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Hot molecular cores, sites of high mass star formation

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Abstract. We model the flux-density distribution of hot molecular cores as in-falling envelopes of gas and dust onto a central massive star. The envelopes are heated by both the stellar luminosity and the accretion luminosity. We find that, in order to reproduce the observed fluxes, these objects require high mass accretion rates $\dot{M} \simeq 10^{-4,-3}\,\mathrm{M_{\odot}yr^{-1}}$ infalling onto central late B-type stars. We discuss the implications of this intense accretion phase on the formation of massive stars.

1. Introduction

Hot molecular cores (HMCs) are compact molecular sources with densities of order $\sim 10^7\,\mathrm{cm^{-3}}$, sizes $D \simeq 0.1\,\mathrm{pc}$, and temperatures $T > 100\,\mathrm{K}$. They are associated with H_2O masers and are found in the proximity of UCHII regions. They have estimated luminosities $L \simeq 2\text{–}3 \times 10^4\,\mathrm{L_{\odot}}$, suggesting the presence of massive stars. Nevertheless, they have not been detected in centimeter-wave continuum, as would be expected if there were appreciable amounts of ionized gas. In fact, Churchwell (1990) calculated that deeply embedded massive stars, of spectral type B0 or earlier, and closer than 10 kpc, should produce H II regions with centimeter flux densities $\geq 10\,\mathrm{mJy}$. Thus, HMCs seem not to be associated with optically thin H II regions. Instead, their properties are determined through millimeter wave and continuum line observations (see the review of Kurtz *et al.* 1999).

There are two possibilities for the source of heating of the cores: *(a)* External heating provided by, for example, a star inside a nearby UCHII region facing the core. In this case, the geometric solid angle limits the luminosity available to heat the core and therefore, the quantity of hot dust and gas in the core; and *(b)* Internal heating provided by the luminosity of a recently formed OB-type star (or stars) inside the core. In this latter case, Walmsley (1995), suggested that in these HMCs massive stars might be undergoing an intense accretion flow, which quenches the development of an UCHII region. For a high accretion rate $\dot{M}$, the accretion luminosity of the flow that is arrested at the stellar surface, $L_{\mathrm{acc}} = GM_*\dot{M}/R_*$, where G is the gravitational constant, M_* is the stellar mass, and R_* is the stellar radius, can be the main heating source. This second possibility would imply that HMCs may represent the youngest phase yet observed in the life of massive stars and could help us understand the process of high-mass star formation.

Recently, Kaufman, Hollenbach & Tielens (1998) modeled the temperature distributions of internally and externally heated hot molecular cores and calculated the column density of hot gas inside the cores. They considered constant

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density distributions and collapsing density distributions ($\rho \propto r^{-3/2}$) for the cores. In the latter case they did not discuss explicitly the effect of the accretion luminosity on the core heating.

To further investigate this problem, we model the flux density distribution (FD) of a dusty envelope collapsing onto a massive central proto-star, heated by the luminosity of the central star plus the accretion shock luminosity. We assume spherical symmetry and choose a dynamical model for the collapsing envelope. We compare the FDs of these models with the observed fluxes in several sources to determine the physical size of the HMCs, the mass accretion rate of the envelopes, and the spectral type of the central stars.

In §2 of this paper we define the parameters of our model and the assumptions that we have made, in §3 we discuss our results, in §4 we discuss the effects of the radiation pressure and the probable evolution of this kind of sources, and in §5 we give our conclusions.

2. The model

We model the HMCs as an envelope of gas and dust that is freely falling onto a recently formed massive central proto-star. The young star is embedded within the dense core and interacts with it through its radiation, heating the core from the inside.

