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The Orbital Surface Density Distribution and Multiplicity of M-Dwarfs

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ABSTRACT

Aims. We present a new estimate to the multiplicity fraction of M-Dwarfs using a log-normal fit to the orbital surface density distribution.

Methods. We used archival data from five M-Dwarf multiplicity surveys to fit a log-normal model to the orbital surface density distribution of these stars. We then used this fit, alongside the companion mass ratio distribution given by Reggiani Meyer (2013), to calculate the frequency of companions over the ranges of mass ratio (q) and semi-major axis (a) that the referenced surveys were collectively sensitive over – [0.60 < q < 1.00] and [0.04 < a < 10,000 AU]. We then extrapolated this to calculate a multiplicity fraction which encompasses [0.00 < q < 1.00] and [0.00 < a < ∞ AU. Finally, we compared our results to multiplicity findings of other spectral types of stars.

Results. Over these constrained region of [0.60 < q < 1.00] and [0.04 < a < 10,000 AU], we found a multiplicity fraction of 0.236 +/- 0.061. We then calculated the multiplicity fraction over all ranges of q (0.00 – 1.00) and a (0.00 – ∞ AU) to be 0.503 +/- 0.136. We also found evidence which suggests that the multiplicity of M-Dwarfs is nearly identical to that of FGK and A stars.

Key words. binary stars – M-Dwarfs

1. Introduction

M-Dwarfs are among the most numerous stars in the universe, and it is suspected that many exist alongside at least one companion. Numerous attempts have been made to find the total fraction of M-Dwarfs which have any number of companions, but this multiplicity fraction is still not well constrained. Working towards knowing this value will have important and broad implications for star formation theories.

Fundamentally, the multiplicity fraction of a population of stars depends on: 1. the companion mass ratio distribution (ψ) and 2. the orbital surface density distribution (ϕ). The mass ratio, q, is defined as: $\frac{M_{secondary}}{M_{primary}}$ where, by definition, $M_{primary} > M_{secondary}$ so that $q \leq 1$. Furthermore, the semi-major axis, a, of a system serves as a measure of the separation between the primary and secondary stars. Using these two components, we calculate the multiplicity fraction as:

$$f = \int_{q_{min}}^{q_{max}} \psi dq * \int_{a_{min}}^{a_{max}} \phi dlog_{10}(a) \tag{1}$$

where $q_{min}, q_{max}, a_{min}$, and a_{max} representing lower and upper bounds for the regions of mass ratio and semi-major axis of interest. The first component, the companion mass ratio distribution, is discussed in Reggiani & Meyer (2013). They find that the formula:

$$\psi = \frac{dN}{dq} = q^{.25} \tag{2}$$

describes this distribution for M-Dwarfs and other types of stars. This work has focused on finding the second component to Equation (1), the orbital surface density distribution. Once this is determined, Equation (1) can be used to calculate the multiplicity of M-Dwarfs by integrating over specific ranges of mass ratio and semi-major axis. Our method for calculating the multiplicity fraction is built upon a key assumption: that the mass ratio distribution does not depend on orbital separation. Evidence for this is provided by Reggiani & Meyer (2013).

2. Methods

2.1. Acquiring the Data

In order to explore the orbital surface density distribution and multiplicity of M-Dwarfs, our first step was to compile data from a variety of different multiplicity surveys: Cortes-Contreras et. al. (2016), Delfosse et. al. (1998), Fischer and Marcy (1992), Janson et. al. (2012), and Ward Duong et. al. (2015). These would later be used as point estimates of the multiplicity fraction for the purposes of fitting a model to the orbital surface density distribution.

It was first necessary to have a firm understanding of the ability of each of these surveys to detect companions at various levels of mass ratio and semi-major axis. To this end, we sought to constrain companion detections to those associated with the values of mass ratio and semi-major axis which each survey was at least 90% complete to. We limited our analysis to include only companions within the range of q which all of the referenced surveys were collectively sensitive to, [0.60 < q < 1.00], as it is important that each set of data be representative over the same range of q. Furthermore, we only considered companion detections which were associated with values of semi-major axis that each survey was confidently able to detect. For each survey, any detected companion which did not have associated physical properties of q between 0.60 and 1.00 and the range in a which the specific survey was 90% complete to was removed from our analysis entirely. Stratifying by these two variables allowed our analysis to ensure the certainty of companion detections and ultimately achieve the most accurate multiplicity fraction possible.

