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About the multiplicity of M dwarfs.

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Abstract

Stellar multiplicity is a common consequence of the stellar formation process. Low-mass stars are the prime constituent of the nearby stellar population, with late-type accounting for the majority of the hydrogen-fusing objects in the Solar neighborhood. The CARMENES input catalogue of M dwarfs (Carmencita) is a comprehensive and homogeneous sample of M dwarfs, with more than 2200 well-characterised main sequence stars, and therefore constitutes a solid basis for the investigation of the multiplicity of these stars. We search for physical companions at all physical separations, from close-orbiting spectroscopic binaries to very wide common proper motion pairs, up to 200 000 au apart from each other. For this, we make extensive use of the latest data from *Gaia* DR3 together with published measurements from the literature. We find that the multiplicity rate in these stars can be as high as 40%, given that candidate systems hinted by *Gaia* are eventually resolved.

1 Introduction

Stellar multiplicity is a common outcome of the stellar formation process [1, 2, 3], with the frequency of multiple systems increasing with the primary stellar mass [4, 5]. In the case of M dwarfs, early studies estimated in 33–42 % the fraction of them that are part of a multiple system [6, 7]. More specifically, the multiplicity rate of M dwarfs has been estimated to approximate to 30 and 20 per cent for a stellar (M dwarf) and substellar (brown dwarf) companion, respectively [8]. Recent estimates suggest that the observed multiplicity of M dwarfs is 26–27 %, or even lower [9, 10, 11, 12]. Although intrinsically small and faint ($\mathcal{M} < 0.62\,\mathcal{M}_\odot$, $\mathcal{L} < 0.076\,\mathcal{L}_\odot$, [13]), M dwarfs represent the majority of the stars in the Universe (e.g. [14, 15]).

Stars in binary systems offer the opportunity to directly measure fundamental parameters, such as masses and radii. Important applications of wide pairs include the calibration of metallicities of M dwarfs [16], the age-metallicity and age-magnetic activity relation [17, 18], and even studies of dark matter in the Milky Way [19]. All in all, multiple systems can help in the important topic of how stars form and develop, and can ultimately serve as pieces in the puzzle of the Galactic constitution. Learning about multiplicity is also interesting in the field of exoplanet searches. For instance, all-sky surveys such as *TESS* or *Kepler* may draw conclusions about planet occurrence, based on the systematic observation of brightness-limited samples of M dwarfs, without taking into consideration the effect of many unresolved binaries disguised as single objects [20].

In this work we present a descriptive study of the multiplicity of M dwarfs, in a volume-limited sample of more than 2200 stars (classified M0.0 V to M9.5 V), from 0.3 au to 206 000 au.

2 Methodology

The sample of our study is Carmencita, the CARMENES input catalogue [21]. Carmencita contains 2216 late-K and M dwarfs, which were intentionally chosen to be independent of multiplicity, age, or metallicity. For every star in this volume-limited sample, we looked for physical companions covering all ranges of separation: from compact object companions, only resolved employing dedicated techniques (e.g., lucky imaging, adaptive optics, speckle interferometry), to wider pairs that can be resolved using the *Gaia* astrometric solution, and in some cases other all-sky surveys.

For the analysis of multiplicity we made extensive use of the third data release of *Gaia* astrometry and photometry (DR3) [22], numerous public all-sky surveys from the ground and space, the Washington Double Star Catalog (WDS) [23], and Virtual Observatory tools such as the Aladin interactive sky atlas [24], the Tool for OPerations on Catalogues And Tables (TOPCAT) [25], and the Virtual Observatory Spectral energy distribution Analyzer (VOSA) [26]. To ensure the correct description of the systems, we eye-inspected individually each one of the systems found, with a special attention to the existing literature and the past characterisations.

We carried out a blind search of equidistant and comoving companions to all the stars in

Carmencita, up to physical separations of 10^5 au, and for the first time, also considering the potential unresolved binaries at very close separations, by using several statistical indicators and data products in *Gaia* DR3. We compiled photometry in *Gaia* DR3, The Two Micron All Sky Survey (2MASS) [27], and the Wide-field Infrared Survey Explorer (AllWISE) [28].

