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Research Note

On the luminosity ratio of pre-main sequence binaries

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Abstract. Assuming random pairing of single stars from the same fundamental IMF as a good scenario for pre-main sequence binary formation, we show how to derive the mass ratio distribution and the fundamental IMF from the observational luminosity ratio distribution, taking into account pre-main sequence evolution. We also determine how the detectability of a brown dwarf as a companion relates to its own mass, the mass of the primary, and the age of the system. Our calculations suggest that for a particular mass of a brown dwarf companion, there is a "best age" for detection, namely when the brown dwarf is in its deuterium burning phase. Clusters with ages 10^6 to 10^7 years would be most favorable to catch brown dwarfs at their "best age".

Key words: binaries: visual – stars: pre-main-sequence – stars: low-mass, brown dwarfs

1. Introduction

In recent years, an increasing body of observational data on pre-main sequence (PMS) binaries has been accumulated (see reviews by Mathieu 1994, Zinnecker & Brandner 1997). It is clear now that the components of PMS binaries are 'coeval', i.e. formed at the same time (Mathieu 1994; Brandner & Zinnecker 1997; Hartigan et al. 1994). It has also been widely discussed that these young binaries form by random pairing in groups or clusters (Leinert et al. 1993; Prosser et al. 1994; see also Bonnell & Kroupa 1998).

One of the important parameters is the mass ratio, which is not easily observable. The luminosity ratio of the components *is* however observable, and therefore we must use some relation between these two quantities to draw the former from the latter. We cannot use standard mass-lumimosity relations for these stars, due to ongoing PMS evolution of the components.

Here we present simple analytical formulae that enable us to relate PMS binary mass ratio distributions and luminosity ratio distributions. We then follow this with a more exact treatment using PMS evolution tracks, which include the effects of deuterium burning. We present simulations of the evolution of the luminosity ratio of coeval binary components, if one member of the young binary system is actually a brown dwarf (i.e. $\leq 0.08 m_\odot$). This provides a useful guide to the detectability of brown dwarfs (BDs) in young binary systems, since the closer the luminosity ratio is to unity, the higher is the detectability, i.e. the probability to detect the second component. Note that *young* BDs are not yet cool enough to considerably change their spectral energy distribution from a black body.

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2. Luminosity ratio distributions. Analytic approach

a) It can be shown (Zinnecker & McCaughrean 1991) that a contracting young PMS star, descending along a convective vertical track in the HR diagram, obeys, to zeroth order, the following relation between mass and luminosity:

$$L \sim m^{8/5} t^{-2/3}, \quad (1)$$

and, consequently, for a coeval pair, we have

$$\frac{L_2}{L_1} \sim \left(\frac{m_2}{m_1}\right)^{8/5}. \quad (2)$$

b) It can also be shown (Piskunov & Malkov 1991) that random pairing of single stars from the same fundamental IMF (here taken for simplicity to be represented by Salpeter (1955) law with a slope $-\alpha$) leads to a mass ratio distribution of

$$\eta(q) \sim q^{\alpha-2}. \quad (3)$$

where $q = m_2/m_1$.
c) From these two equations, we derive for the luminosity ratio distribution

$$\zeta(b) \sim b^{\beta}, \quad (4)$$

where $b = L_2/L_1, \beta = (5\alpha - 13)/8$. For a Salpeter value of $\alpha = 2.35$, we have $\beta = -0.16$, so that $\zeta(b)$ is slightly decreasing towards unity. To obtain a flat luminosity ratio distribution, α should be 2.6.

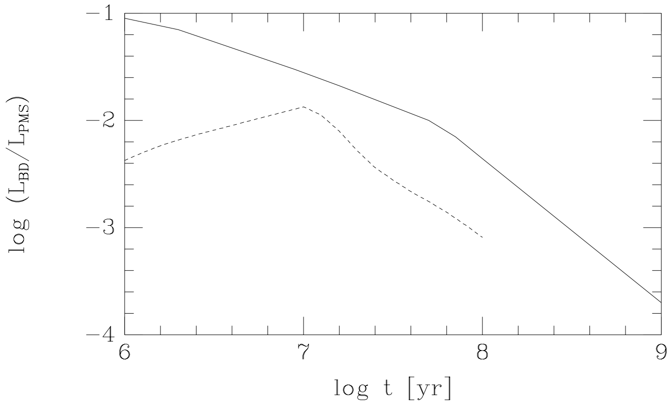

Fig. 1. Luminosity ratio evolution of a pair with masses 0.50 and 0.02 $m_{\odot}$. The solid line gives the Brandner et al. (1997) prediction; the dashed line shows our calculation using D'Antona & Mazzitelli (1994) tracks.

Similarly, for MS stars, taking for their mass-luminosity relation roughly $L \sim m^2$, we have $\beta = (\alpha - 3)/2$. Again, for $\alpha = 2.35$ we have $\beta = -0.32$, a steeper function than in the PMS case.

Consequently, in order to properly restore $\eta(q)$ and the IMF from observational luminosity ratio distribution for PMS stars, we need to take into account PMS evolution (i.e. the age). Note that our estimates are not valid for pairs containing at least one non-convective component, i.e. the mass of the primary and the age of the system should satisfy, (according to D'Antona & Mazzitelli 1994 tracks), the following approximate relation

$$\log t < -2.2 \log m_1 + 7 \tag{5}$$

for $0.6 < m_1 < 2.5 m_{\odot}$, where m_1 is the mass of the primary.

