BROWN DWARF COMPANIONS

Predictions from dynamical decay models

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Abstract Some popular star formation theories envision binary formation as the end product of cloud core fragmentation followed by dynamical evolution within small-N stellar groups. To explore these scenarios, we simulate the dynamical decay of small-N stellar groups by direct orbit integrations and analyze the multiplicity and contents of the stable decay products. Our simulations include a wide range of component masses, including very-low mass stars and brown dwarfs. We find: (1) Brown dwarfs have a low multiplicity and are in general rare companions to stars. (2) When all the small-N clusters are given the same specific energy, there is a significantly smaller mean separation distribution for brown dwarf binaries than for stellar binaries. (3) Brown dwarfs companions to stars with wide (separations > 100 AU) should be members of hierarchical triples, in the sense that the stellar primary itself is expected to be a binary. (4) Spectroscopic binary brown dwarfs should often be the central binary of a hierarchical triple. Although observations tend to support some of these predictions, puzzles remain.

Introduction

Many, if not most, stars are observed to be members of binary or multiple systems. Multiple star properties provide critical constraints on the star formation process, but the detailed mechanisms that define the binary frequency, period, and mass ratios are still poorly understood. Recent observational advances include the determination of multiplicity fractions and distributions across a broad range of primary masses. These observations indicate that (1) the multiplicity fraction among very low-mass stars (VLMs) and brown dwarfs (BDs) appears to be about 15%, significantly lower than it is for higher mass stars, (2) the separation distribution for VLMs and BDs is narrower and is peaked towards smaller values than for solar-type stars (4 AU instead of 40 AU, see Close et al.), (3) the so-called "brown dwarf desert" – a strong deficit of BD companions to stars – extends to periods of a few years (see Halbwachs et al.), and (4) the frequency of BD companions to main-sequence stars at wide separations > 1000 AU is apparently "normal" and in accord with expectations from wide stellar companions (see Gizis et al.).

The observations mentioned above can be interpreted in the framework of dynamical processes occurring in small-N stellar clusters formed from fragmenting cloud cores. In one popular scenario, BDs are substellar objects because they have been ejected from small, newborn multiples that decay through dynamical interactions (Reipurth & Clarke; Reipurth, this volume). This interpretation qualitatively explains some of these observations. More quantitative predictions are possible when the dynamical evolution of small-N clusters is calculated by detailed numerical integrations. We have recently presented statistically robust predictions of BD properties arising from dynamical interaction calculations (Sterzik & Durisen 2003a). In the following, we will discuss our main results regarding VLMs and BDs as members of binary and multiple systems.

1. Brown dwarf companion frequencies

Dynamical evolution within a cluster of point-like objects having diverse masses will favor the formation of a relatively hard binary consisting of the two most massive bodies. The less massive objects will most likely become unbound or remain in a hierarchical orbit around the central binary. This basic dynamical behavior is well-known and is sometimes referred to as "dynamical biasing". If cluster masses are assumed to be drawn randomly from an initial mass function (IMF) extending from the substellar regime to many solar masses, then most VLMs and BDs will become single objects after a short dynamical interplay as unstable members in the primordial multiples. But deviations from strict dynamical biasing are also expected. For instance, the influence of dissipative processes during dynamical evolution (e.g., competitive accretion, disk collisions, and stellar tides) will increase the cross section for binding low mass objects (McDonald & Clarke).

We have also found that the way masses are assigned within clusters can significantly alter the final pairing statistics (Durisen, Sterzik & Pickett). If stellar clusters are formed via hierarchical fragmentation of molecular clouds, the mass of each individual core limits the total mass budget for the cluster of stars it will form. This tends to produce a more uniform distribution of stellar masses within clusters relative to a pure random mass assignment from an IMF. In our statistical treatment of small-N clusters, we refer to this as a “two-step” approach to mass assignment, because a cluster mass is chosen (step one) and then the sum of the chosen component masses (step two) is required to equal it. Using this approach to treat large numbers of clusters while also requiring that the overall stellar and substellar IMF be consistent with observations, we find that cluster decays produce the pairing statistics for substellar objects shown in Table 1.