3 Results

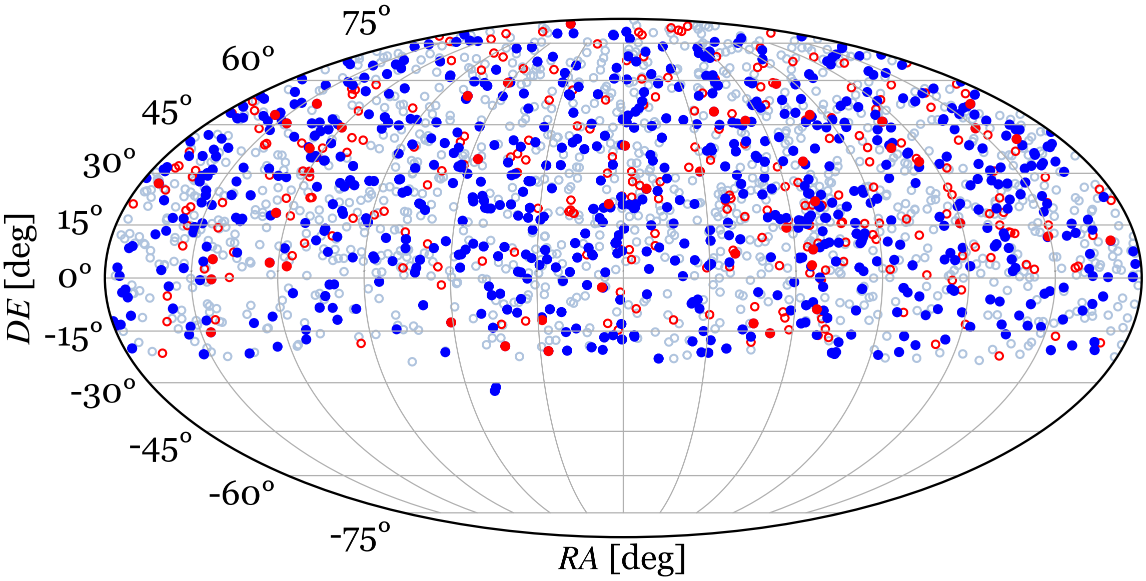

Figure 1: Location in the Mollweide-projection sky of all the stars in the sample of M dwarfs, including their companions, in equatorial coordinates. The coloured circles show single stars (empty grey), stars that belong to a multiple system (filled darker blue), and candidates to unresolved binarity for bona fide singles (empty red) and widely separated components of multiple systems (filled red).

We found that approximately 38% of the M dwarfs in the sample belong to an identified multiple system with a companion of *any* mass (Fig. 1). Under this broad definition of multiplicity, the number of single, binaries, triples, quadruples, and quintuples systems for every 100 M dwarfs in all the range of subtypes (from M0.0 V to M9.5 V) represented as S:B:T:Q:Q, is 62.3:40.1:13.3:2.8:0.8:0.2. On the other hand, the classical definition of multiplicity requires that the M dwarf is the primary component (i.e., the most massive) of the system. We calculated the multiplicity fraction (MF) and the stellar companion fraction (SCF), accounting for observational biases, finding that:

- The MF and SCF both decrease as a function of spectral type, as expected.
- For M dwarfs in which multiplicity is confirmed, the MF and SCF are 29.0% and 35.1%, respectively.

- Binaries outnumber by far the higher order systems: For every 100 M dwarfs with a companion, the ratio S:B:T:Q4:Q5 is 70.9:23.4:4.6:0.6:0.1.
- The MF becomes 40.4% if the unresolved binary candidates are also confirmed.

In the process of identifying multiplicity in our stars, we discovered several pairs with an astrometry compatible with physical parity, but that were not found either in the WDS catalog or in the literature. Some of them are isolated pairs (i.e. binaries), whereas some are components of known systems.

Several statistical indicators in *Gaia* DR3 can be used to find probable cases of non-resolved multiplicity, this is, of double or possibly higher order multiples, in stars previously thought to be single. In a small sample of 16 of these cases, which additionally show notable radial velocity standard deviations as measured by *Gaia*, we performed a systematic search for spectroscopic binaries using medium resolution ($R = 46\,000$) spectra with the high-resolution FIbre-fed Echelle Spectrograph (FIES) at the 2.56m Nordic Optical Telescope (NOT). We discovered that 13 of them are spectroscopic binaries of several types, including two clear triple-lined triples, two are high rotators (so the multiplicity could not be identified properly), and one is single.

With this, to the known physically bound systems reported in the literature, we add 48 newly discovered pairs, and propose 300 candidates to very compact binaries, to date unresolved, except for the few for which we were able to characterise spectroscopically.

When possible, we determined descriptive parameters of the multiplicity (angular and physical separation, positional angle, binding energies, orbital periods), fundamental parameters of the components (luminosities, masses, radii, effective temperatures, surface gravities), compile astrometry (positions, proper motions, parallaxes, radial velocities), photometry in up to 10 passbands, and *Gaia* statistical indicators. Additionally, we give an individual description of the components, including their candidacy for unresolved binarity.

In the cumulative distribution of physical separations, changes of slope are apparent and measurable, and we could fit them to two distinct power laws following the general form of Öpik's law. This observational evidence has been motivated in the literature by the existence of at least two different formation mechanisms. We deem the scarcity of multiple systems at very close and very wide separations to an observational effect (because of the amount of unresolved pairs), and to a real configuration (because of the smaller binding energies are more likely disrupted by gravity), respectively.

4 Conclusions

In this work we perform a systematic, complete study and description of multiplicity for all separations: from very compact systems in close-in orbits, to wide and very wide pairs, some of them in very fragile configurations placed in the limit of dynamical stability.

We computed the classically defined multiplicity fraction and the stellar companion fraction in different un-biased samples. The multiplicity fractions derived are in agreement with similar studies published in the last three decades. This work, however, estimates that the actual multiplicity fraction of M dwarfs could be as high as ∼40% if the unresolved systems hinted by *Gaia* are, indeed, real. In this regard, we have demonstrated using spectroscopic scrutiny in a small subsample of these that, in fact, many single stars are indeed compact systems of two or three stars. If all the candidates to unresolved multiples were confirmed, the global multiplicity fraction of M dwarfs could increase by approximately 11 %.

Finally, we provide homogeneous observational data for the investigation of the different formation mechanisms of close and wide binaries in stars of small mass. The study of multiplicity can serve in a myriad of topics of astrophysical interest, including an empirical test for models of stellar formation, to prove the hypothesis of whether all stars form in multiple systems.

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