One is the loneliest number: multiplicity in cool dwarfs

CARLOS CIFUENTES,1 JOSÉ A. CABALLERO,1 AND SERGIO AGUSTÍ2

1Centro de Astrobiología (CSIC-INTA), Madrid, Spain
2Lyceé Français, Madrid, Spain

(Received May 24, 2021; Accepted May 26, 2021)
Submitted to RNAAS

ABSTRACT
Stars in multiple systems offer a unique opportunity to learn about stellar formation and evolution. As they settle down into stable configurations, multiple systems occur in a variety of hierarchies and a wide range of separations between the components. We examine 11 known and 11 newly discovered multiple systems including at least one M dwarf with the latest astrometric data from Gaia Early Data Release 3 (EDR3). We find that the individual components of systems at very wide separations are often multiple systems themselves.

Keywords: Binary stars (154), Close binary stars (254), Late-type stars (909), Visual binary stars (1777), Wide binary stars (1801)

1. INTRODUCTION
Systems of two or more stars bound by gravity, or multiple star systems, are a common by-product of the stellar formation process. By analysing these systems we aim to understand the mechanisms behind the star formation and evolution, particularly of low-mass objects. The competition of the system components for stable orbits eventually resolves into a hierarchical arrangement in hierarchical systems (Duchêne & Kraus 2013). When a system reaches dynamical stability, it organises hierarchically in nested orbits that can be treated individually as two-body problems (see e.g. Evans 1968; Tokovinin 2014). Evidence suggests that most (if not all) stars form in multiple systems and at least one component (usually the least massive) is ejected into a distant orbit during the pre-main sequence phase (Duchêne & Kraus 2013). Very close binary systems \(r < 10\) au are not formed by fragmentation in situ, but produced from wider multiple systems (Bate et al. 2003). In many physical star systems, seemingly single distant components are resolved as multiple systems themselves, typically binaries, which implies that known double or triple systems in wide orbits would actually be hierarchical triples or quadruples. This fact is in consonance with the suggestions by Basri & Reiners (2006) and Caballero (2007), who proposed a major prevalence of wide triples over wide binaries. These findings challenge the fundamentals of star formation because the separations of wide systems cannot be the direct product of a collapsing cloud core.

Using N-body simulations, Reipurth & Mikkola (2012) found that extreme hierarchical architectures can be reached on timescales of millions of years with the appropriate exchange of energy and momentum. In their work, one component in a triple system is dynamically scattered into a very wide orbit at the expense of shrinking the orbit of the remaining binary. Low-mass objects are preferentially ejected in three-body dynamics. Reipurth & Mikkola (2012) noted that these ejected companions can also be binaries.

In this work we examine the characteristics of known and new multiple systems containing at least one M dwarf by using the astrometry from Gaia EDR3. In particular, we compare distances, proper motions, and radial velocities to determine if the systems are physically bound.
2. SAMPLE

We study 53 stars in 22 multiple systems, 11 of which are known systems tabulated in the Washington Double Star catalog (Mason et al. 2001, e.g. Caballero 2007; Caballero et al. 2012; Dhital et al. 2010; Janson et al. 2014), 4 are known systems with new candidate members, and 11 are newly discovered systems. All of them contain at least one M dwarf in different hierarchical configurations, including 12 double, 5 triple and 4 quadruple systems, plus one quintuple system. They are located between 14.1 pc and 276.1 pc. The spectral classifications of the primary components range from F7 V to M5.5 V, and of their physical companions from F9 V to L1. We estimated spectral types for 22 stars from luminosities and absolute magnitudes, as described below.