In order to adequately investigate a broad range of semi-major axis, we utilized data from surveys which employed radial velocity (Delfosse et. al. (2016), Fischer and Marcy (1992)) and direct imaging (Cortes-Contreras et. al., Janson et. al. (2012), and Ward Duong et. al. (2105)) methods. Combining these sources allowed our analysis include data which is overall sensitive to a range of semi-major axis of [0.04 < a < 10,000 AU].

Because it covers such a wide range of semi-major axis (3 - 10,000 AU), the data from Ward-Duong et. al. 2015 was split into two bins by orbital separation: 0 - 1,000 AU and 1,000 - 10,000 AU. This split is further justified by the fact that the survey utilized two different companion-confirmation methods for these two orbital separation regimes (archival plate analysis and adaptive optics imaging for the near and far separations respectively).

2.2. Fitting the Model

Next, we sought to fit a log-normal model to the orbital surface density distribution of the M-Dwarf multiple systems. This model, which we call ϕ, is described by:

$$\phi = \frac{dN}{dlog_{10}(a)} = A * \frac{e^{-(log_{10}(a)-log_{10}(\mu))^2/(2log_{10}(\sigma)^2)}}{log_{10}(\sigma) * \sqrt{2\pi}} \tag{3}$$

which has 3 free parameters: the base-10 log of mean ($log_{10}(\mu)$), the base-10 log of standard deviation ($log_{10}(\sigma)$), and the amplitude (A). In order to fit the model and find the best values for these parameters, values of the multiplicity were calculated by plugging in possible values of $log_{10}(\mu)$ (ranging from -2 to 5), $log_{10}(\sigma)$ (ranging from -2 to 4), and A (ranging from 0 to 1) into Equation (3) in increments as small as 0.001 and then assuming each iteration of this to be the ϕ component of Equation (1) (the ψ is given by Equation (2)). Model multiplicity estimates were then calculated from Equation (1) by integrating the ψ component from 0.60 to 1.00 and the ϕ component over the range of semi-major axis associated with each survey. We then compared these model multiplicity estimates to the estimates of multiplicities from the surveys via the reduced-chi squared test. The 6 data points and 3 free parameters lead to 3 degrees of freedom for this test. The best fit model to this distribution allowed us to performs further calculations.

2.3. Calculating the Frequency

Next, we used our model for the orbital surface density distribution alongside the companion mass ratio distribution model from Reggiani and Meyer 2013 to calculate the multiplicity of M-Dwarfs as:

$$f = \int_{q_{min}}^{q_{max}} q^{.25} dq * A * \int_{a_{min}}^{a_{max}} \frac{e^{-(log_{10}(a)-log_{10}(\mu))^2/(2log_{10}(\sigma)^2)}}{log_{10}(\sigma) * \sqrt{2\pi}} dlog_{10}(a) \tag{4}$$

This formula was first integrated over the ranges of q and a that encompass the survey data: 0.6 < q < 1.0 and 0.04 < a < 10,000 AU. This calculation resulted in a frequency that is representative over these limited ranges of q and a. These ranges were later expanded to 0.0 < q < 1.0 and 0 < a < ∞ AU to allow for the calculation of a universal M-Dwarf multiplicity fraction. The error on the multiplicity fraction was calculated as the 90% confidence interval of the probability distribution function of the frequency.