We assume that the system consists of a central heating source, with a total bolometric luminosity, $L_{\rm core} = L_* + L_{\rm acc}$, where L_* is the stellar luminosity, surrounded by a spherically symmetric envelope, with inner radius $R_{\rm d}$ and outer radius $R_{\rm core}$. The inner radius of the envelope is equal to the dust destruction radius. We ignore the interaction of radiation from the central object with envelope matter located inside this radius. The effect of an energetic stellar wind is not taken into account. In spherical symmetry this is justified as long as the mass accretion rate is larger that the wind mass loss rate, $\dot{M}_{\rm acc} > \dot{M}_{\rm w}$, since the wind terminal speed is of the order of the free-fall velocity. When this condition is satisfied, the ram pressure of the accretion flow will prevent the wind from escaping from the stellar surface. In reality, the angular momentum of the infalling envelope will deviate the flow from spherical accretion and material will be deposited in a circumstellar disk around the star. In this latter case, the stellar winds could escape more easily through the poles. Our models will still be valid if the stellar winds are ejected in narrow bipolar cones, coexisting with the accreting envelope as in the case of low mass proto-stars (Adams, Lada & Shu 1987), as long as these cones of missing material represent a small fraction of the total core material. Also, the deviations of the density profiles from the spherically symmetric ones will be important only within the centrifugal radius (Adams & Shu 1986). As long as this region is small compared to the size of the core, our modeled FDs will be appropriate.

2.1. Density distribution

We examine two different types of density distributions: one resulting from the collapse of the singular isothermal sphere (SIS, see Shu 1977), and the other, from the collapse of the singular logatropic sphere (SLS, McLaughlin & Pudritz 1997).

The logatropic equation of state, $P = P_0 \ln(\rho/\rho_0)$, has been invoked to explain the linewidth-size relations observed in molecular clouds (Lizano & Shu 1989; Myers & Fuller 1992; McLaughlin & Pudritz 1996) since the sound speed, given by $c^2 = dP/d\rho = P_0/\rho$, behaves like the observed velocity dispersion in these clouds. In the above equation, ρ_0 is an arbitrary reference density.

The logatropic and SIS collapses occur in the same general fashion: an expansion wave moves outward into a cloud at rest and the gas behind it falls onto the central proto-star. The infalling matter close to the center has free-fall density and velocity profiles that are given by $\rho \propto r^{-3/2}$ and $-v \propto r^{-1/2}$, respectively, while in the outer region the density tends to the hydrostatic equilibrium configuration: $\rho(r) \propto r^{-2}$ for the SIS, and $\rho(r) \propto r^{-1}$ for the SLS. Nevertheless, there are important differences in the behavior of both types of collapsing clouds.

The mass accretion rate, in the collapse of the SIS, is constant: $\dot{M}^i = a^3/G$, where a is the isothermal sound speed. Instead, in the collapse of the SLS, the mass accretion rate is a steep function of time given by

$$\dot{M} = \frac{(2\pi G P_0)^{1/2}}{4G} m_0 t^3, \tag{1}$$

where the reduced mass is $m_0 = 0.0302$.

For a given M_* and $\dot{M}$, the age of the system in the SIS is given by $\tau^i_{\rm age} = M_*/\dot{M}$, while it is longer for the SLS:

$$\tau_{\rm age} = 4\frac{M_*}{\dot{M}} = 4\tau^i_{\rm age}. \tag{2}$$

Furthermore, for a given central star, the mass of the infalling envelope is given by

$$M_{\rm env} = M_* \left(\frac{m(x)}{m_0} - 1 \right), \tag{3}$$

where $m(x)$ is the dimensionless mass function of the dimensionless variable x. The dimensionless variable is $x = r/at$ for the SIS, where r is the distance to the central star, and $x = 4(2\pi G P_0)^{-1/2} r t^{-2}$ for the SLS. For $t = \tau_{\rm age}$, the location of the expansion wave is $x = 1$. Then, we use the infalling density distribution within $r_{\rm ew}$ and the hydrostatic density distribution outside this radius. In particular, at the expansion wave, $m(1) = 2$ for the SIS and $m(1) = 1$ for the SLS. Thus, at a given time, within the expansion wave, the SLS has only 3 % of the mass in the star, the rest is contained in the envelope. In contrast, for the SIS, where $m^i_0 = 0.975$, about half of the mass is in the star and half in the envelope. Also, eqns. (2) and (3) imply that, for a given M_* and $\dot{M}$, the isothermal envelope has less mass than the logatropic envelope. Finally, for simplicity, we assume that the density distribution is not affected by the finite core size.

2.2. Central stars

To determine the accretion luminosity, we need to specify not only the mass accretion rate, but also the mass, radius and luminosity of the central star.

