# Multiplicity at the very low mass end of the H-R diagram

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**Summary.** We review the properties of multiplicity of very low mass stars and brown dwarfs in different environments and at different ages. We will compare the main results of surveys performed in the field, where the objects are relatively old (1–5 Gyrs) and isolated, in the Pleiades young (∼120 Myr) open cluster, and in the young (∼5 Myr) Upper Scorpius OB association (USco). While the field and Pleiades populations seem to have very similar properties, the preliminary results obtained in Usco seem to show significant differences. If confirmed, it would mean that the phenomenons responsible for the "final" properties of multiplicity of ultracool dwarfs (spectral type later than M6) are still at work at the age of Usco, but are already over at the age of the Pleiades. We will also discuss the observed properties in the context of the predictions of the most recent models of formation and evolution.

## 1 Introduction

Multiple systems are important testimonies of the formation and evolution of a population of astrophysical objects. The properties of the out-coming population, and in particular the properties of multiplicity, depend directly on both the mechanisms involved and on the initial conditions. Little is known about the formation processes responsible for the formation of very low mass stars and brown dwarfs. In order to address these questions, a large number of authors have performed detailed studies of the properties of multiplicity of very low mass stars and brown dwarfs over the last 5 years (see e.g [1, 25, 27, 23, 15, 3, 4, 6, 8, 9, 10, 17, 19, 34]). The major observed properties, such as the apparent lack of wide multiple systems at evolved ages and the possible preference for equal-mass systems, provide important constraints for the models of formation and evolution. The relatively low multiplicity fraction observed in the field and in the Pleiades for visual binaries still needs to be complemented by spectroscopic studies before a meaningful comparison can be made with the predictions of the models. In section 2, we will review in details the results obtained in the field, then in sections 3 and 4, we will compare it to the properties observed in the younger Pleiades cluster and Usco OB association.

Finally in section 5 we will give a brief overview of other types of multiple systems including ultracool dwarfs, and in section 6, we will discuss the comparison between these different environments/ages, and the predictions of the most recent models of formation and evolution.

## 2 Multiplicity of ultracool dwarfs in the field

The study of multiplicity of ultracool dwarfs in the field has been an intense field of research over the last few years. Several teams have been doing a lot of work in this field. Table 1 gives a very brief overview of the different studies reported in the literature on that topic over the last two years. The different results are consistent, as one could expect since they use overlapping samples coming from the 2MASS, SDSS and DENIS surveys.

**Table 1.** Study of multiplicity among field ultracool dwarfs

| Authors | Spectral range | Binary Fraction |
|---|---|---|
| [9] | M8–L0.5 | 15±7% |
| [15] | M8–L5 | 15±5% |
| [6] | T5–T8 | $9^{+15}_{-4}$% |
| [4] | M7–L8 | 15±5% |
| [34] | M6–M7.5 | $9^{+4}_{-3}$% |

Figure 1 shows the multiplicity fraction (defined as the number of multiple systems divided by the total number of objects) as a function of the spectral type. Although it is strictly incorrect to quantitatively compare these results, because they were obtained under very different conditions, covering very different ranges of mass ratios and separations, we observe a clear trend for a decreasing multiplicity fraction toward lower effective temperatures.

Figure 2 shows the distribution of mass ratio of ultracool field dwarfs, compared to that of more massive early-M dwarfs from [11, 21] and to that of F–G dwarfs from [12]. There is an apparent preference for equal mass systems among ultracool binaries. This result is only preliminary and must be considered with great caution, because the sample of ultracool dwarfs was unfortunately limited in magnitude rather than in volume (see e.g [15, 4]), implying a strong bias toward equal-mass systems. Assuming it is real, it would mean a great difference with the early-M dwarfs, which distribution is rather flat, only slightly increasing toward mass ratios of unity, and with more massive F–G dwarfs, which show a peak at about $q$ =0.4.

