of the disk is much higher than 5000 K. For $M_{K'}^{(\rm d)} < -8.6$ estimated by Morino et al. (1998), we have

$$\left(\frac{M}{10\ M_\odot}\right)\left(\frac{\dot{M}}{0.01\ M_\odot\ {\rm yr}^{-1}}\right) > 0.40 . \quad (22)$$

Thus, we find no difficulty in one of the interpretations proposed by Morino et al. (1998) that the nebula around IRc2 is illuminated at the $K'$ band by the accretion disk around a protostar embedded in IRc2. Although a polytropic protostar of $N \approx 4$ can have a radius $\gtrsim 300\ R_\odot$ at some stages (Morino et al. 1998), a more rigorous analysis has led us to the conclusion described in § 3.

The profiles of the absorption lines from such a disk must be very complicated (e.g., Calvet, Hartmann, & Kenyon 1991). The local velocity dispersion must be much smaller than the rotation velocity of the disk because the disk is generally geometrically thin. The profile of the absorption line from a narrow annulus in the disk is as follows: If the line is optically thin, it is deepest near the outermost parts of the profile with velocity roughly $\pm(GM/r)^{1/2}\sin i$, where $r$ is the radius of the annulus and $i$ is the inclination angle of the disk to the observer. If the line is optically thick, the profile is almost rectangular with the FWHM $\sim 2(GM/r)^{1/2}\sin i$. The profile of the line from the total disk can be obtained by summing up the contribution of each annulus, whose effective temperature is given by equation (19). The line width of the total disk would not be much different from the line width of the annulus whose effective temperature is equal to the mean effective temperature of the disk or whose radius is given by equation (20),

$$\Delta V \approx 2\left[\frac{GM}{r(T_{\rm eff})}\right]^{1/2}\sin i \approx 181\sin i\left(\frac{M}{10\ M_\odot}\right)^{1/3}\left(\frac{\dot{M}}{0.01\ M_\odot\ {\rm yr}^{-1}}\right)^{-1/6} \times \left(\frac{T_{\rm eff}}{4500\ {\rm K}}\right)^{2/3} {\rm km\ s}^{-1} . \quad (23)$$

In the case of IRc2, the $K'$-band light observed by Morino et al. (1998) must be the one scattered by dust around IRc2. The light must be scattered mostly by the dust in the cavity formed by the outflows from the protostar. Therefore, the inclination angle $i$ of the disk is to the dust, not to the Sun. Because the total opening angle of the cavity is about 60°, we have $i \approx 15°$ for the mean inclination angle of the disk seen by the dust. Thus, we have the width $\Delta V \approx 47$ km s$^{-1}$ for $M = 10\ M_\odot$, $\dot{M} = 1 \times 10^{-2}\ M_\odot$ yr$^{-1}$, and $T_{\rm eff} =$ 4500 K.

Because the $K'$-band luminosity comes mostly from a part of the disk far from the stellar surface as seen from equation (20) and the results in § 3, the total accretion luminosity comes mainly from the stellar surface and its neighborhood. Assuming steady accretion in the disk or the accretion rate at the protostellar surface be equal to that in the part of the disk emitting most of the disk $K'$-band luminosity, we have from equations (4) and (21) the total accretion luminosity ($f_{\rm k} \to 1$)

$$\log\frac{L_{\rm acc}}{L_\odot} = 5.09 + \log\left(\frac{10\ R_\odot}{R}\right) - \frac{3}{5}(M_{K'}^{(\rm d)} + 8.6) . \quad (24)$$

