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Brown dwarfs from decaying accreting triple systems

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Abstract. We investigate the dynamical decay of non-hierarchical accreting triple systems and its implications on the ejection model as Brown Dwarf formation scenario. We analyse the end states of these systems and determine the fraction of Brown Dwarfs formed as well as the semi-major axis distribution of the formed Brown Dwarf binaries. Furthermore we estimate how destructive such triple interactions can be to disks surrounding the Brown Dwarfs.

Key words. binaries: close – methods: N-body simulations – stars: formation – stars: low-mass, brown dwarfs – stellar dynamics

1. Introduction

In the past few years many Brown Dwarfs have been detected (e.g. Basri 2000). They were found at many different star-formation sites like Taurus (Briceño et al. 2002), Orion (e.g. Muench et al. 2002), Ophiuchus (e.g. Allen et al. 2002) and the Chamealeon cloud (e.g. López Martí et al. 2004), as cluster members (Moraux et al. 2002; Martín et al. 1998) and as free-floating objects (Kirkpatrick et al. 2000). Based on the frequency of detection it is widely believed that they should be as common as low-mass stars. In addition to their similar abundance many of them also show accretion features like ordinary TT stars and it was even possible to detect circumstellar disks around them (Jayawardhana et al. 2003; Pascucci et al. 2003; Natta & Testi 2001). Also some of them are known to form binary and higher order systems (Bouy et al. 2003).

This might indicate that Brown Dwarfs have been formed like ordinary TT stars, especially since their accretion features, vanish af-

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ter about the same time as it is the case with TT stars (see e.g. Liu et al. (2003)). Indeed most of the observed properties of Brown Dwarfs can be understood this way. However, one feature that lacks a clear understanding are the properties of Brown Dwarf binaries. Kroupa et al. (2003) argue that if Brown Dwarfs are formed like low-mass stars they should have the same pairing statistics and binary properties, scaled down to the substellar regime. On the contrary, from surveys of Close et al. (2003), Martín et al. (2003) and many more, as well as from the model calculation of the standard starformation scenario of Kroupa et al. (2003), it has been found that the observed properties of Brown Dwarf binaries are not a natural extension of the trends seen among stars with decreasing primary mass. Based on this Kroupa et al. (2003) conclude that Brown Dwarfs may not be formed with the same scaled down properties as stars and further infer that, in order to form Brown Dwarfs, their accretion phase must be interrupted by other processes. Several processes have been suggested in the literature. Whitworth & Zinnecker (2004) suggest that the strong, ionizing UV radiation of hot O and B stars might be very efficient producing Brown Dwarfs from preexisting cloud cores. For low-mass star forming regions harbouring Bown Dwarfs, like the Chamaeleon cloud, there must be a different process at work due to the lack of massive stars.

Reipurth & Clarke (2001) suggested that the ejection of fragments from unstable multiple systems out of their surrounding molecular cloud may lead to an early end of the accretion process of the fragments and, consequently, leave some of them substellar. This formation scenario is constantly challenged by observational studies (Briceño et al. 2002; Natta & Testi 2001,and more). They argue that because accretion features are observed around objects with an age of up to 10 Myr, which is about the lifetime of disks around T Tauri stars, close collisions, required for the ejection of fragments, cannot have happened as they tend to truncate the disks, severely limiting their lifetime, which in turn should make the frequency of detection much lower than actually observed. On the other hand the amount of material that is stripped off the disk is also sensitive to the parameters of the perturber orbit. However, for accreting small-N clusters the encounter parameters have not been studied in great detail to address this questions.

Here we want to explore by means of N-body calculations under which conditions Brown Dwarfs can be formed in decaying accreting triple systems and obtain statistics of escaping Brown Dwarfs and binaries. Some results in this contribution will be published together with a detailed explanation of our model in Umbreit et al. (submitted).