The distribution of separation of ultracool dwarfs gives the most peculiar and constraining parameter. Figure 3 compares the distribution of separations of ultracool dwarfs to that of F–G dwarfs reported by [12]. The shape is similar (gaussian like), with a peak at 8 AU. While the different surveys were more sensitive to multiple systems with large separations, they did not discover any companion at separation greater than ∼20 AU, indicating a strong cut-off in the distribution of separation and a lack of wide multiple systems. This remarkable difference with

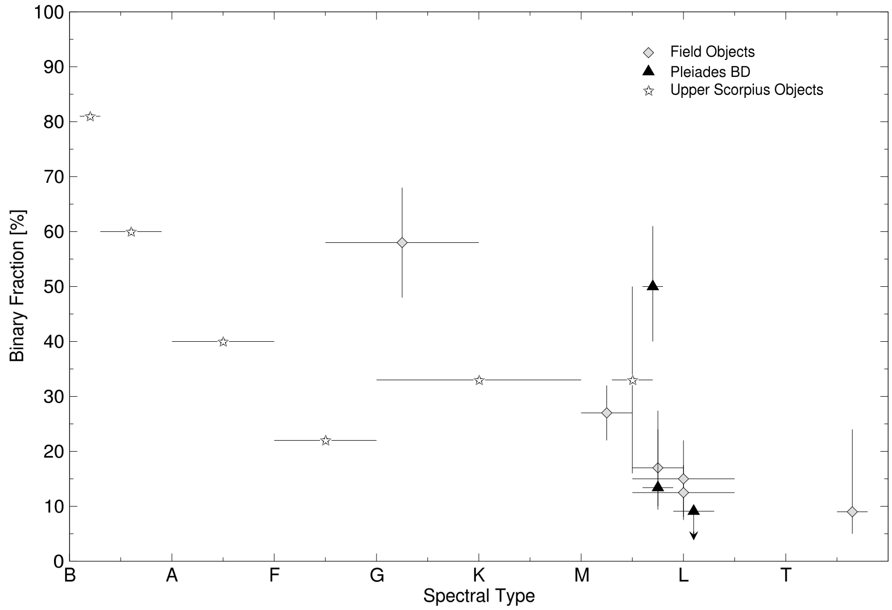


**Fig. 1.** Binary fraction vs Spectral type. Although these results have been obtained under very different conditions, and should therefore not be compared, there seems to be a trend for decreasing binary fraction toward cooler effective temperatures.

more massive objects gives major constraints on the models of formation and evolution. To date, only few wide multiple systems have been observed. [26] first reported a binary with a separation of 30 AU, just above the cut-off. [14] and [16] simultaneously reported another interesting binary at a separation of ∼30 AU [31] recently reported another of these objects with a separation of 30 AU. The most interesting wide-binary was recently reported by [2], with a separation over 200 AU. Another candidate was reported by [20], with a separation of 240 AU. These two objects really contrast with any other companion ever observed, at a separation ∼8 times larger than the largest multiple systems reported to date.

## 3 Multiplicity of ultracool dwarfs in the Pleiades open cluster

The study of multiplicity of ultracool dwarfs in the Pleiades open cluster has also been an intense field of research. One of the first brown dwarfs discovered in the Pleiades was a spectroscopic binary (PPL15, [1]). Table 2 gives a brief overview of the different results obtained over the last few years.

