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The properties of G-dwarf multiple stars

P. Kroupa

Argelander-Institut für Astronomie, Universität Bonn, Auf dem Hügel 71, 53121 Bonn, Germany
e-mail: pavel@astro.uni-bonn.de

The distribution functions of multiple stellar systems, together with the stellar IMF, comprise some of the most important astrophysical distribution functions. They constrain planet- and star-formation theory, are required for understanding the origin and nature of stellar populations in various environments, and are essential for population synthesis in galaxies and for calculating the stellar-dynamical evolution of realistic star clusters.

Following the work of Abt & Levy (1976), Duquennoy & Mayor (1991, hereinafter DM) pose the important question as to how G-type stars are distributed in multiple systems. By doing so they produced a research paper with historical impact, the results of it standing solid and to a large extent unaltered by further developments even today.

The epochal study by DM used the Cross-cOrrelation RAdial VELocity (CORAVEL) instrument constructed in collaboration with the optician André Baranne (Baranne et al. 1979) and put in operation in 1977 with funding from a Fonds de la Recherche (FNRS) grant that Michel Mayor acquired in 1972 for a long-term high-precision spectroscopic survey of solar neighborhood stars to quantify their astrophysical parameters. The grant also covered the long-term costs of the observations, and Michel confirms having always been well-supported by the FNRS and Geneva University. Indeed, the Swiss 1 m telescope at the Observatoire de Haute Provence (OHP) was dedicated to this program. In 1984 Michel Mayor was elected associate professor at Geneva University, and hired Antoine Duquennoy with the money left in his FNRS grant. Antoine obtained his Ph.D. degree on studying binary and triple stars by analyzing the huge amounts of radial velocity measurements of G type stars acquired over many years. The final fruits of this work were presented to the scientific community as Duquennoy & Mayor (1991).

The complete ("extended") list of CORAVEL observations over 13 years of 291 F0-G9 stars in the Gliese (1969) catalog was published by Duquennoy et al. (1991), including the description of the observations, data reduction, calibration, and probable errors. The unbiased, volume-limited sample of 164 stars was extracted and analyzed for multiplicity by DM. In their Sect. 2, Duquennoy and Mayor provide a historical backdrop and report in particular on observational biases and interpretations of the arrived-at distribution functions (mass ratios, periods) that plagued prior studies, notably the one by Abt & Levy (1976). It is an essential read for anyone interested in binary-star properties, because even subtle biases in the observations can have a strong effect on the derived distribution functions, as stressed by Tout (1991) in an important paper. The stellar sample subject to investigation is defined in Sect. 3 of DM, and Sect. 4 reports the results of the spectroscopic survey documenting, for each star, its type, parallax, and mean radial velocity and uncertainty, and also listing the orbital solution for each star.

In Sect. 5 the authors summarize the observational data, discussing in turn the spectroscopic binaries, the visual binaries, and common-proper-motion pairs for which additional information is compiled from available catalogs. The deduced fraction of triple and quadruple systems is also delved into here, with the finding that triples and quadruples make up only about 7 and 2 percent of G-dwarf systems, respectively, and that the binary fraction is between 50 and 60 percent of all systems. A very thorough incompleteness study is presented in Sect. 6, where the question is posed as to which mass ratios and periods are missed given the shortcomings of the various observational techniques, such as flux limits and limited coverage over 13 years. The great results are reported in Sect. 7, where the famous eccentricity, period, and mass-ratio distributions are presented and the eccentricity–period diagram is discussed for all systems together, as well as the short- (<1000 days) and long-period (>1000 days) systems separately.

There is a detailed discussion of the circularization period (near 11 days for stars of Galactic-disk age), the famous log-normal period distribution function is presented, and the mass-ratio distribution is quantified. While short-period binaries are deduced to have the same mass-ratio distribution as long-period binaries, the former have a different eccentricity distribution by being bell-shaped, whereas the long-period systems appear to be distributed according to the thermal distribution. This convincingly demonstrates that short and long-period binaries have either different formation modes or different evolutionary histories. As a noteworthy result, the mass-ratio distribution was found to be consistent with the then measured form of the Galactic-field stellar mass function, suggesting that the components of a binary essentially form independently of each other according to the laws that make stars from a molecular cloud. Duquennoy & Mayor continue to discuss very-low-mass companions (mass $<0.1\ M_{\odot}$) in Sect. 8, finding no certain cases but a few strong candidates. Finally, Sect. 9 presents the conclusions of this epochal work.

Why did DM have such an impact in comparison to other studies, in particular the one by Abt & Levy (1976)? Abt & Levy resorted to a flux-limited stellar sample and still had to use classical spectroscopic analysis based on measuring 9 spectral lines at 20 epochs over a time span of typically 1800 days for 135 solar-type stars with a resulting typical precision of 1.3 $\mathrm{km\,s^{-1}}$, augmented with common-proper-motion pairs. A number of their orbital solutions had to be refined with follow-up work (Morbey & Griffin 1987). DM, on the other hand, applied the cross-correlation technique thought up by Fellget (1955) and then pioneered in the form of an instrument by Griffin (1967). This technique allows the simultaneous cross-correlation of thousands of spectral lines such that 6–8 stars can be measured per hour with a resulting precision of about 100 m/s (Griffin 1967). Further refinements by DM were to use a distance-limited sample (avoiding luminosity biases that would prefer binaries with equal-mass components) and the much longer time span of 13 years allowing the detection of spectroscopic binaries with periods up to about 4500 days. Consequently, the Abt & Levy period distribution peaks at a substantially shorter period, and the mass-ratio distribution has an unphysical maximum near equal-mass components.