For each star, we acquired publicly available all-sky survey data and images with the Aladin interactive sky atlas (Bonnarel et al. 2000), and manipulated them with the Tool for OPerations on Catalogues And Tables (TOPCAT; Taylor 2005). First, we obtained astrometry (equatorial coordinates in the J2016.0 epoch, parallaxes, and proper motions) and photometry ($G_{BP}$, $G$, and $G_{RP}$) from Gaia EDR3 (Gaia Collaboration et al. 2021). Next, we compiled additional photometry in the $JHK_s$ passbands of the Two Micron All-Sky Survey (2MASS; Skrutskie et al. 2006) and in the $W_1$-$W_2$-$W_3$-$W_4$ passbands of the Wide-field Infrared Survey Explorer (AllWISE; Cutri et al. 2014). Using the photometry from up to 10 passbands and parallactic distances we derived luminosities and effective temperatures for the single stars as in Cifuentes et al. (2020). Finally, we used the mass-luminosity and mass-absolute magnitude relations by Pecaut & Mamajek (2013) and Cifuentes et al. (2020) to derive masses and spectral types.

3. MULTIPLICITY

In order to test the physical binding of each system member candidate, we quantified the similarity of distances and proper motions. For each pair of objects we computed the proper motion ratio, $\Delta \mu / \mu$, and the proper motion position angle difference, $\Delta \text{PA}$. We considered a pair as physical if all the following conditions are met: $\Delta \text{PA} < 15 \text{ deg}$, $\mu$ ratio $< 0.15$, and $\Delta d < 0.10$. Of the 22 investigated systems, 7 do not comply with the criteria above. Of them, 3 are close pairs with Gaia proper motions perturbed by their relative orbital motion. The remaining 4 pairs are wide: one does not have parallax measured by Gaia for the secondary (WDS 06104+2234), one exhibits a high Renormalized Unit Weighted Error (RUWE) value in Gaia (i.e. larger than 1.4, which is indicative of a problematic astrometric solution; KO 4), and only for the other two (KO 6 and SLW 1299) we disprove their physical connection based on the astrometric analysis.

In Table 1 we list the names of the 53 stars, spectral types, angular separations ($\rho$), position angles ($\theta$), projected physical separations ($s$), and remarks. The full version of this table with all astro-photometric parameters and derived masses, binding energies, orbital periods, and reference codes can be downloaded in csv format from our GitHub repository\footnote{https://github.com/ccifuentesr/cif21-multiplicity (10.5281/zenodo.4757508)}. Additionally, one-page pdf charts with a detailed description of each system are also available in the repository. The least-bound system in our sample is FMR 83 with $U_g^* \sim -7.1 \times 10^{33} \text{ J}$ (Rica & Caballero 2012), while the pair with largest projected separation (54 800 au) and orbital period (10.9 $10^6$ yr) is WDS 07400-0336 (Montes et al. 2018).

4. RESULTS

We concluded the following: (i) In 6 multiple systems the astrometric data from Gaia suggest additional multiplicity in at least one member. (ii) With current data, the pairs LSPM J0651+1845/LSPM J0651+1843 and HD 77825/1RXSJ090406.8-155512 are the only wide binaries with no evidence of close binarity of the individual components in the Gaia solution. (iii) The young candidate member in $\beta$ Pictoris, PYC J07311+4556, is a wide member in a quadruple, perhaps quintuple, physical system. This current configuration is expected if the system is actually young (18.5$^{+2.0}_{-2.4}$ Myr, Miret-Roig et al. 2020) and still undergoes a process of dynamical stabilization.
REFERENCES