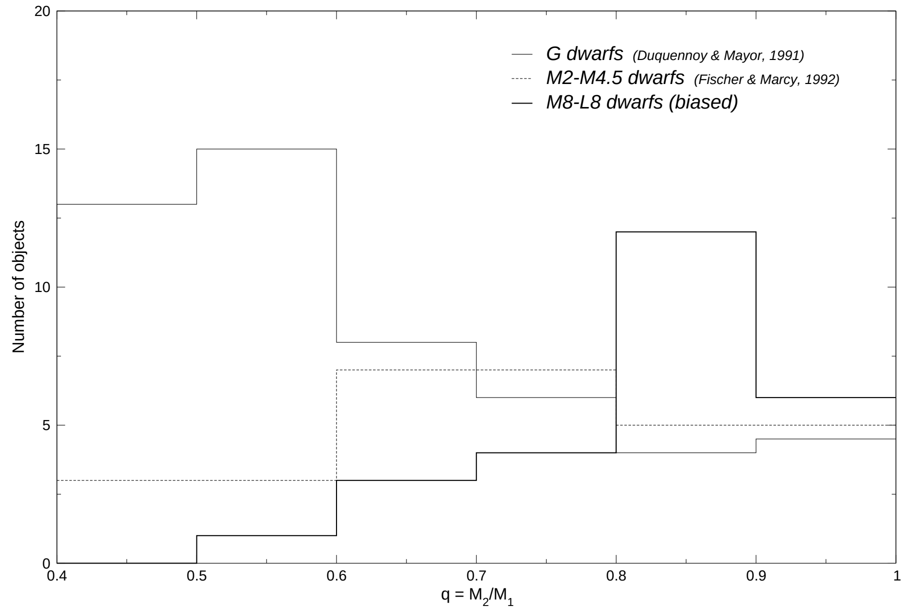


**Fig. 2.** Distribution of mass ratio of field ultracool binaries, compared to that of G and early-M dwarfs. There seems to be a preference for equal mass ultracool binaries, but this result should be considered with caution since the corresponding sample was biased toward equal mass systems.

### 3.1 Binary Fraction

The **visual** binary fractions reported successively by [26, 23] and [5] are consistent one with each other. The first upper limit found by [26] at less than 3% only is not so surprising. Considering the cut-off at about 20 AU in the distribution of separation observed for field objects, and assuming that the properties in the field and in the Pleiades are similar, one indeed expects to find only very few multiple systems at separations greater than the limit of sensitivity of their HST/NICMOS survey (27 AU). The next results obtained at higher angular resolutions with WFPC2 [23] and ACS [5] are consistent one with the other, but disagree completely with the **photometric** binary frequency reported by [32]. Using colour-magnitude diagrams, they report a binary fraction as high as 50%. The 3 surveys covered similar ranges of mass ratios. The discepancy could therefore only be due to the limit of separation of the HST surveys. If confirmed, this difference would mean that most of the brown dwarf binaries in the Pleiades are spectroscopic binaries. The values obtained with the HST surveys are only lower limit on the overall binary fraction. The spectroscopic binary fraction has not been measured neither in the field nor in the Pleiades, but statistical studies have shown that it could be as high as ∼35% ([28]), leading to an overall binary fraction consistent with that reported by [32]. We nevertheless suspect the photometric survey to suffer, among other things, from a significant contamination by foreground objects, leading to an overestimated binary fraction. Similar photometric surveys using 3 colours have been shown to give a

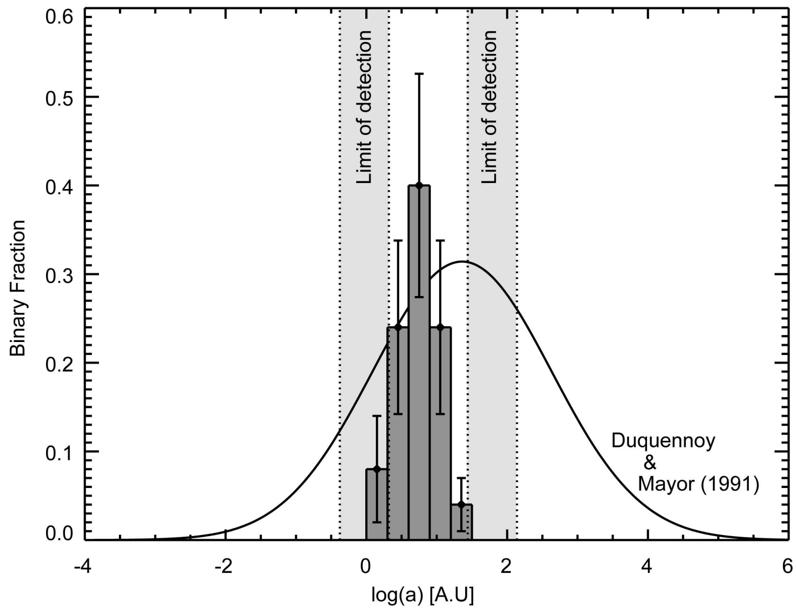


**Fig. 3.** Distribution of separation of field ultracool binaries, compared to that of G dwarfs from [12].

contamination as high a 20% ([29]). Surveys looking for spectroscopic binaries will be the main challenge of the coming years in order to precisely and accurately determine the properties of ultracool binaries over the whole separation range.

Figure 1 shows the multiplicity fraction reported in the Pleiades by [5] and [32]. The [5] values are very similar to that observed in the field for objects with similar masses ([6]).

