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ON THE FORMATION OF BROWN DWARFS

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RESUMEN

Las propiedades de las enanas marrones presentan problemas para la teoría de la formación estelar. Como sus masas son mucho menores que la masa de Jeans de las nubes interestelares, las enanas marrones se forman probablemente por fragmentación secundaria, y no por el colapso directo del núcleo de la nube molecular. Para evitar la acreción de masa posterior, las jóvenes enanas marrones deben salir de las regiones de alta densidad donde se formaron. Proponemos que las enanas marrones se forman en las regiones externas, ópticamente delgadas, de los discos circunbinarios. Las interacciones dinámicas subsecuentes con sus binarias causan que las enanas marrones sean dispersadas a grandes distancias, o que escapen del sistema a baja velocidad.

ABSTRACT

The observational properties of brown dwarfs pose challenges to the theory of star formation. Because their masses are much smaller than the typical Jeans mass of interstellar clouds, brown dwarfs are most likely formed through secondary fragmentation processes, rather than through the direct collapse of a molecular cloud core. In order to prevent substantial post-formation mass accretion, young brown dwarfs must leave the high-density formation regions in which they form. We propose here that brown dwarfs are formed in the optically thin outer regions of circumbinary disks. Through post-formation dynamical interaction with their host binary stars, young brown dwarfs are either scattered to large distance or removed, with modest speed, from their cradles.

Key Words: **STARS: LOW MASS, BROWN DWARFS**

1. INTRODUCTION

Brown dwarfs are entities with mass below that required for hydrogen burning to ignite ($< 0.075 M_{\odot}$) and above that associated with gaseous giant planets ($\sim$ a few Jupiter masses, M_J). Although the existence of brown dwarfs was proposed by Kumar in 1963, their cool dim nature consigned them to a strictly theoretical status for more than three decades. Recently, however, improved observational capabilities have led to the discovery of many brown dwarfs, prompting a renaissance in our understanding of these objects. Because the mass of brown dwarfs is much smaller than the usual Jeans mass for a typical molecular cloud, Lin et al. (1998) claimed that the encounter between two protostellar discs might increase the Jeans mass locally. Reipurth & Clarke (2001) suggested that brown dwarfs are substellar objects because they have been ejected from newborn multiple systems. They use a simple model of timescales to show that this could happen. Bate, Bonnell & Bromm (2002) used a smoothed particle hydrodynamics code to show that brown dwarfs could be formed through the collapse and fragmentation of a turbulent molecular cloud and thus confirmed the suggestion of Reipurth & Clarke (2001).

However, if all brown dwarfs have to be ejected to avoid accreting too much mass, one might ask how it would be possible that they are sometimes wide companions of solar-type stars. In this paper, we propose a formation scenario for brown dwarfs which provides a natural explanation for the current observational situation. We suggest that brown dwarfs could be formed through disc fragmentation and we study the "escape zone" where the brown dwarfs could be ejected and become field stars.

In principle, we demonstrate that in some cases, the brown dwarfs get ejected but in other cases, they could become long-period companions. We also study the criteria for survival of the brown dwarf pair. However, we do not intend to study the problem of the brown dwarf desert here.

2. STABILITY OF BROWN DWARF COMPANIONS AROUND BINARY STARS

We now investigate the orbital stability and evolution of brown dwarfs formed in circumbinary rings. These companions are perturbed by the tidal disturbance of the binary star's gravitational potential. For computational convenience, we assume that these newly fragmented brown dwarfs quickly become centrally condensed and that the residual gas

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does not contribute significantly to the gravitational potential, so that the dynamics of the system may be described by a few-body approximation.

In this section, we further simplify the interaction procedure to a three-body (the host binary star plus a brown dwarf) problem. The mass of each brown-dwarf fragment is sufficiently small that they do not significantly perturb each other on the short term of several thousand binary periods. In order to make a direct comparison with some existing results, we first treat the brown dwarfs as massless particles. But in general, we carry out a full 3-body integration in which the contribution due to the finite mass of the brown dwarf is included.

We consider a range of ratio ($\mu = M_1/(M_1+M_2)$) of masses (M_1 and M_2) for the two components of the binary stars. Following the approach by Holman & Wiegert (1999), we consider, for the host binary system, a range of orbital eccentricity (e_*). The semi-major axis of the binary is set to be unity, so that all other length scales are scaled with its physical value. We also adopt $G(M_1 + M_2) = 1$, so that the binary orbital period is 2π.