The intrinsic luminosity of stars with mass between 10 and 25 $M_\odot$ can be represented by a power law $L_{\rm int}/L_\odot \approx 4.8 \times 10^3 (M/10\ M_\odot)^{2.9}$, which approximates the luminosity of zero-age main-sequence stars in this mass range with errors less than 5% (e.g., Nakano et al. 1995). From this relation and equation (24), we find that $L_{\rm acc} > L_{\rm int}$ is fulfilled at $R < 80\ R_\odot(M/15\ M_\odot)^{-2.9}$ for $M_{K'}^{(\rm d)} = -8.6$. This condition for $R$ is satisfied at all stages shown in Figure 1 even if we consider the possible increase of $R$ by a factor of 2 by shell deuterium burning. For brighter $K'$ magnitude, $L_{\rm acc} > L_{\rm int}$ is more easily satisfied. This means that the luminosity of IRc2 is dominated by accretion and that the protostellar mass of IRc2 is significantly smaller than that estimated by assuming its luminosity as intrinsic unless the protostellar envelope is extended to several $10^2\ R_\odot$ by rapid rotation. For the model shown in Figure 2, for example, we obtain $M \approx 9.7\ M_\odot$ from the total luminosity $1 \times 10^5\ L_\odot$ (stellar luminosity $L = L_{\rm acc} + L_{\rm int} \approx 5.2 \times 10^4\ L_\odot$ with $L_{\rm acc} \approx 4.8 \times 10^4\ L_\odot$ and $L_{\rm int} \approx 4 \times 10^3\ L_\odot$, and the rest from the disk), while $L_{\rm int} = 1 \times 10^5\ L_\odot$ gives $M \approx 30\ M_\odot$.

## 5. SUMMARY

By near-infrared spectroscopic observation of the Orion KL Nebula, Morino et al. (1998) found that the protostar in IRc2 must have a radius $\gtrsim 300 R_\odot$ if the illuminating source of the nebula at $K'$ band is the protostar. We have investigated the evolution of protostars accreting mass at such high rate as $\sim 10^{-2}\ M_\odot$ yr$^{-1}$ expected in the Orion KL molecular cloud core with a simplified stellar model to check whether a huge protostellar radius $\gtrsim 300\ R_\odot$ can be realized.

We have found that the protostar is fully convective at almost all stages of the stellar mass $M \lesssim 15\ M_\odot$ for the case of $\dot{M} = 1 \times 10^{-2}\ M_\odot\ \mathrm{yr}^{-1}$, and thus a polytrope of index 1.5 is a good approximation to the stellar structure. This is partly because the energy released by core deuterium burning is too large to be transported outward by radiation. The maximum radius $\lesssim 30\ R_\odot$ is attained at $M \sim 7\ M_\odot$. The shell deuterium burning, which would occur afterwards, cannot greatly blow up the protostar because the energy released by deuterium burning is small and also because the protostar is already shrinking rapidly. The only remaining possibility to make a huge protostar would reside only in the rotation of the surface layer almost at the breakup velocity. In this case magnetic coupling of the protostar with the disk around it and angular momentum loss in a wind should be inefficient, contrary to the cases of low-mass young stellar objects. Similar results have been obtained for some other values of $\dot{M}$.

We have found no difficulty in the alternative interpretation proposed by Morino et al. (1998) that the illuminating source of the nebula at the $K'$ band is the accretion disk around the protostar in IRc2 with $\dot{M} \sim 1 \times 10^{-2}\ M_\odot\ \mathrm{yr}^{-1}$. In this case we have found the width (FWHM) of the absorption lines scattered by dust in the bipolar cavity to be $\sim 50\ \mathrm{km\ s^{-1}}$. A velocity-resolved spectroscopy should provide a test for this model.

We also discussed that the accretion rate $\sim 10^{-2}\ M_\odot\ \mathrm{yr}^{-1}$ expected in the IRc2 region is compatible with the velocity dispersion (FWHM) 3.7 km $\mathrm{s^{-1}}$ of the Orion KL Nebula, which however gives the *standard* accretion rate $0.975 C_{\mathrm{eff}}^3/G \approx 1 \times 10^{-3}\ M_\odot\ \mathrm{yr}^{-1}$. This is because the accretion rate can be significantly higher than the standard rate in the early stages as shown by simulations on dynamical contraction and that the accretion can be stopped in an early stage of dynamical contraction by the protostellar outflow.

Unless the protostar has a huge radius because of the rapid rotation of the envelope, the luminosity of IRc2 is dominated by accretion. Therefore, the protostellar mass of IRc2 is significantly smaller than that estimated by assuming its luminosity as intrinsic. The total accretion luminosity of the protostar is significantly higher than the $K'$-band luminosity because the stellar radius is much smaller than the radius of the disk region emitting most of the $K'$-band luminosity.

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