**Table 2.** Study of multiplicity among Pleiades ultracool dwarfs

| Reference | Spectral range | Binary Fraction |
|---|---|---|
| [26] | M5–L0 | <3% for sep.>27 AU |
| [23] | M6–M9.5 | 15±5% for sep.>7 AU |
| [32] | M6–M8 | 50±10% photom. |
| [5] | M6–M9 | $13^{+14}_{-4}$% for sep.>7 AU |
| [5] | M9–L3 | <9.1% for sep.>7 AU |

Finally, there seems to be a difference in the multiplicity fraction within the brown dwarf regime itself. Table 2 shows that the binary fraction for M6–M9 dwarfs might be slightly higher than that for cooler objects between M9-L3, although the small number statistics and the large error bars do not allow to draw any firm conclusion.

Since only few multiple systems have been discovered in the Pleiades, it is not possible to perform any statistically meaningful analysis of the distribution of mass ratio and separations. One must nevertheless note that all the multiple systems resolved have separations less than 12 AU, and all have mass ratio close to unity. If confirmed, it would mean that the properties of multiplicity of ultracool dwarfs in the Pleiades are very similar to that of older isolated field objects. Any mechanism responsible for these properties should therefore have occurred before the age of the Pleiades.

# 4 Multiplicity of ultracool dwarfs in the Upper Scorpius OB association

Two studies have been recently performed in the Upper Scorpius OB association, one with ACS on-board HST looking for companions among a sample of 12 M5.5–M7.5 dwarfs ([19]), and one with adaptive optics on the VLT among a sample of 58 M0-M7.5 dwarfs. In both cases the targets are confirmed members of the association. As shown in Figure 4, the two studies have similar sensitivities, although NACO proves to give a better resolution at closer separation. The HST study used 3 optical colours which were used to perform a preliminary selection of non-physical pairs, while in its current state the NACO study used only K-band images, therefore with no mean to distinguish real companions from foreground/background sources. The HST optical colours (V, $i'$ and $z'$) providing only poor constraints, second epoch measurements proving common proper motion and spectroscopy are required in both studies to confirm the multiplicity of the candidates.

[19] have performed a search for multiple systems among a sample of 12 bona-fide brown dwarfs using HST/ACS. They resolve 3 candidates, leading to a raw observed **visual** binary fraction of 25±14%, and deduce a binary fraction corrected for biases of 42%. This value is clearly higher than that obtained in the field and in the Pleiades, and if confirmed, would indicate that the dynamical evolution is still on-going at the age of Usco (∼5 Myr).

In June 2005 we resolved 9 binary candidates among the 58 targets of our NACO sample, leading to an observed binary fraction of ∼15%, consistent within the large error bars with the one reported by [19], eventhough it covers a larger spectral class range. Considering only the 28 objects of our sample within the same spectral class range as [19], we resolve 5 binary candidates among a total sample of 28 objects, leading to a slightly higher observed binary frequency of ∼18%. These values must be corrected for biases, which has not been done at the time this proceeding is written, since most of the candidates still need confirmation by second epoch imaging and spectroscopy.

Two wide binary candidates (separation of 0.9″, corresponding to ∼120 AU at the distance of USco) have been observed with LIRIS at the WHT in La Palma. In both cases the companions have near-infrared J, H and K colours consistent with a spectral type similar to that of the primary. We acquired a spatially resolved spectrum for one the two, which confirm that the companion has the same spectral type as the primary within 1 subclass. The probability to find two objects with similar spectral class within 1” being extremely low, we consider that these objects are physical pairs. The first one still requires spectroscopic measurements to confirm