Since we assume they are formed in circumbinary rings, we consider brown dwarfs with orbital semi major axes larger than those of the binary systems. At the onset of the computation, all three stars are located at their apocenter with respect to their common center of mass. It is possible that the fragments may have a range of orbital eccentricity (e_b). Here, we consider two limiting eccentricities for the brown dwarf ($e_b = 0$ and 0.4). We also set the ratio (μ_b) of the brown dwarf's mass to that of the binary to be 0.05 and we assume the brown dwarfs to rotate in the same direction as the orbit of the binary.

2.1. *Ejection criteria*

We choose a range of initial orbital semi-major axis for the brown dwarf for the $e_b = 0$ case. For each set of model parameters, we adopt four values for the brown dwarf's angle of apocenter, 0°, 90°, 180° and 270° with respect to the binary system's.

In all our models, the orbital semi-major axis of the brown dwarf is larger than that of the binary system. We are primarily seeking a critical initial semi-major axis (a_c), larger than which the brown dwarf survives the binary system's perturbation within a timescale T_d. Our definition of survival is that the distance from the center of mass of the system to the brown dwarf (starting with all four values of the apocentric arguments) must be smaller than a critical value R_d. The value of R_d is arbitrarily set to be 25 binary separations. In order to compare with

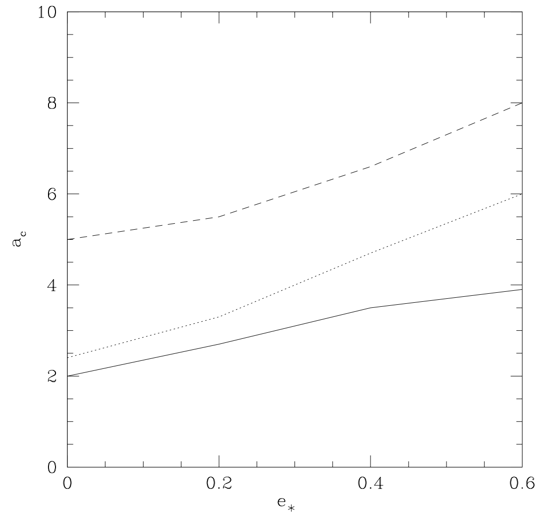

Fig. 1. The critical semi major axis as a function of eccentricity when the mass ratio of the binary system $\mu = 0.1$. The solid line represents the result for models with brown dwarfs treated as massless test particles which initially move on circular orbits. These models are analogous to those obtained by Holman & Wiegert (1999). The dotted line represents the results for models in which brown dwarfs are assigned the finite mass $\mu_b = 0.05$. The brown dwarfs are assumed to have circular orbits about the center of mass of the binary system initially. The dashed line represents the results of models in which brown dwarfs have mass $\mu_b = 0.05$ and initial eccentricity $e_b = 0.4$.

the results of Holman & Wiegert (1999), we choose $T_d = 10^4$ binary periods. Based on several test runs, we find that the value of a_c does not change significantly if T_d is increased to 10^6 binary periods. Thus, we find a_c to be a useful parameter to classify our results (Dvorak et al. 2004). Although we use a totally different numerical scheme from Holman & Wiegert (1999), we are able to precisely reproduce the results in Table 7 of their paper when we set the mass of brown dwarf to be zero as they have. But in general, we choose $\mu_b = 0.05$.

¿From these models, we find that the brown dwarfs' "escape zone" (with semi-major axis $a < a_c$) is expanded slightly when they have finite mass (see Fig.1 & 2 for the comparison.) The expansion of the "escape zone" is larger for $\mu = 0.1$ cases than that for the $\mu = 0.5$ cases because the motion of the secondary star is more affected by the finite mass of the brown dwarf. This effect is particularly noticeable for the $\mu = 0.1$ and $e_* = 0.6$ case where a_c is expanded from 3.9 of massless particles to 6.0 of brown-dwarfs with $\mu_b = 0.05$. The hydrodynamical simulations indicate that fragmentation of circumbi-