2. Numerical Simulations

In order to investigate the ejection scenario numerically we integrate a large number (1000) of realizations of triple systems with an initial mass of $0.04\mathrm{M}_\odot$ and with constant mass growth $\dot{M}$, using the CHAIN-code of Mikkola & Aarseth (1993). To cover all geometrically possible initial configurations we follow the approach of Anosova (1986,Fig. 1) We then multiply the initial position vectors by a constant factor to give the desired maximum separation of 200 AU. During the integration the fragments accrete mass at a given rate which we will vary to investigate the influence of $\dot{M}$ on our results. For $\dot{M}$ we choose 1, 2 and 5 times the value suggested by Reipurth & Clarke (2001) of $\dot{M}_{RC} \approx 1.4 \cdot 10^{-6}\,\mathrm{M}_\odot \cdot \mathrm{yr}^{-1}$ per fragment. The accreted gas is assumed to be at rest with respect to the reference frame, so no linear momentum is transferred onto the bodies while their masses are increased. We further assume a certain radius around the origin outside of which the accretion of the fragments is stopped if the system has decayed. This radius serves as an 'effective' cloud radius, determining the region where the bodies accrete a significant amount of gas. In order to decide whether a system has decayed, we employ two simple escape criteria. First, we require that the escaper and the binary are unbound with respect to each other. Second, we require that the distance between the escaper and the center of mass of the binary is more than seven times the initial mean harmonic distance.

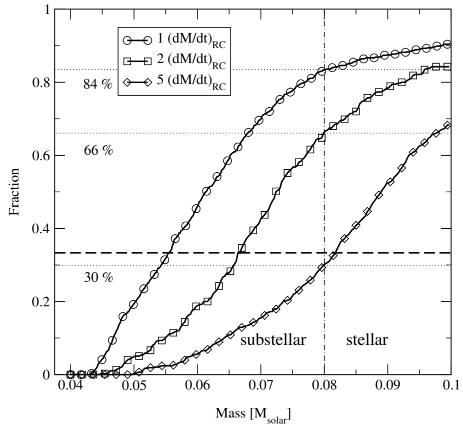

Fig. 1. Cumulative histogram of the mass of the ejected single objects. Shown are the results for different accretion rates in multiples of $1.4\,10^{-6}\,M_{\odot}yr^{-1}$. The dashed line represents the estimate of Reipurth & Clarke (2001) of ejected embryos with a lower mass than $0.08\,M_{\odot}$. (picture from Umbreit et al. (submitted))

3. Number of Brown Dwarfs

In Fig. 1 the fraction of systems, accreting gas at rest, that ejected a single member with a mass lower than a given mass m is shown. The fraction of Brown Dwarfs in our simulation turned out to be rather high, with a value of up to 84%. The fraction decreases with increasing accretion rate down to 30% for $5 \cdot \dot{M}_{RC}$. Considering that in reality the accretion process is likely to be competetive, increasing the formation probability of Brown Dwarfs, our numerical results seem to confirm that the ejection scenario can be very efficient.

Compared to the estimate of Reipurth & Clarke (2001), however, we get almost three times more Brown Dwarfs for the same accretion rate. To account for that difference we want to discuss the toy model as described in Reipurth & Clarke (2001) here briefly. The decay of triple systems can be approximately described by a decay equation, which is an exponential function characterized by the half life of decay. The shorter the half life the earlier the systems decay and consequently the higher is the probability to form a Brown Dwarf. The half life time is proportional to the crossing time, which in turn depends on the time varying masses $M(t)$ and is also indirectly proportional to the total energy E of the triple. In order to calculate the total energy Reipurth & Clarke (2001) set, for simplicity, the mean harmonic distance R of the fragments constant. This leads to an expression for the total energy of

$$E(t) = -3G\frac{(\dot{M} \cdot t + M_0)^2}{R} \tag{1}$$

with G being the gravitational constant and M_0 the initial mass of the fragments. Dropping the assumption $R = const.$ our own calculations show, however, that the total energy becomes

$$E(t) = E_0\left(\frac{\dot{M}}{M_0} \cdot t + 1\right)^5 . \tag{2}$$

As one can see, the energy depends now much more strongly on the accretion rate $\dot{M}$ and decreases, due to $E_0 < 0$, with the 5^{th} power of t, instead of a power of 2 in the $R = const.$-case. As a result of this, the systems shrink much faster, making the half life of decay significantly shorter and likewise the Brown Dwarf formation probability higher.

