*Transactions IAU, Volume XXXIA*
*Reports on Astronomy 2018-2021*
*Maria Teresa Lago, ed.*
© 2021 International Astronomical Union
DOI: 00.0000/X000000000000000X

**COMMISSION G1** **BINARY AND MULTIPLE STAR SYSTEMS**

**PRESIDENT** **Virginia Trimble**
**VICE-PRESIDENT** **Christopher Adam Tout**
**SECRETARY** **John Southworth**
**ORGANIZING COMMITTEE** **Scott William Fleming, Ilya Mandel, Brian D. Mason, Terry D. Oswalt, Alexandre Roman-Lopes**

**TRIENNIAL REPORT 2018–2021**

## 1. Activities of IAU Commission G1 during 2018-2021

by Virginia Trimble (President),
as transcribed by David Soderblom (Division G President)

It has been a very good three years for binary and multiple systems of stars! If you go to the Astrophysics Data System (which we all know and use more often than we are perhaps prepared to admit) and ask it for any author in the period 2018-02 to 2021-02 and then, sequentially, "binary star," "double star," and "multiple system of stars" there comes back (or did on about 10 March 2020, for the three headings) 9,914 papers with 77,340 citations; 2,496 papers with 14,756 citations, and 3,982 papers with 24,069 citations, respectively. Thus if the three were human beings, they would have $h$ indices of 88, 50, and 57 respectively. There is a small catch: the words do not have to be contiguous in the abstract or keywords, they just both have to be there, so a few of the papers retrieved are not even about astronomy. It is a bit like a very earnest, literal-minded dog, who, asked to bring *The Times*, returns with three discordant watches.

The most-cited binary star paper was B.P. Abbott et al.: "GWTC-1: A gravitational wave transient catalog of compact binary mergers observed by LIGO and Virgo during the first and second observing runs." (Physical Review X 9, 1040). The second half of run 3 was cancelled because of Covid19, and the best way to keep up to date on the subject is via the LIGO Wiki and one of their own web sites:

https://www.ligo.orgidetections/031catalog.php.

These detections have spawned a very large number of associated optical observing attempts and theory of the evolution of close, massive binary systems. Particularly notable has been:

- The event GW170817, a pair of neutron stars with a $\gamma$-ray burst and other electromagnetic counterparts;
- a possible NS+BH merger;
- GW190814 with no EM counterpart found;
- and one that fell in the gap between masses of neutron stars and black holes as found in X-ray binaries.

The wave form before a merger tells you the masses of the component stars, the wave form afterwards the mass of the-merger products. The difference, times $c^2$ is the inherent energy released in gravitational waves. The amplitudes of the events as seen by Virgo, LIGO, et al. tell you the energy flux received at earth, so the combination reveals the luminosity distance to the event. If there is a host galaxy whose redshift can be determined, we have an independent handle on the Hubble constant, by a method they are calling "a standard siren."

This leads naturally to the second most cited binary star paper from the triennium (this favors things early in the time frame of course), which is A.G. Riess et al. (2019 Astrophys. J. 876, 85) on the distance to the Large Magellanic Cloud. They use Cepheids, of course, but also detached eclipsing binaries. Provided you can calibrate stellar surface brightness vs. color, this constitutes a geometrical method, like heliocentric parallax, called dynamical parallax, suggested at a 1996 conference by a stalwart of the binary community, Bohdan Paczynski [in 1997 M. Livio, M. Donahue & N. Panagia, eds. *The Extragalactic Distance Scale*, Cambridge University Press p. 273], where Paczynski claimed that one could reach 1% accuracy in distance for all Local Group galaxies. It is therefore probably relevant that the LMC detached eclipsing binary data come from G. Pietrzynski et al. (2019, Nature, 567, 200), with nine of the authors from the Nikolaus Copernicus Astronomical Center in Warsaw (Paczynski's one-time home institution), and with others from other Polish institutions, as wells as Chile, USA, and Germany. They used data from the ESO Very Large Telescope Interferometer. At the 1996 conference, Paczynski said firmly that only the geometric methods – heliocentric, dynamical, and expansion – parallaxes are distance measurements. The others (Cepheid, supernovae, RGB tips, etc.) are merely distance indicators. The published version is less formal about this, so you might or might not be impressed that Riess et al. (2019) calibrate a Hubble constant of $74.03 \pm 1.41$ km/s/Mpc.