Table 1. Companion frequencies (*CF*) for two mass ranges of sub-stellar objects (T: .01–.05 $M_\odot$, L: .05–.08 $M_\odot$) as a function of spectral type of the primary. The mass ranges for the primary stars are indicated.

Spectral type Mass range [$M_\odot$]	L .05–.08	M- .08–.27	M+ .27–.47	K .47–.84	G .84–1.2	F+ >1.2
CF(L)	.02	.04	.03	.03	.01	.01
CF(T)	.06	.05	.04	.03	.02	.01

Our dynamical evolution simulations yield a relatively low percentage of substellar objects as bound members in binary or multiple systems. In fact, in our calculations, only about 8% of L-type BDs and only 2% of all early type stars have BD companions. The observed BD companion frequency of about 15% for VLMs (Close et al.), though somewhat higher than the 9% entry for M- in Table 1, is consistent to within the uncertainties of both the theoretical and empirical numbers. The binary separations for the Close et al. sample of VLMs and BDs, with typical masses of $0.1M_\odot$, are observed be 10 times smaller than for $1M_\odot$ stars, which agrees well with results from our simulations when we assume that all clusters have similar specific energy. This lends some support to arguments we have made (Sterzik & Durisen 2003b) in favor of this assumption.

Although considerable efforts have been undertaken to determine the dependence of BD companion frequencies on their primary mass, it is not easy to compare the predicted and observed fractions quantitatively. The first BD, Gl 229B, was actually found as a visual companion of an M1 star. Initially, because observers expected the frequency of BD companions to be as high as that for stars, intensive searches by various research groups were conducted, but only a few visual BD companions have been found. The BD desert is characterized by a firm upper limit of $<1\%$ for the fraction of close BD companions to solar-type stars with orbital periods below one year (Halbwachs et al.).

2. Peculiar brown dwarf systems

We will now discuss more exotic configurations that are rare, both in observations and in the simulations. They nevertheless give important clues concerning the formation dynamics of BDs.

2.1 Brown dwarfs in higher-order multiples

Triple and higher-order systems produced in our decay calculations add up to more than 11% of all systems. About one-third of those triples contain at least one BD and fully 10% contain two BDs. The latter is a non-trivial fraction. We infer that multiple BD companions to stars should be found at the percent level. The preferred configuration is a close BD companion to a primary star with a mass ratio which is not too extreme. The third BD companion populates an outer hierarchical orbit. Typical outer orbit sizes are about ten to a hundred times larger than those of the inner orbit. It is interesting to note that at least one configuration has been found in which a close BD binary (GJ569B, semi-major axis ≈ 1 AU) orbits an M2 type primary at a distance of 50 AU (Martin et al.). According to our simulations, a significant minority (about 10%) of cases where we find two BDs in triples actually do have such configurations, and a few of these match the observed system parameters surprisingly well.

Genuine BD triple systems, i.e., triples composed entirely of BDs, are rare in the simulations and make up only about 0.2% of all simulated triple systems. Observations will sooner or later find dynamically stable BD multiples, if they exist, because there should be a strong detection bias in magnitude-limited surveys.

2.2 Wide brown dwarf companions

Despite the established BD desert at very narrow separations and the apparent void of BD companions in the intermediate separation range (10 AU to 1000 AU), L and T-dwarf common proper motion companions to M to F main-sequence stars with separations > 1000 AU seem to be comparatively common (Gizis et al.). Figure 1 illustrates the dependence of the mass ratio on separation for different types of BD companions based on our simulations. With few exceptions, BD binaries (small filled circles) have narrow separations, typically below 10 AU. Their mass ratios are evenly distributed. BDs as secondaries to stars (large open circles) tend to have a similar separation distribution but preferentially populate the lower mass ratio regime. Only a few low mass ratio binary systems have larger separations. BDs as outer components of triple systems are plotted as large, filled circles. In general, they have large separations and small mass ratios. According to this, we expect that stellar primaries of wide, low-q BDs will mostly turn out to be binaries or higher-order systems. Observations are needed to test this prediction.