Fig. 2 shows the resulting decay curves for the accretion-of-gas-at-rest as well as the $R = const.$ approximation. As it was to be expected from the energy curves, the $R = const.$-approximation underestimates significantly the number of Brown Dwarfs, while with the 'gas at rest'-approximation almost all ejected fragments should be Brown Dwarfs. However, there is a significant difference between our numerically obtained and the analytic number of Brown Dwarfs. The reason, we think, might be that the assumption that the number of systems that have not yet decayed is a simple exponential function over time, is not strictly valid.

4. Binary Semi-Major Axis

In Fig. 3 the binary semi-major axis distribution is compared to the observed volume-limited sample of Bouy et al. (2003). There is a remarkable agreement between these two distributions as they both have the peak value at

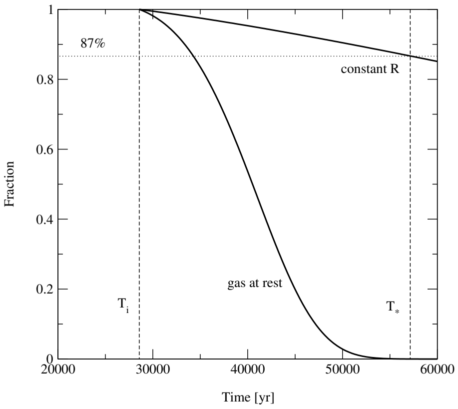

Fig. 2. The probability that an equal mass triple system has not yet decayed after a time t for the different models. T_* is the time when the fragments reach the Brown Dwarf limit of $M = 0.08\mathrm{M}_\odot$ and T_i is the time the fragments effectively start to interact with each other, which was chosen to be the time when they reach $0.04\mathrm{M}_\odot$. (picture from Umbreit et al. (submitted))

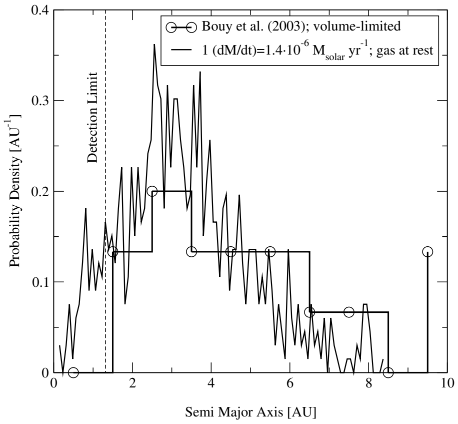

Fig. 3. Semi major axis distribution of the Brown Dwarf binaries obtained in our simulation of decaying triple systems, accreting gas at rest, and the observed volume-limited sample distribution of Bouy et al. (2003). (picture from Umbreit et al. (submitted) with slight modifications)

$a \approx 3$ AU and approximately the same, rather steep, slope to both sides of it. That our distribution fits almost perfectly the one obtained from observations is certainly a coincidence given the arbitrariness of our initial conditions. However, what we can predict is that, according to our model, the distribution cannot be flat for a semi major axis below the peak value, but must decrease. Due to the detection limit of the observations of Bouy et al. (2003) it is not clear whether the observed distribution will also decrease with decreasing a or not. We also found that the peak of the semi-major axis distribution does not change much with the accretion rate, only the cut-off is lower for higher rates.