Basri, G., & Reiners, A. 2006, AJ, 132, 663, doi: 10.1086/505198
Bate, M. R., Bonnell, I. A., & Bromm, V. 2003, MNRAS, 339, 577, doi: 10.1046/j.1365-8711.2003.06210.x
Bonnarel, F., Fernique, P., Bienaymé, O., et al. 2000, A&AS, 143, 33, doi: 10.1051/aas:2000331
Caballero, J. A. 2007, A&A, 462, L61, doi: 10.1051/0004-6361:20066814
Caballero, J. A., Genebriera, J., Miret, F. X., Tobal, T., & Cairo, J. 2012, The Observatory, 132, 252. https://arxiv.org/abs/1205.5572
Cifuentes, C., Caballero, J. A., Cortés-Contreras, M., et al. 2020, A&A, 642, A115, doi: 10.1051/0004-6361/202038295
Cutri et al., R. M. 2014, VizieR Online Data Catalog, II/328
Dhital, S., West, A. A., Stassun, K. G., & Bochanski, J. J. 2010, AJ, 139, 2566, doi: 10.1088/0004-6256/139/6/2566
Duchêne, G., & Kraus, A. 2013, ARA&A, 51, 269, doi: 10.1146/annurev-astro-081710-102602
Evans, D. S. 1968, QJRAS, 9, 388
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2021, A&A, 649, A1, doi: 10.1051/0004-6361/202039657
Janson, M., Bergfors, C., Brandner, W., et al. 2014, ApJ, 789, 102, doi: 10.1088/0004-637X/789/2/102
Mason, B. D., Wycoff, G. L., Hartkopf, W. I., Douglass, G. G., & Worley, C. E. 2001, AJ, 122, 3466, doi: 10.1086/323920
Miret-Roig, N., Galli, P. A. B., Brandner, W., et al. 2020, A&A, 642, A179, doi: 10.1051/0004-6361/202038765
Montes, D., González-Peinado, R., Tabernero, H. M., et al. 2018, MNRAS, 479, 1332, doi: 10.1093/mnras/sty1295
Pecaut, M. J., & Mamajek, E. E. 2013, ApJS, 208, 9, doi: 10.1088/0067-0049/208/1/9
Poveda, A., Allen, C., Costero, R., Echevarría, J., & Hernández-Alcántara, A. 2009, ApJ, 706, 343, doi: 10.1088/0004-637X/706/1/343
Reipurth, B., & Mikkola, S. 2012, Nature, 492, 221, doi: 10.1038/nature11662
Rica, F. M., & Caballero, J. A. 2012, The Observatory, 132, 305. https://arxiv.org/abs/1207.5251
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163, doi: 10.1086/498708
Taylor, M. B. 2005, in Astronomical Society of the Pacific Conference Series, Vol. 347, Astronomical Data Analysis Software and Systems XIV, ed. P. Shopbell, M. Britton, & R. Ebert, 29
Tokovinin, A. 2014, AJ, 147, 87, doi: 10.1088/0004-6256/147/4/87
Table 1. Relative astrometry of our multiple systems.