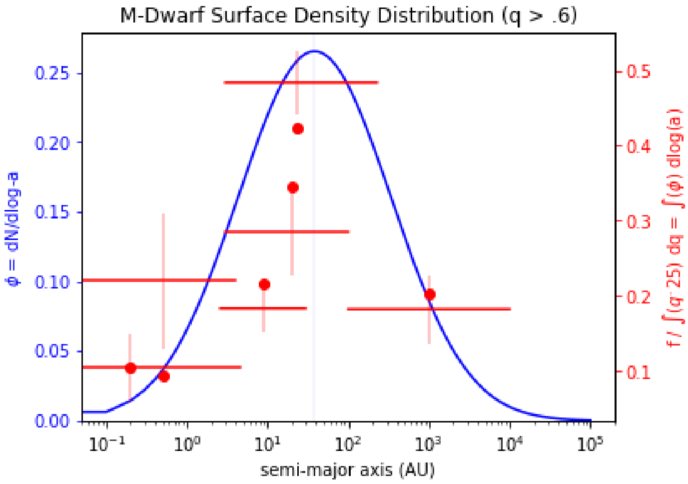

Fig. 1. This figure depicts our fit to the orbital surface density distribution of M-Dwarfs. The left axis and blue curve visualize the best fit log-normal model, described by Equation (3) and the best fit parameters given in Section (3.1). The right axis and red features represent the multiplicity estimates calculated from the survey data and our model's attempt to recover these. The y-axis value of each horizontal line represents the multiplicity estimates from the surveys, and the x-axis range represents the range in semi-major axis that each survey is sensitive to. The vertical lines represent the Poisson counting errors of the corresponding survey frequency estimates. Integrating the blue curve over the range of semi-major axis covered by any given red horizontal line results in values represented by the red points. These points visually represent how well our model fits the data.

3. Results

3.1. Orbital Surface Density Model

The best-fit to point estimates of frequency from the five M-Dwarf surveys resulted in the parameters of $log_{10}(\mu)$, $log_{10}(\sigma)$, and A being 1.582, 0.946, and 0.629 respectively. This fit returned a reduced chi-squared parameter value of 2.137. With 3 degrees of freedom, the chi-squared probability distribution indicates that the probability of achieving a value greater than or equal to 2.137 is 0.093. Despite this low probability, we do not reject the null hypothesis that the data came from this model because it exceeds the 0.05 significance level. The log normal model with the best-fit parameter values of $log_{10}(\mu)$, $log_{10}(\sigma)$, and A, shown in Figure 1, describes the orbital surface density distribution of M-Dwarfs.

3.2. Multiplicity Fraction

Integrating Equation (4) over the constrained regions of q (0.6 < q < 1) and a (0.04 < a < 10,000 AU) resulted in a multiplicity fraction of 0.236 +/- 0.061. Following this process, a universal multiplicity fraction was found by integrating Equation (4) over 0.0 < q < 1.0 and 0.0 < a < ∞ AU to be 0.503 +/- 0.136.

4. Discussion

4.1. The Multiplicity of M-Dwarfs

The results of our work suggest that around half of all M-Dwarfs have a companion. Because our study encompasses very small mass ratios, many of these companions may be Brown Dwarfs.

4.2. Comparisons to Other Spectral Types

We sought to compare the multiplicity of M-Dwarfs to that of the sun-like FGK and more massive A type stars over the constrained range of mass ratio and semi-major axis ($0.6 < q < 1.0$ and $0.04 < a < 10{,}000$ AU). To compare to the FGK multiplicity, we extrapolated the model of orbital surface density from Raghavan et. al. 2010 to integrate over the above range of a. This, alongside the companion mass ratio distribution described in Equation (2) and the full multiplicity equation, Equation (4), was used to find an FGK star multiplicity fraction of 0.230 +/- 0.032, where the error is estimated as the Poisson counting error based on the survey of Raghavan et. al. (2010). We used the same method for the A star multiplicity fraction, this time referencing De Rosa et. al. (2013), and found a multiplicity fraction of 0.238 +/- 0.026.

In summary, we find the multiplicity fraction over $0.6 < q < 1.0$ and $0.04 < a < 10{,}000$ AU for M, FGK, and A stars to be 0.236 +/- 0.061, 0.230 +/- 0.032, and 0.238 +/- 0.026 respectively. We note that these three values are all within error of one-another, suggesting that the multiplicity fraction does not vary with spectral type. Future studies may explore the multiplicity fraction of OB type stars and Brown Dwarfs to see if this trend holds with the most massive stars and smaller sub-stellar objects.

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References

Cortes Contreras et. al. 2016 , Astro. & Astrophys., FC23
De Rosa et. al. 2013, Mon. Not. R. Astro. Soc. 437, 1216 1240
Delfosse et. al. 1998, Astro. & Astrophys., 344, 897 910
Fischer and Marcy 1992, The Astrophys. Journal, 396, 178 194
Janson et. al. 2012, The Astrophys. Journal, 754, 44 70
Raghavan et. al. 2010, The Astrophys. Journal , 190, 1 42
Reggiani and Meyer 2013, Astro. & Astrophys., 553, A124
Ward Duong et. al. 2015, Mon. Not. R. Astro. Soc . 000, 1 34