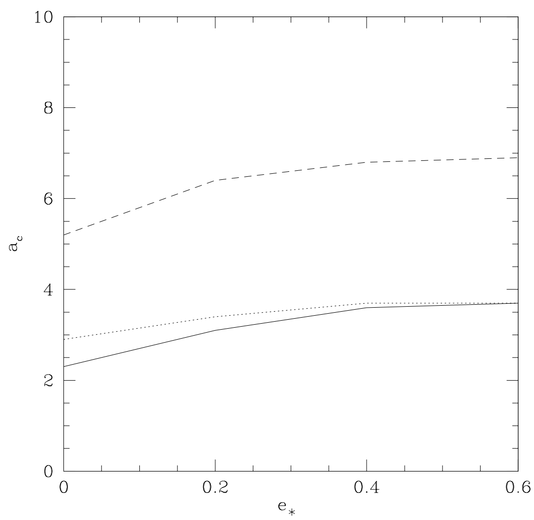

Fig. 2. The same as in Fig.1 except that the mass ratio of the binary system $\mu = 0.5$.

nary disks occurs primarily at around 1-2 binary separations away from their center of mass because this is the location where disk gas may accumulate as a consequence of the binary star's tidal torque. Thus *most of the low-mass fragments formed in the circumbinary rings have a high probability of being ejected by the gravitational perturbation of their host binary systems.*

We now consider a series of models with $e_b = 0.4$ while all other parameters are similar to those for the $e_b = 0$ case. The increases in a_c in Fig. 1 and Fig. 2 clearly indicate that brown dwarfs with eccentric orbits are definitely less stable than those with circular orbits.

2.2. *Large radial excursion of marginally stable systems.*

In general, the binary systems and the fragments formed in unstable circumbinary rings have non circular orbits. Thus most brown dwarfs formed close to the binary are likely to be ejected. But brown dwarfs with initial semi major axis $a_b \sim a_c$ can be scattered to large distances from the center of mass of the system without escaping from its gravitational potential.

We illustrate three such examples each with $a_b \sim a_c$. In model 1, we choose $\mu = 0.1$, $e_* = 0.4$, $a_b = 4.4$, $e_b = 0$ and the argument of the brown dwarf's apogee, $\theta_b = 90°$. In this case, the brown dwarf reaches to 200 binary separations by the end of simulation, i.e. $t = T_d$. In model 2, ($\mu = 0.1$, $e_* = 0.6$, $a_b = 7.8$, $e_b = 0.4$, and $\theta_b = 180°$), the brown dwarf's orbit expands to 50 times the binary's initial separation at $t \sim 0.6T_d$. But subsequently at $t = T_d$, the extent of the brown dwarf's radial excursion is reduced to approximately its initial value. In model 3, ($\mu = 0.5$, $e_* = 0.2$, $a_b = 6.3$, $e_b = 0.4$, and $\theta_b = 270°$), the excursion reaches 100 initial binary separations. These examples indicate that wide and marginally stable orbits exist and that *under some marginal circumstances, brown dwarfs can be scattered to large distance from, but remain bound to, some main-sequence binary stars.* The recent discovery of a brown dwarf candidate at a distance of $\sim$ 100 AU from a young binary star, TWA 6 Hya may be examples of such a system.

2.3. *Ejection speed of escapers*

Brown dwarfs with $a_b < a_c$ are ejected from the gravitational potential of their host binary system. We now examine their escape speed by a series of calculations.

¿From the distribution of the escape speed, we found that the ejection speed is typically half the orbital speed of the binary. For $R_b \sim 3 \times 10^{15}$ cm, $a \sim R_b$, and the total mass of binary system $\sim 1M_\odot$, the binary's orbital speed would need to be $\sim 3 - 5$ km s^{-1}. Our results show that the escape speed of the brown dwarf ejecta is $\sim 1 - 3$ km s^{-1}. In a young stellar cluster, as in Orion, this ejection speed is a fraction of the velocity dispersion of the cluster, which is in dynamical equilibrium. Thus *brown dwarfs ejected from the close proximity of the binary would not generally escape the gravitational potential of the cluster.* This result is consistent with the large concentration of brown dwarfs in young stellar clusters such as the Orion complex (Lucas & Roche 2000).

3. FORMATION OF BROWN DWARF PAIRS

Indeed, close brown dwarf binaries have been found (Koerner et al. 1999), but these systems are generally not orbiting around binary main sequence stars. Similar to single brown dwarfs, close binary brown dwarfs may also be strongly perturbed by the gravity of the binary and be ejected.