Sterzik & Durisen (2003) found a very similar semi-major axis distribution. They calculate pairing and binary statistics by integrating many small-N clusters neglecting hydrodynamical interaction by the remaining gas as well as any ongoing accretion. They constrain their initial conditions by a clump mass spectrum, which determines the total masses of the clusters, and a composite single star mass spectrum. They conclude that, once Brown Dwarfs have formed in sufficient numbers as to fit the observed Brown-Dwarf-IMF of the galactic field, the subsequent decay of the emerging multiple systems with the given constraints can explain the observed binary properties. They also point out that, because they scale their results by fixing the virial speed for all systems choosing $\mathrm{v}_{vir} = 3.3\,\mathrm{km{\cdot}s}^{-1}$, their Brown Dwarf systems are already in a very compact configuration close to the final binary separations. Indeed for a triple Brown Dwarf system, all having masses of $0.08\mathrm{M}_\odot$ one must place them within a volume of roughly 10AU. The findings of Sterzik & Durisen (2003) therefore imply that from a purely dynamical point of view Brown Dwarfs must have formed in extremely compact configurations in order to explain the observed Brown Dwarf binary separations of. It still has to be shown that fragments, which will eventually become Brown Dwarfs, are initially mostly formed within such small volumes. Bate et al. (2002) argue that the radii of the fragments, once the have reached the opacity limit of fragmentation, should be at least 5 AU and their initial separations consequently larger than 10 AU. They also find in their numerical simulation no binary fragments form-

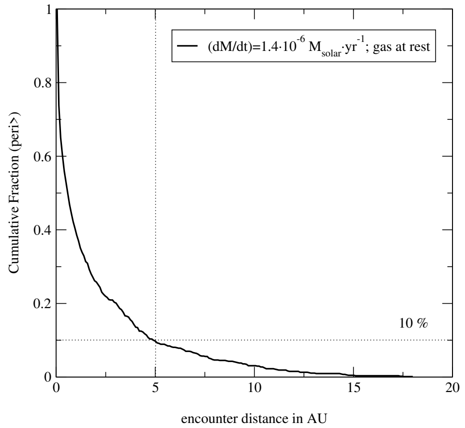

Fig. 4. Fraction of systems that ejected a Brown Dwarf with the last encounter having an encounter distance that is larger than a certain distance d.

ing with a lower initial separation. In our model the same compactness, required for the formation of close binaries, is reached by the loss of energy during accretion. Therefore our fragments can form at much wider separations.

5. Disk Sizes

As we mentioned in section 1, the early ejection of a fragment from an unstable triple system requires a close collision that should truncate its accretion disk to a very small size, thus reducing the disk life-time significantly. Here we want to estimate how large the disk radius should be from our simulations. The size of a disk after a close collision depends mainly on its encounter distance. Fig. 4 shows the fraction of Brown Dwarfs suffering a collision with an encounter distance larger than a certain value before the final decay. As it can be easily seen, only 10% of the Brown Dwarfs had suffered an encounter that was wider than 5AU. Using the approximation that the disk radius after the encounter is half the encounter distance (Hall et al. 1996) this would mean that these Brown Dwarf disks should have radii as low as a few AU. However, one should also bear in mind that this approximation is only strictly valid for parabolic encounters. We find for our triple systems, that at the time of closest approach the majority of the Brown Dwarf orbits are rather hyperbolic, given their velocity and distance. Preliminary results of our simulations of triple collisions, where the ejected body is surrounded by a disk, seem to indicate that the disk radii are larger for these encounter parameter, usually as large as the encounter distance but sometimes much more. Still, the fraction of disks around ejected Brown Dwarfs that exceed a size of 5AU should remain rather low.

6. Conclusions

We have shown numerically as well as analytically that the ejection scenario is, in principle, able to produce many Brown Dwarfs even for initially moderately compact systems. The higher abundance of Brown Dwarfs compared to the analytical estimate of Reipurth & Clarke (2001) is related to the shrinkage of system, which caused the total energy of the triple system to decrease much more steeply. Furthermore, our obtained semi-major axis distribution is in remarkable agreement to the observations of Bouy et al. (2003). Our preliminary results of triple collisions with a disk seem to indicate, that the typical size of a disk around an ejected Brown Dwarf is only of the order of a few AU. However, since accretion rates of young Brown Dwarfs are very low (Muzerolle et al. 2003), it is still possible that Brown Dwarfs can retain even very small disks for a longer time.

Given the high number of single Brown Dwarfs formed in our simulations and the agreement of the properties of our Brown Dwarf binaries with observations, we conclude that the ejection scenario remains a viable option for forming Brown Dwarfs.

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