It has been a particularly fruitful triennium for space-related contributions to binary star research. While Kepler turned off in late November 2018, TESS (the NASA Transiting Exoplanet Survey Satellite) and GAIA (undoubtedly an acronym for something, but its goal is positions, proper motions, and other facts about a billion or more stars in the Milky Way and whatever else drops photons on its detectors). Just for fun, A. Clare et al. (2018 A&A 618, 20) used both the old and the new, TESS, Kepler, CoRoT, and MOST data, to improve knowledge of limb darkening, essential in the interpretation of light curves of eclipsing binaries as well as transiting exoplanets.

In the"ingenious methods" department, we find S.J. Murphy et al. (2018 MNRAS 474.4322) who located 341 new K binaries from the phase modulation of light curves of pulsating stars recorded by Kepler. P. Kervella et al. (2019 A&A 623, 72), on the other hand, compared proper motions from GAIA Data Release 2 with the corresponding numbers from Hipparcos vs. Gaia positions. Thirty percent of the stars out to 50 pc showed 3-$\sigma$ or more differences. For many of these 6,741 stars with proper motion anomalies, the cause is likely to be an unseen companion. In the specific case of the $\alpha$ Centauri system, comparison of the proper motions on the two time scales demonstrates that Proxima Cen is bound to the other two stars. This has been a very long-standing issue.

Unlike Kepler and CoRoT, TESS has observed the majority of the sky, and so has provided light curves for thousands of binary stars with total- or partial eclipses. This archive includes many systems of particular interest, or that benefit from a long observational history. The data have led to the discovery of multiply-eclipsing systems such as BD Ind (T. Borkovits et al. 2021, MNRAS in press, arXiv:2103.00925); pulsations in high-mass binaries such as V453 Cyg (J. Southworth et al. 2020 MNRAS 497, L19); new apsidal motion periods (D. Baroch et al. 2021 A&A in press, arXiv: 2103.03140 who propose to use the TESS data to test gravitational theories), and a detailed study of

AI Phe (P.F.L. Maxttd et al. 2020 MNRAS 498, 33). They have used the Kepler light curves, modern (ground-based) Echelle spectroscopy, and a range of modeling codes to zero in on the masses and radii of the stars to 0.1–0.2% precision (the two members of the G-1 Commission Committee who identified this paper as a highlight of the triennium slightly disagreed on the precision). TESS continues to prowl the sky and will provide repeat observations of many systems, enabling a range of studies in the time domain.

The GAIA data releases to date have also been most fruitful in identifying new binary systems and improving our knowledge of previously-known ones. In roughly chronological order, some of the highlights include:

- K. El-Badry & H-W. Rix (2018 MNRAS 470, 4884) identified several thousand wide systems with a white dwarf component and concluded that WD recoil was important in determining the distribution of separations.
- P. Kervella et al. (2019, ASA 623 and 117) have investigated the multiplicity of Galactic Cepheids and RR Lyrae stars among both common proper motion pairs and stars with proper motion anomalies between Gaia and HIPPARCOS data.
- F. Jimenez-Esteban, E. Solana, & C. Rodrigo (2019, MNRAS 157, 78) have compiled a catalog of wide- and multiple systems among bright stars by combining Gaia data with observations from the Virtual Observatory.
- K. Hartmann & S. Lepine (2020 ApJS 247, 66) take us to still larger numbers with a catalog of 99,203 wide binaries found in Gaia, supplemented by the SUPERBLINK catalog of high proper motion stars

Sometimes, of course, just one peculiar star like V473 Lyr, a sort of Cepheid, is worth an individual study, this one employing X-ray data to identify a low-mass companion (N.R. Evans et al. 2020 AJ 159, 12).