It is unclear whether a star, formed under very high accretion rates, will have a normal ZAMS radius. In fact, Adams & Shu (1985), using the results of Stahler, Shu & Taam (1980) for the formation of low mass stars, found that the stellar radius is an increasing function of accretion rate: $R_* \propto \dot{M}^{0.33}$. Furthermore, Stahler, Palla & Salpeter (1986) studying the formation of primordial massive stars, found the same type of behaviour: $R_* \propto \dot{M}^{0.41}$. In addition, Beech & Mitalas (1994) and Bernasconi & Maeder (1996) have studied the formation of solar composition massive stars under constant accretion rates. These latter authors do not find these enlarged radii, maybe because they studied accretion rates smaller than $10^{-4}\,\mathrm{M_\odot yr^{-1}}$. It is then quite probable that the OB stars, formed under intense accretion flows inside HMCs, will have a radius larger than the ZAMS radius since they have not had time to get rid of excess internal energy. Thus, we chose to consider for the central stars of the HMC models, both, stars with ZAMS radii, and stars with stellar radii $R_* = 10^{12}$ cm. This latter value for the radius is within the range of radii found by the authors mentioned above.

Finally, since it is also unclear what the corresponding luminosity of a star will be, for the time being, for a given mass, we adopt the ZAMS luminosity of Thompson (1984).

2.3. Temperature profile of the dust envelope

We adopt a simplified calculation of the temperature profile proposed by Kenyon, Calvet & Hartmann (1993). The basic idea of this approximate treatment is to consider radiative equilibrium for the outer optically-thin dusty envelope and to assume the standard diffusion approximation in the inner optically thick-region. The radius that divides the optically thin and thick regions is called the 'photospheric radius', R_{ph}. Since the total luminosity is conserved, at this radius $L_{\mathrm{core}} = 4\pi R_{\mathrm{ph}}^2 \sigma T_{\mathrm{ph}}^4$, where σ is the Boltzmann constant and $T_{\mathrm{ph}} = T(R_{\mathrm{ph}})$. Also, we impose that $\tau_{\mathrm{R}}(T_{\mathrm{ph}}) = \frac{2}{3}$, where $\tau_{\mathrm{R}}(T_{\mathrm{ph}})$ is a Rosseland mean optical depth weighted by the Planck function evaluated at T_{ph}. Both, the optical depth and the luminosity conditions are used to find R_{ph} and T_{ph}, for a given density distribution. In addition, the dust is sublimated for temperatures higher than $\sim 1500\,\mathrm{K}$ (*e.g.*, Adams & Shu 1985), producing an inner dust free cavity. For details see Osorio, Lizano, & D'Alessio (1999; hereafter O99).

3. Results

A detailed discussion of the models and comparison with several observed sources can be found in O99. Here we want to highlight the results.

Figure 1 shows the observed fluxes of the source G34.24+0.13MM (Hunter *et al.* 1998). It also shows the three model FDs with $R_{\mathrm{core}} = 0.07$ pc and a central B3 star with a mass $M_* = 10\,\mathrm{M_\odot}$, a radius $R_* = 3.5 \times 10^{11}$ cm, and a stellar luminosity $L_* = 10^3\,\mathrm{L_\odot}$. The dotted line corresponds to the collapse density distribution of the SIS with $\dot{M} = 1.8 \times 10^{-3}\,\mathrm{M_\odot\,yr^{-1}}$; the dot-dashed line corresponds to the collapse density distribution of the SLS with $\dot{M} = 6.5 \times 10^{-4}\,\mathrm{M_\odot\,yr^{-1}}$. In order to match the observed fluxes at mm wavelengths, we require massive envelopes with high accretion rates. For the case of the density distribution of the collapse of the SIS, since the envelope is less massive than that of the SLS, one requires a higher mass accretion rate which produces infrared emission at 20 μm,