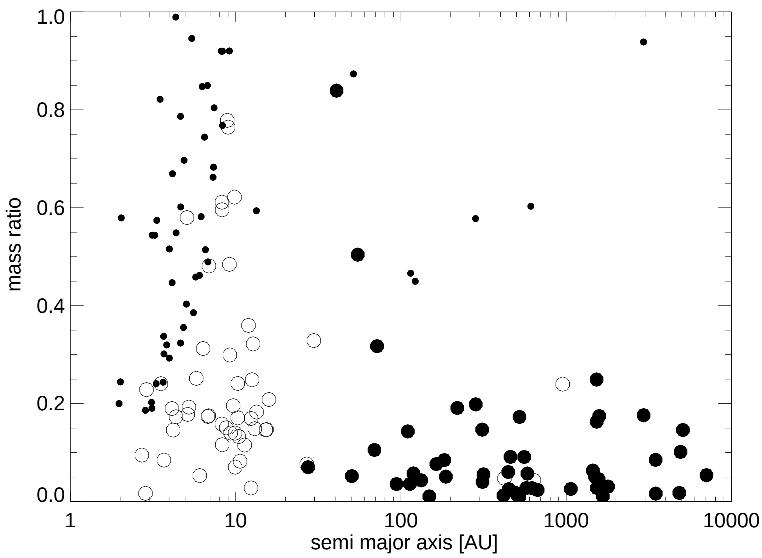

Figure 1. Simulated mass ratio versus semi-major axis distribution for various BD secondary populations. Binary BD: small filled circles; BD companions to stars: large open circle; BD companions in triples: large filled circles.

2.3 Very close brown dwarf binaries

Only three spectroscopic VLM or BD pairs are known, namely PPl15, 2M0253 and 2M0952 (Basri & Martin, Reid et al.). The formation of spectroscopic binaries of any mass is still an enigma. Dynamical interactions in small-N clusters cannot alone account for them. It is interesting to note that spectroscopic binaries tend to occur more often in hierarchical systems (Tokovinin & Smekhov; Melo). One way to shrink an inner orbit is through the combined action of the Kozai effect and tidal friction in hierarchical triples (Kiseleva, Eggelton & Mikkola). A perpendicular orbit configuration (which is required to start the process) occurs frequently in decaying few-body clusters (Sterzik & Tokovinin). We speculate that an enhanced fraction of very close BD binaries might be found in hierarchical triples. This is another prediction that awaits observational tests. We note, however, that the known spectroscopic BD pairs do not seem to be accompanied by a third, low-mass system member. Their origin remains puzzling.

3. Summary

We use numerical integrations to simulate the dynamical evolution and decay of small-N stellar clusters in fragmenting cloud cores. The statistical analysis of stable end products containing VLMs and BDs as members of multiple systems yields the following results: (1) Brown dwarfs have a low multiplicity and are in general rare companions to stars. (2) Brown dwarf binaries have smaller mean separations than stellar binaries. (3) Spectroscopic (sub-)stellar binaries cannot be formed by dynamical interactions alone. (4) Wide brown dwarf companions tend to be members of hierarchical triple systems. (5) Triples formed by dynamical interactions have preferred orbit configurations that could lead to significant orbital evolution (shrinkage) of the inner binary.

Results (1) and (2) are corroborated by observations. An observational analysis of primaries having wide BD companions will reveal the correctness of prediction (4). The presence of spectroscopic binaries (3) is problematic. Processes related to (5) might be a way to explain them.

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