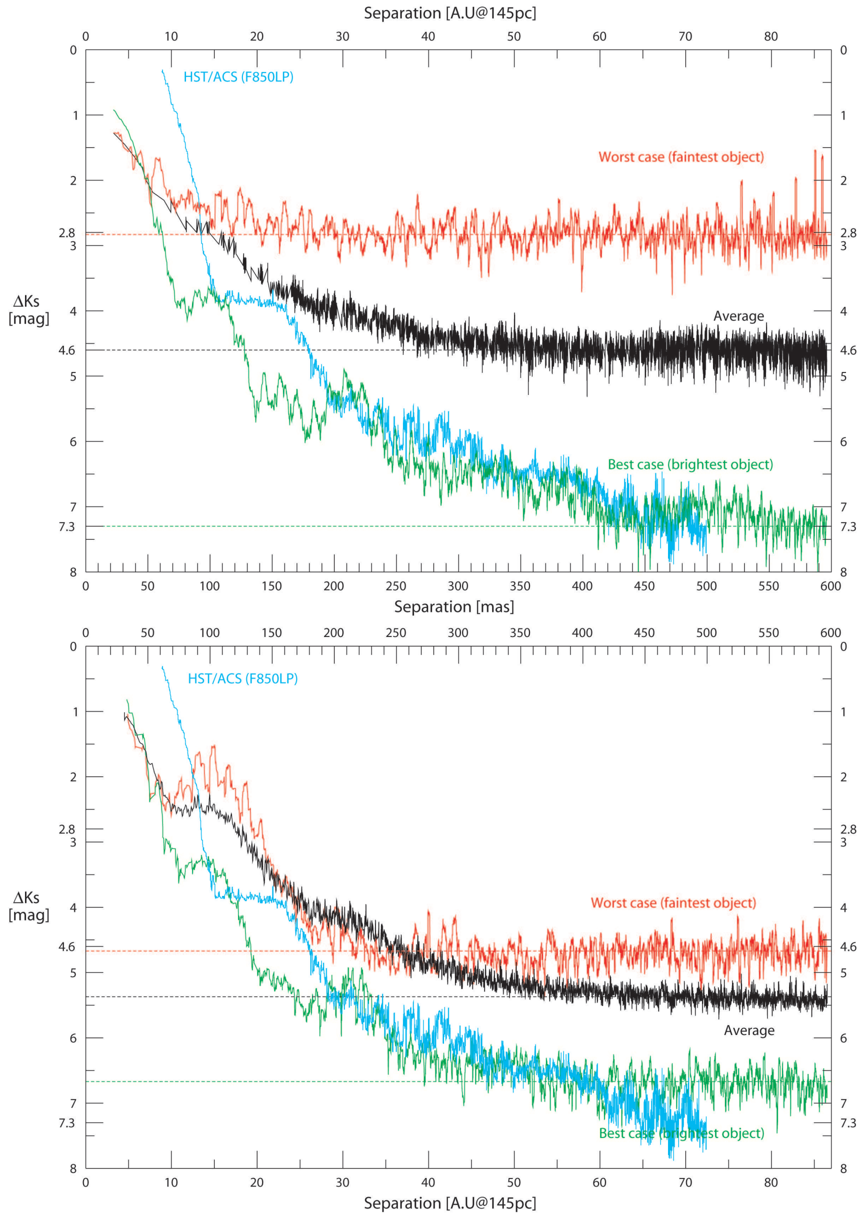


**Fig. 4.** Sensitivity of the NACO and HST ([19]) studies of Upper Scorpius VLMS and BD. At shorter separation, diffraction limit on an 8 m telescope wins. Moreover, the Ks band images of NACO are much more sensitive to low mass companions than the optical ACS images.

its multiplicity, but the probability to find an object with consistent near-infrared colours within 1" is also very low. With separations of ∼120 AU, these two objects indicate that the frequency of wide multiple systems among ultracool dwarfs might be higher than that observed in the field or in the Pleiades.