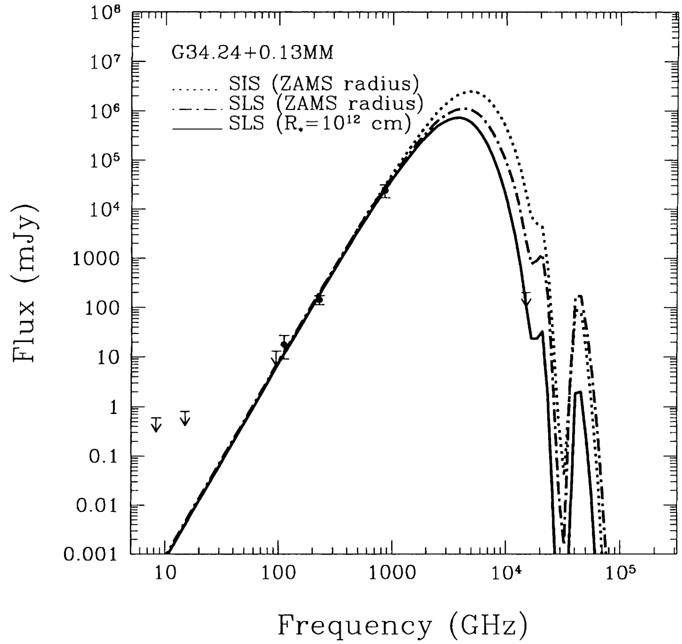

Figure 1. Observed fluxes of the source G34.24+0.13MM. The dotted line corresponds to the collapse density distribution of the SIS with $\dot{M} = 1.8 \times 10^{-3}\,M_{\odot}yr^{-1}$, and the dot-dashed line corresponds to the collapse density distribution of the SLS with $\dot{M} = 6.5 \times 10^{-4}\,M_{\odot}yr^{-1}$. The continuous line shows the the SLS model, with a star that has $R_* = 10^{12}$ cm.

higher by orders of magnitude than the observed constraint at this wavelength. On the other hand, the model of the logatropic collapse density distribution has a smaller excess at $20\,\mu$m which can be attenuated invoking a high extinction, external to the HMC, $A_V \simeq 80$ mag. This value of the extinction is high, even though HMCs are found inside dense regions in molecular clouds. More generally accepted values are $A_V \lesssim 30$ mag (*e.g.*, Testi *et al.* 1998). The continuous line in this figure shows the FD of the SLS model discussed above, but with a star that has a radius $R_* = 10^{12}$ cm, as discussed in § 2.2. One can see that the excess emission at $20\,\mu$m is reduced, and now fits the constraint at $20\,\mu$m, with no external extinction required, since the accretion luminosity decreases for this large stellar radius. Instead, even if one used a large stellar radius for the SIS density distribution, one still requires $A_V > 80$ mag to attenuate the excess emission at $20\,\mu$m.

Motivated by this result, in the comparison with observations of several sources below, we present only models that assume a SLS collapse distribution. In addition, the central stars are assumed to have radii, $R_* = 10^{12}$ cm, and we neglect the effect of any external extinction. It is likely that, in the real sources, a combination of some external extinction ($A_V < 30$ mag) plus a star with a radius somewhat larger than its ZAMS value could be work. Figure 2 shows the observed fluxes of several HMC sources, together with the model FDs.

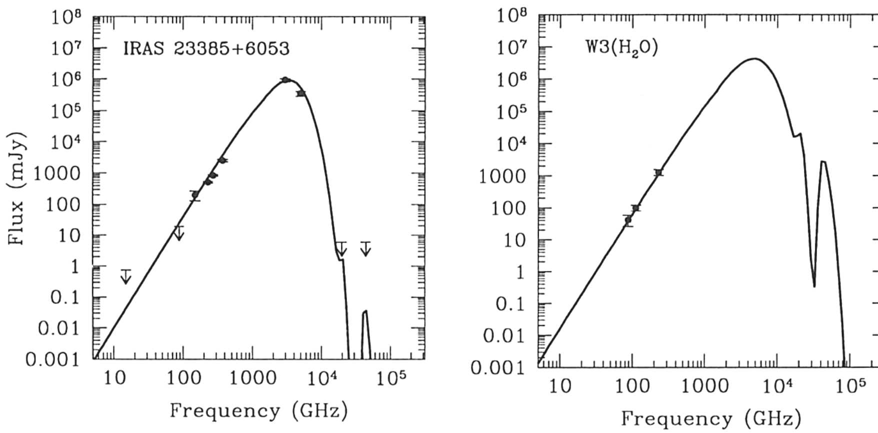

Figure 2. Comparison of the model FFDs with observed fluxes of different sources labeled in each panel.

