Origins: From the Protosun to the First Steps of Life
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Circumstellar disk fragmentation and the origin of massive planetary companions, brown dwarfs, and very low-mass stars

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Abstract. The low-mass end of the initial mass function remains poorly understood. In this mass range, very low-mass stars, brown dwarfs, and massive planets are able to form through a variety of physical processes. Here, we study the long-term evolution of disk-fragmented systems around low-mass stars, for the epoch up to 10 Myr (the typical lifetime of an embedded cluster) and up to 10 Gyr (the age of the Milky Way). We carry out N-body simulations to study the decay of disk-fragmented systems and the resulting end products. Our simulations indicate rapid decay and frequent physical collisions during the first 10 Myr. We find that disk fragmentation provides a viable mechanism for explaining hierarchical triple systems, the brown dwarf desert, single and binary brown dwarfs, and very low-mass binary systems in the solar neighbourhood.

Keywords. Stars: formation, stars: low-mass, stars: brown dwarfs, galaxy: solar neighbourhood, planets and satellites: general

1. Introduction

Brown dwarfs, very low-mass stars, and very massive planets (hereafter, low-mass objects; LMOs) are among the most abundant objects in the Milky Way. Their faint luminosities make it challenging to study physical and kinematic properties of even the nearest neighbours of the Sun. These LMOs cover an interesting transition region between (or including) the highest-mass planets that can be formed through core-accretion and the lowest-mass stars that can form through core collapse in dense molecular clouds. Various mechanisms have been proposed to explain the origin of LMOs in the Galactic field, including extrapolations of the above-mentioned mechanisms into the LMO regime, and the mechanism of circumstellar disk fragmentation. The LMOs discovered in our Galaxy likely represent a combination of all these processes. In this work we explore the hypothesis that all LMOs are a result of the disk fragmentation process. The study presented here is described in detail in Li *et al.* (2015) and Li *et al.* (2016).

2. Modelling the outcome of circumstellar disk fragmentation

Stamatellos & Whitworth (2009) carried out an ensemble of smoothed-particle hydrodynamics simulations to study disk fragmentation among $0.7\,M_\odot$ stars with massive circumstellar disks. Their simulations are carried out until most gas is dissipated. We carry out 9000 N-body simulations, for which the initial conditions are statistically identical to the outcome of Stamatellos & Whitworth (2009)'s simulations. We carry out simulations of these few-body systems up to 10 Gyr. The results are analysed in detail for the period up to $t = 10$ Myr, which corresponds to the time in the embedded cluster, and subsequently up to 10 Gyr, roughly the age of the field star population in the Milky Way.

3. Implications for the Galactic field star population

Most of the disk-fragmented systems are highly unstable and decay within a million years, after which the number of merging and escape events reduces exponentially with time, until a roughly stable situation is reached after a Gyr. Despite the large initial number $(3-11)$ of companions per system, $\sim 30\%$ of the primary stars end up as single, $\sim 60\%$ with one companion, $\sim 10\%$ with two companions, and a small fraction ($\lesssim 0.1\%$ with more than two companions. Most companions escape, while $20-25\%$ of the host stars experience physical collisions with companions. Planetary-mass and brown-dwarf companions rarely obtain orbits smaller than 50 au, while low-mass stars do appear in this regime. Systems with more than one companions remaining show both planetary-type and hierarchical configurations, with period ratios in the range $10-10^4$ and $10-10^3$, respectively. The hierarchical systems (with companions orbiting a common center of mass in orbit around the host star) are often highly inclined or retrograde. Ejected companions typically have velocities below $5\,\mathrm{km\,s^{-1}}$. Among these, $1.5-5\%$ escapes as low-mass binary systems with semi-major axes of $10-50$ au that often contain one or two brown dwarfs.

Our results contribute to explaining the properties of the stellar population in the solar neighbourhood. Among the 77 known objects within 5 pc of our Sun, 88% are of stellar type late-K or M or brown dwarfs. Among these 77 objects, 40 are single, 13 are in binaries, and 4 are in triple systems. The vast majority of these binaries and multiples consists of, or contains, very low-mass stars and brown dwarfs. Notable examples include GJ 1245 and EZ Aquari, which are both very low-mass triples, and Epsilon Indi, which consists of a main-sequence star with a double low-mass companion. Other examples of such hierarchical double-companion systems include HIP68532 and HIP69113 (Kouwenhoven *et al.* 2005, 2007). Such types of systems are regularly observed in our simulations, but are difficult to form through conventional (core-collapse) star formation processes. The challenge of explaining the origin of the stellar and binary population still exists, but disk fragmentation provides a viable explanation for the abundance, binary/triple properties, and kinematics of very low-mass stars and brown dwarfs in the solar neighbourhood.

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