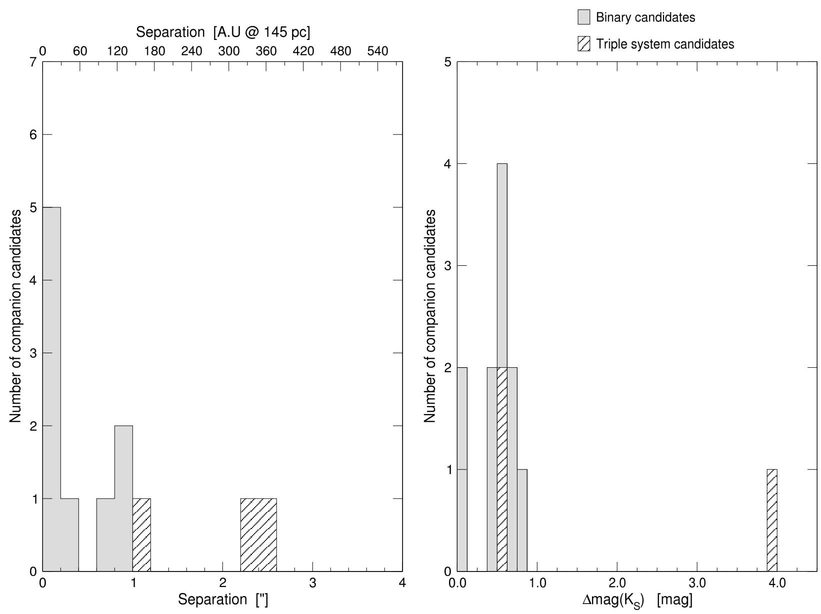


**Fig. 5.** Distribution of separations and of difference of magnitude (Ks) of the sample of multiple systems discovered with NACO in USco.

All three candidates resolved by [19] have mass ratios close to unity. Figure 5 shows the distribution of difference of magnitude of the binary candidates we resolve with NACO. It shows that all objects have small differences of magnitude (less than 1.5 mag). This effect must be real, since we were sensitive to difference as large as 7.3 mag, and it indicates that most of the candidates have mass ratios close to unity, as observed in the field and in the Pleiades. Second epoch images confirming the multiplicity of the candidates are required to confirm this result.

## 5 Ultracool dwarfs in other types of multiple systems

Ultracool dwarfs have been found in many other types of multiple systems. [13] have observed a white dwarf-ultracool dwarf pair. Oppenheimer et al. (private comm.) have recently reported a new case of a brown dwarf orbiting an A star. Surveys around G-dwarfs have found few ultracool dwarf companions and the enigmatic "brown dwarf desert". Several multiple systems of higher orders including very low mass stars and brown dwarfs companions have been reported to dates, such as GJ

569B ([18]), GJ 900 ([22]) and HD 130948 ([33]). The properties of all these multiple systems give very important constraints on the formation and evolution of these objects, and possibly indicate that ultracool dwarfs form in several competing or complementary ways.

## 6 Discussion

The properties of visual multiple systems among the Pleiades and field ultracool dwarfs appear to be very similar, while there seems to be major differences between these two and the population of young Upper Scorpius very low mass stars and brown dwarfs. If, as it is thought, most objects are born in OB associations like Upper Scorpius, this would mean that dynamical evolution is still actively on-going at the age of Upper Scorpius (∼5 Myr). In particular, the larger fraction of wide multiple systems observed in Upper Scorpius must be disrupted within the age of the Pleiades (∼120 Myr), since only few of them are reported either in the Pleiades or in the field.

The two most accepted scenarios of formation of very low mass stars and brown dwarfs are the so-called "star-like" model, which assumes that very low mass stars and brown dwarfs form like stars from the contraction of a molecular cloud, and the "ejection" models, which assume that ultracool dwarfs are ejected embryos from protostellar clusters (see e.g contribution by Delgado-Donate in this volume, and references therein). Although these two models are sometimes presented as distinct and independent mechanisms occurring in separate places, recent hydrodynamical simulations show that the contraction of a molecular cloud leads to the formation of ultracool objects via both processes. The real question of the origin of ultracool dwarfs is therefore not so much which of these two processes is at work, but what are their respective efficiencies, and under which conditions. The properties of multiplicity can address this question, and tentatively give hints of the answers. Together with the growing number of wide multiple systems reported recently by various authors in the field ([24, 31, 14, 16, 2]) and in young associations ([20, 7, 30]), the wide multiple systems we report in USco challenge the models of formation involving gravitational interactions and ejection. That scenario cannot produce such a significant number of wide multiple systems, since they would be destroyed very early in the process of ejection. Although certainly at work, this mechanism can probably not explain the formation of the majority of the very low mass objects. On the other hand, the star-like model fails to explain the cut-off in the distribution if separations at evolved ages, as well as the preference for equal mass systems. While important and fast progresses have been made both on the theoretical and observational sides over the last five years, it seems still too early to draw any firm conclusions regarding the validity of the different models of formation and evolution. These models have not reach yet a level of sophistication allowing direct comparisons with the observations, while the observations must provide improved statistical studies, spanning a larger range of separations and of mass ratios, on larger samples, and should be extended to more environments (young, evolved, dense and loose associations, as well as isolated objects).

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