| Star name | Comp. | Sp. type | $\rho$ [arcsec] | $\theta$ [deg] | $s$ [au] | Remarks |
|-----------|-------|----------|----------------|--------------|---------|---------|
| LEHPM 494 | A     | m5.5 V   |                |              |         |         |
| 2MASS J00210589-424443 | B     | L0.6 V   | 77.78          | 317.0        | 2083.4  |         |
| NLTT 6496 | A     | M4.5 V   |                |              |         |         |
| NLTT 6491 | B     | m4.5 V   | 299.13         | 190.6        | 9391.9  |         |
| LP 655-23 | A     | M4.0 V   | 19.81          | 339.8        | 597.3   |         |
| DENIS J043051.5-084900 | B     | M8 V     |                |              |         |         |
| 2MASS J06101775+2234199 | A     | M4.0 V+  |                |              |         |         |
| LP 362-121 | BaBb  | M6 V+m7 V | 65.16         | 89.2         | 1866.9  |         |
| BD+37 1541 | A     | f0: V    |                |              |         |         |
| Karmn J06353865+3751139 B | B     | m2.5 V   | 3.88           | 201.5       | 848.7   |         |
| LSPM J0651+1845 | A     | m4.5 V   |                |              |         |         |
| LSPM J0651+1843 | B     | m4.5 V   | 111.72         | 150.6        | 7133.4  |         |
| 1RXS J073138.4+455718 | AaAb  | M3 V+m4.5 V | 431.39        | 296.0        | 24127.1 |         |
| 1RXS J073101.9+460030 | B     | M4.0 V   | 307.80         | 266.3        | 17214.6 |         |
| [SLS2012] PYC J073111+4556 | C     | m4 V     |                |              |         |         |
| HD 61606 A | A     | K3 V     |                |              |         |         |
| HD 61606 B | B     | K7 V     | 57.90          | 112.7        | 815.2   |         |
| BD-02 2198 | C     | M1.0 V   | 3894.18        | 296.7        | 54822.6 |         |
| 1RXS J074948.5-031712 | A     | M3.5 V   |                |              |         |         |
| 2MASS J07495087-0317194 | B     | m3.5 V   | 1.93           | 266.3        | 32.8    |         |
| 2MASS J07494215-0320338 | C     | m3.5 V   | 234.86         | 214.0        | 4002.1  |         |
| LP 209-28 | “A”   | m3: V    | 666.68         | 208.5        | 69836.7 |         |
| LP 209-27 | “B”   | m4 V     |                |              |         |         |
| HD 77825 | A     | K2 V     | 220.02         | 262.9        | 6026.0  |         |
| 1RXS J090046.8-155512 | B     | M2.5 V   | 7.39           | 335.7        | 186.8   |         |
| 2MASS J13181352+7322073 | A     | m3 V     |                |              |         |         |
| Gaia DR2 1688578285187648128 | B     | M3.5 V   | 7.39           | 335.7        | 186.8   |         |
| HD 130666 | A     | G5 V     | 29.54          | 336.6        | 3072.3  |         |
| 2MASS J14474531+4934020 | B     | m4.5 V   |                |              |         |         |
| TYC 2565-684-1 | A     | g1 V     | 43.64          | 306.2        | 8644.3  |         |
| 2MASS J15080798+3310222 | B     | m3 V     |                |              |         |         |
| HD 134494 | A     | K01V     |                |              |         |         |
| BD+33 2548B | B     | f9 V     | 23.38          | 285.0        | 6455.7  |         |
| Gaia DR2 1288848427727490048 | C     | m3 V     |                |              |         |         |
| HD 149162 | AaAbAc | K0 Ve+k6 V+m5 V | 252.03          | 138.4        | 11405.7 |         |
| G 17-23 | B     | M3.0 V   | 252.03         | 138.4        | 11405.7 |         |
| LSPM J1633+0311S | C     | D:       | 258.42         | 138.4        | 11694.8 |         |
| G 125-15 | Aab   | M4.5 V+M5 V | 45.78          | 347.4        | 1835.1  |         |
| G 125-14 | B     | M4.5 V   | 45.78          | 347.4        | 1835.1  |         |
| LP 395-8 A | B     | M3.0 V+M0 V | 1.22           | 355.5        | 56.6    |         |
| LP 395-8 B | B     | m3.5 V   | 11.02          | 307.4        | 325.1   |         |
| Gaia DR2 182951684884360832 | C     | m9: V    |                |              |         |         |
| HD 212168 | A     | G0 V     |                |              |         |         |
| CPD-75 1748B | BaBb  | k3 V+    | 20.90          | 79.3         | 489.2   |         |
| DENIS J220244.3-750342 | C     | M8 V     | 264.82         | 128.9        | 6198.7  |         |
| SLW J2305+0613 A | "A"   | M1.7 V   | 242.37         | 260.9        | 18656.7 |         |
| SLW J2305+0613 B | "B"   | M3.2 V   | 451.70         | 261.7        | 11668.3 |         |
| SLW J2305+0613 C | "C"   | M3.7 V   | 12.46          | 221.6        | 321.9   |         |
| HD 221356 | A     | F7 V     |                |              |         |         |
| 2MASS J2331016-040618 | BC    | M8.0 V+L3.0 V | 5.78           | 165.1        | 215.5   |         |
| 2MASS J23313095-0405234 | D     | L1 V     | 451.70         | 261.7        | 11668.3 |         |
| StKM 2-1787 | A     | K4 V     |                |              |         |         |
| TYC 1174-953-2 | B     | M2.5 V   |                |              |         |         |

Note—Table 1 is published in its entirety in the electronic edition of Research Notes. A portion with fewer columns is shown here for guidance regarding its form and content.