3.1. *Survival of pairs*

In order to test the survival probability of the brown dwarf binaries, we first place a massless test particle to simulate the dynamics of a secondary companion around the brown dwarf (For some interesting cases, a series of models with masses for both brown dwarf companions are included). This approximation allows us first to explore the range of parameters which may be favorable for the survival of the brown dwarf pairs. Based on the results in Fig.1 and Fig. 2, we can identify the range of model parameters which leads to ejection of brown dwarf fragments. As a test, we adopt $\mu = 0.5$ for the binary star and choose $\mu_b = 0.05$, $a_b = 2.3$ and apogee at 0° for the primary of the brown dwarf binary. The secondary of the brown dwarf binary is assigned an initial semi major axis 2.5 and apogee at 0°. Thus the separation of the brown-dwarf pair is 0.2, which is inside the Roche radius of the primary ($R_R = (\mu_b/3)^{1/3} = 0.25$). We also assume that the center of mass of the brown-dwarf pair is initially on a circular orbit around the center of mass of the binary system and the brown-dwarf secondary is on a circular orbit around the brown-dwarf primary.

Then we try four cases of different eccentricities of the central binary stars: $e_* = 0.0,\ 0.2,\ 0.4,\ 0.6$. Our results indicate that the brown-dwarf pairs would survive their ejection from the neighborhood of the binary in the low-eccentricity ($e_* = 0.0$ and $e_* = 0.2$) limit. But in the limit that the binary system has a large eccentricity (*i.e.* for the $e_* = 0.4$ and $e_* = 0.6$ models), the brown dwarf pairs have a tendency to become dissociated. Therefore it is plausible that brown dwarf pairs may remain bound to each other during their ejection from the binary system's gravitational potential. But it is also possible for their ejection to produce two freely floating single brown dwarfs.

The above approximation provides a useful tool for us to identify the range of parameters which allows a brown dwarf pair to survive. The massless approximation for the secondary is applicable to brown dwarf binaries with extreme mass ratios. We now takes the next iteration by replacing the ($\mu_b = 0.05$) primary and a massless secondary brown-dwarf pair with a system of two equal-mass ($\mu_b = 0.025$) brown dwarf companions. We find, with the identical four sets of model parameters as above, that brown dwarf binaries remain intact as they are ejected by their host binary stars.

We also enlarge the separation of the brown-dwarf binary to 0.3, which is larger than its Roche radius. Again all four sets of initial conditions are used. In all cases, the brown dwarf binary is disrupted during its close encounters with the binary star.

3.2. *Pair capture*

We now explore the possibility that both brown dwarfs were formed as single objects and that they have captured each other to become a binary. In order to evaluate this probability, we repeat the earlier simulation in which 24 particles are placed in a ring around the binary system. The main difference from the earlier models is that a mass of $\mu_b = 0.05$ is assigned to each particle. The corresponding Roche radius for each individual particle is ~ 0.25 which is comparable to their initial separation. All the particles are ejected from the gravitational potential of the binary system but no particle captured any other particle. We did not see any case in which the capture happened. We thus conclude that this second scenario is very unlikely.

4. SUMMARY

For single brown dwarf satellites around binary systems, our dynamical calculations show that when they are formed in dynamically unstable regions, they are likely to be ejected from the gravitational potential of the binary system. These results provide an explanation for the common sighting of field brown dwarfs.

For binary brown dwarf satellite pairs, the calculations of four body (main sequence binary with brown dwarf pair) interactions show that these brown-dwarf pairs can remain bound to each other during the ejection if their initial separation is well within their Roche radius (which is typically $R_R \sim 0.2 - 0.25$ binary separation).

We are grateful for friendly conversation with Matthew Bate, Michael Sterzik and Bo Reipurth. Particularly, Michael Sterzik and Bo Reipurth pointed out that the words "Main-Sequence" probably should be replaced by "Solar-Type Stars" in the viewgraphs of the oral presentation of this paper.

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DISCUSSION

Clarke – Do the brown dwarfs ever form as pairs in the disc fragmentation calculations by Laughlin?

Jiang – Since the disc fragmentation calculations were done by Greg Laughlin, he knows more about these details.

Participants relax during the reception.

LOC and friends during the reception.