Table 1 shows the parameters of the sources labeled in both panels. It also shows the parameters of the source in Figure 1. Table 2 shows the characteristics of the modeled cores: the dust destruction front, R_d, the photospheric radius, R_{ph}; the photospheric temperature, T_{ph}; and the volume density at the external radius, $n(R_{core})$; the total luminosity, L_{core}, the fraction of the accretion luminosity, to the total luminosity, L_{acc}/L_{core}; the core mass within R_{core}, M_{core}; and the present age of the core given by eqn. (3). One can see that all the modeled cores require very high accretion rates to reproduce the millimeter and submillimeter fluxes, $10^{-4}\,M_\odot yr^{-1} \lesssim \dot{M} \lesssim 10^{-3}\,M_\odot yr^{-1}$. Also, the central stars are late B type stars and the ages of the systems are $\lesssim 10^5$ yr. Clearly, high spatial resolution observations at far and mid infrared wavelengths are crucial to constrain the model parameters.

Table 1. Model parameters

source	M_*^a ($M_\odot$)	L_* ($L_\odot$)	$\dot{M}$ ($M_\odot yr^{-1}$)	R_{core} (pc)	β	d (kpc)
G34.24+0.13MM	10.0	1.0×10^3	6.5×10^{-4}	0.07	2.0	3.7
W3(H_2O)	15.8	2.5×10^4	5.0×10^{-4}	0.10	1.6	2.2
IRAS 23385+6053	12.6	2.8×10^3	1.0×10^{-3}	0.10	1.6	4.9

Note: ^{a}: For all the models $R_* = 10^{12}$ cm.

4. Radiation pressure onto dust grains and the end of the accretion phase

The radiation pressure onto dust grains imposes an upper limit on the amount of mass that a massive star can accrete. Kahn (1974) found that the radiation pressure of the diffuse infrared radiation field inside a dusty envelope around

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Table 2. Structure of modeled Hot Molecular Cores

source	R_d (AU)	R_{ph} (10^3 AU)	T_{ph} (K)	$n(R_{core})$ (10^6 cm^{-3})	L_{core} (10^4 L$_\odot$)	L_{acc}/L_{core} %	M_{core} (M$_\odot$)	τ_{age} (10^4 yr)
G34.24+0.13MM	35	3.8	72	2.4	1.6	94	131	6.1
W3(H_2O)	42	3.3	98	0.7	4.2	42	121	12.6
IRAS 23385+6053	54	7.0	62	2.5	3.1	91	382	5.0

a massive proto-star decelerates the flow allowing a maximum luminosity to mass ratio $L/M_* = 5436\,\mathrm{L_\odot/M_\odot}$. He considered an optically thick dusty cocoon plus an optically thin envelope, and assumed an analytic form for the Rosseland mean opacity $\chi_{\rm R} = \chi_{\rm R0}(T/T_{\rm s})^2$. From his eqn. [65] one can see that this ratio is inversely proportional to the cube of the dust sublimation temperature, $T^3_{\rm sub}$, and proportional to χ_{R0}, the Rosseland mean opacity for radiation at a color temperature $T_{\rm s} = 22{,}000$ K. Kahn used $T_{\rm sub} = 3675$ K and $\chi_{R0} = 600\,\mathrm{cm^2 g^{-1}}$. We find that the sublimation temperature for the grain mixture in our models (see §2.4) is $T_{\rm sub} \simeq 1500$ K. Also, the value of χ_{R0} must be increased by a factor of ~ 8 to agree with our value for the Rosseland mean opacity at $T \simeq 1000$ K, taken from D'Alessio (1996). These modifications, due to the current known properties of the standard grain mixture used in this work, imply that the maximum luminosity to mass ratio derived by Kahn would currently be $L/M_* = 8872\,\mathrm{L_\odot/M_\odot}$. This result agrees with the detailed modeling of the dust destruction process carried out by Wolfire & Cassinelli (1987). They found that very massive stars, with masses $M_* = 60$, 100 and 200 M$_\odot$, can only be formed with modifications of the standard MRN grain mixture. The cases they studied have luminosity to mass ratios larger than $L/M_* = 8974\,\mathrm{L_\odot/M_\odot}$. On the other hand, Jijina & Adams (1996) found that the maximum luminosity to mass ratio is less restrictive for a rotating collapse than for the spherical infall. In any case, all our HMC models have luminosity to mass ratios $L_{core}/M_* < 2700\,\mathrm{L_\odot/M_\odot}$, which implies that accretion can continue onto the central star.