The DM survey determined the multiple-star properties of solar-like stars within about 20 pc distance of the Sun to an unprecedented precision that has not been surpassed by any other survey to this day. But, what are the binary properties of stars with different masses? The components of massive stars appear to be more similar; that is, random pairing from the stellar mass function can be ruled out for these, as deduced by a pioneering modeling effort of the Bright Star Catalogue by Eggleton et al. (1989), and more recently from observations of star-forming regions (Goodwin et al. 2007; Kroupa 2008). The CORAVEL survey was extended to the southern hemisphere, and for K-dwarfs Mayor et al. (1992) provide a preliminary report finding that there is no substantial difference to the G-dwarf distribution functions. The authors state: "Among the most important CORAVEL surveys, we can mention a sample of about 900 dwarf stars (F to M) in the solar vicinity. This sample will give us properties of the duplicity of low-mass stars, mainly with primary masses M_1 from 0.3 to 1.2 $M_\odot$". While the scientific community waits for these results to hopefully appear as research papers soon, DM has become a benchmark against which all multiplicity surveys are being compared. For example, multiplicity surveys in the close solar neighborhood of M dwarfs (Fischer & Marcy 1992) yield very similar results to the G-dwarf data of DM, although more recent work by Marchal and Delfosse may be suggesting a deficit of M dwarf binaries at long periods compared to G-dwarfs. Observations in star-forming regions (e.g. Duchêne et al. 2007) have led to the understanding that stars are born with a higher binary fraction than observed in the Galactic field as specified by the DM distribution functions.

While the DM results remain essentially unchanged at present, a small correction to the mass-ratio distribution of short-period binaries due to the presence of an unnoticed bias was suggested subsequently: the mass-ratio distribution of G dwarf binaries with a period shorter than about 1000 days differs from the long-period distribution by being skewed towards equal-mass components (Mazeh et al. 1992). Also, the fraction of triple and quadruple systems may have been slightly underestimated by DM due to the presence of more spectroscopic binaries with outer companions (Tokovinin et al. 2006).

The results obtained by DM led to a new determination of the stellar IMF by correcting the star counts for unresolved binaries (Kroupa et al. 1993). In turn, this new IMF contradicted an important conclusion reached by DM, namely that late-type stars are paired randomly from the IMF. But, this conclusion turned out to be the correct hypothesis after all *if* most stars form in modest clusters (Kroupa 1995), because binaries with low-mass companions are disrupted more efficiently due to their weaker binding energy so that the steeper initial mass-ratio distribution evolves to the flatter one observed by DM. This simultaneously solved the problem that the Galactic field has a significantly lower binary fraction than star-forming regions because long-period binaries are disrupted in their birth clusters. An improved mathematical representation of the true initial period distribution function of late-type stars was therewith arrived at and was subsequently used often in modeling realistic star clusters. Based on the results of DM, the eigenevolution model for the evolution of short-period binaries and inverse dynamical population synthesis were born here.

Having met Antoine at a conference in Garching in about 1991, I was very eager to meet up with him again throughout 1993 and 1994 to discuss these matters, as I knew he would be thrilled by the new results on the probably true, underlying initial-period (i.e. energy) distribution function of binaries. I had hoped to collaborate with him. But alas, on June 19, 1994, Antoine fell asleep while driving home from a morning marathon competition and died in a car accident.

History follows its own rules, and in collaboration with the Swiss team, Latham et al. (1989) had suggested the presence of a substellar companion to the star HD 114762. Around 1989 Michel Mayor convinced the director of the OHP, Philippe Veron, to commission the construction of ELODIE, achieving a precision of only 15 m/s. On the basis of the DM survey, the sample of stars that were not spectroscopic or visual binaries were selected for further observation. Among these 142 solar-type stars was 51 Peg, and already after a few months in the winter of 1994/95 the Swiss team had a first ephemeris of its radial-velocity variation. Confirmation of the stability of the orbital solution in the season of 1995 led to the very first announcement of the detection of an extra-solar planet (Mayor & Queloz 1995). Given such spectacular and historical success, CORALIE was built in 1998 as a dedicated instrument for planet searches at the 1.2 m telescope on La Silla. Most recently, HARPS started its operation in 2003 with a radial-velocity precision of about 0.3 m/s. This is a factor 1000 improvement in 25 years over the old CORAVEL.

The original Swiss search for an exact description of multiple stars has evolved through tremendous technological and methodological progress into the age-old quest for the existence of other worlds. As such, DM represents a truly great scientific story leading to the establishment of rigorous longlasting scientific knowledge and the stimulation of interest by the public who see a return on their investment into a truly astronomical enterprise.

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