3. Young pairs containing a brown dwarf

The probability of detecting a brown dwarf (BD) in a binary system depends on the luminosity ratio of the system, and the latter is a function of the masses of the components and of the system age. Thus, the probability represents a hypersurface in (m_1, m_2, t) space. For a given detectability limit (e.g., luminosity ratio not less than 0.03), if one fixes one of the parameters, say m_1, one can find out a relation between two others.

As predicted by Brandner et al. (1997), the luminosity ratio of a young pair, containing an M star with $m = 0.5 m_{\odot}$ and a BD with $m = 0.02 m_{\odot}$, is high enough for the BD to be detected for ages up to about 10^7 years with direct imaging in the near-infrared (using, e.g., HST/NICMOS or ground-based adaptive optics).

It can be seen from Fig. 1, that our calculation using the D'Antona & Mazzitelli (1994) tracks disagrees with the prediction of Brandner et al. (which is based on predictions of the evolution of the luminosity of a BD by Black 1980 and Burrows et al. 1995) of a high luminosity ratio for an age of 1 - 10 Myr. According to our new plot, the luminosity ratio increases in this range due to a decrease of the luminosity of the primary and the

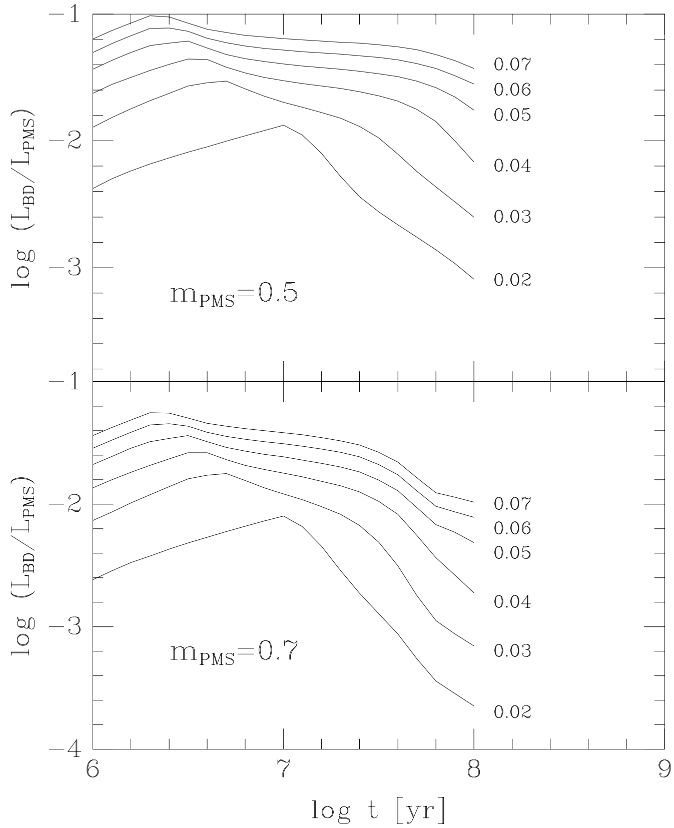

Fig. 2. Theoretical luminosity ratio evolution of pairs with primary mass $0.5 m_{\odot}$ (top panel) and $0.7 m_{\odot}$ (bottom panel). Masses of secondaries are also indicated.

approximately constant luminosity of the BD due to deuterium burning (see D'Antona & Mazzitelli 1985). From the point of view of BD detectability, the best ratio is reached at 10 Myr (see Stringfellow 1991 for isolated BD), although even then, the ratio is still only $\sim$ 0.01, and thereafter the luminosity of the BD decreases rapidly.

However, other combinations of the primary and secondary (i.e. BD) masses can be more promising for BD detection. We have calculated a set of luminosity ratios for 0.7 and 0.5 $m_{\odot}$ primaries and different (0.02 - 0.07 $m_{\odot}$) secondary masses. As can be seen from Fig. 2, the luminosity ratio is in the range of 0.1 - 0.03 for pairs with component masses 0.7 & 0.05 $m_{\odot}$ (and higher) or 0.5 & 0.04 $m_{\odot}$ (and higher). In the latter case, the luminosity ratio stays high enough at ages of 10^6 to even 10^8 yr such that the probability of detecting a BD is improved. Note that, to zeroth order, our conclusions are in qualitative agreement with Eq. (2): Zinnecker & McCaughrean's (1991) estimates cover ages in the range $10^5 - 10^7$ years and ignore deuterium burning.

4. Conclusions

Under the assumption of random pairing as a good scenario for binary formation, it is shown how the observational luminosity ratio distribution relates to the mass ratio distribution and the fundamental IMF. We have also found how the luminosity ratio between a brown dwarf and its primary PMS relates to the brown dwarf mass, the mass of the primary, and the age of the system. Our calculations suggest that for a particular mass of a brown dwarf companion, there is a "best age" for detection, namely when the brown dwarf is in its deuterium burning phase. Clusters with ages 10^6 to 10^7 years would be most favorable to catch brown dwarfs at their "best age".

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