Nevertheless, the luminosity to mass ratio, given by

$$\frac{L_{\rm core}}{M_*} = \frac{L_*}{M_*} + \frac{G\dot{M}_*}{R_*}, \tag{4}$$

will increase with time mostly because the luminosity of the central star increases very steeply with stellar mass, and $M_* \propto t^4$ for the SLS collapse. Therefore, within a very brief period, this ratio will surpass the critical luminosity to mass ratio (see Figure 7 of O99) and radiation pressure will be able to halt the collapse of matter onto the central star. This is only a transient process since, as the accretion is shut-off, so is the accretion luminosity, an important contributor to the total luminosity. Thus, one is tempted to speculate that, if after the flow is impulsively reversed a stellar wind can also turn on, it could help clear out the accreting flow. An H II region can then be produced, although in this scenario, its evolution would be governed by the reversal of the accretion flow, a complex problem worth studying in detail.

5. Conclusions

Our main results can be summarized as follows:

1. The observed FDs of several HMCs can be reproduced by massive envelopes accreting onto young massive central stars. In order to fit the available data, we require early B-type stars with high mass accretion rates, $\dot{M} > 5\times 10^{-4}$ $M_\odot yr^{-1}$, and time-scales $\tau \lesssim 10^5$ yr. At this stage, the accretion luminosity is a dominant heating mechanism.

2. Models of the structure of massive stars formed under the intense mass accretion rates that increase with time discussed in this work, are necessary to determine the characteristics (*e.g.*, mass, radius, intrinsic luminosity) of this type of objects.

3. Mid- and far-IR high angular-resolution observations (to avoid contamination of nearby massive stars) are crucial to constrain the total luminosity of the HMCs.

4. We speculate that, when a critical luminosity to mass ratio is achieved, the in-fall will be reversed by a powerful stellar wind and a detectable UCHII region can appear.

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Discussion

Stecklum: How do you solve the angular momentum problem (angular momentum transport) using optical symmetric models?

Lizano: At late stages of the accretion, a disk might be important but the major conditions are the high accretion rate and the large mass of the hot core. Rotation is not yet included in the model, but I doubt that this will change the emergent spectra considerably.

Maeder: Recently, we have computed grids of birth lines with different accretion rates and compared them with observations of pre-MS stars. The results (Norberg *et al.* , in preparation) will support your results that the accretion rates should fastly grow with time, or with the already accreted mass. Now a short question: why this logatropic equation of state rather than the equation of perfect gases, well applicable to such a diluted medium?

Lizano: I certainly would like very much to see your results. As for you question, the logatropic equation of state, has been invoked to explain the linewidth-size relations observed in molecular clouds, the so-called Larson's relations. In particular, it is observed that the velocity dispersion of molecular lines decreases with density as $\Delta v^2 \propto \rho^{-1}$. This velocity dispersion is supersonic and it not due to thermal pressure at temperatures $T \simeq 10$–$20\,\mathrm{K}$ in molecular clouds. It is not known how turbulence can provide this type of pressure support. Thus, the logatropic EOS was used empirically to mimic the pressure support observed as non-thermal components of molecular linewidths, since the associated sound speed, $c^2 = dP/d\rho = P_0/\rho$, behaves like the observed velocity dispersion in molecular clouds.

Langer: You say you are in need of stellar models of accreting stars with high accretion rates. I believe such models exists, albeit in the binary literature, for accretion rates up to $10^{-2}\,\mathrm{M}_{\odot}\mathrm{yr}^{-1}$. From these models you might be able to extract the dependence of radius and luminosity on accretion rate, especially the critical accretion rate, above which the stars become very extended and luminous (which, I believe, is not strongly dependent on the time-history of the accretion).

Lizano: Thanks, I will certainly look this up in the binary literature. Nevertheless, it would be interesting to verify if the time-history affects the stellar structure. Indeed a lot of binary accretion models are available, although in this case it is accretion onto a core hydrogen burning star.