But reaching a million binaries from Gala Data Release 3 was perhaps inevitable. In any case, K. El-Badry, H-W Rix, and T. Heinz have done it (2021 MNRAS accepted and arXiv2101.05282v3). The duplicity of individual targets will be considered first during the reduction of Gaia data to be published in DR3, due in the first half of 2022.

Coming back to earth and some of our more traditional territories, we found *The Updated Multiple Star Catalogue* (A. Tokvinin 2018 ApJS 235, 6). It reports about 2000 hierarchical systems with three to six or seven components, The highest multiplicities are often found in moving groups. For all the systems recorded, the ratios of large to small perioids or semi-major axes suggest all are stable. Multiple stars appear also in A.M. Price-Whelan et al. (2018 AJ 151, 16), a compilation from early in the triennium of APOGEE binary companions of evolved stars. From another ambitious project, E.L. Nielsen et al. (2019 AJ 158, 63) report that the Gemini planet imager, looking at 300 stars, found three brown dwarf companions, with properties suggesting that brown dwarfs form by gravitational instability. This was the paper with the largest number of citations in the triennium retrieved from ADS with the key words double star.

Turning to the theorists, Y. Gotberjet al. 2018 (A&A 615, 78) discussed subdwarfs and Wolf-Rayet stars together, on the grounds that both have had their envelopes stripped off as products of binary star evolution. K.J. Shen et al. (2018, Ap. J., 865, 15) came out in favor of white dwarf pairs (double degenerates) as the progenitors of type Ia supernovae. There were, of course, other papers supporting SN Ta from binaries with one white dwarf being driven above the Chandrasekhar limit by mass flow from a main sequence star or red giant. companion (single degenerate scenario), various observations claimed as relevant to the issue (no obvious surviving companion star, but also no obvious WD pairs that if merged would reach the Chandrasekhar limit in the next very many years) suggest that the answer is probably "both please." One is then puzzled that the events all look so similar.

E.R. Stanway and J.J. Eldridge (2018 MNRAS 69, 75) have redetermined the ages of various older stellar populations (including but not limited to globular clusters) using evolution of stellar populations that include a contribution from binaries. The populations come out a bit younger than in earlier work.

Another aspect of binary evolution is the gradual circularization of the orbits by tidal effects. For systems in clusters, it ought to be the case that the time scale to get the binaries to their current orbits (that is, the maximum period at which all orbits are circular) and the age of the cluster from its H-R diagram would be the same. It is not at all clear that this is the case (A.C. Nine et al. 2020 AJ 160, 169), although the situation is improving (A.J. Barker 2020 MNRAS in press, arXiv: 2008:0362; C. Terquem 2021 MNRAS in press, arXiv:2102.10047). It should be possible to observe the tidally-driven orbital decay of hot Jupiters with current (NGTS and TESS) or future (PLATO) facilities, providing more information about tidal processes and a nice example of synergies between different fields of astronomy.

Just under the line for the triennium, from the on-line version of *Science* comes ANIA radio study of the jets of Cygnus X-1, the first X-ray binary established as containing a black hole. Done with the VLBA, this is the equivalent of an optical study of a visual binary and has upped the best estimate of the BH mass from 14.8 to 21.2 solar masses. The O star has correspondingly grown to about 40.6 solar masses. We suppose that, in so far as "one is a discovery" this slightly eases the problems in making from stars black holes as massive as some of those in LIGO events.

Another case of a single star deserving its own paper was the peculiar Type II Cepheid whose period evolution and orbital elements have been investigated by G. Csornyei & L. Szabados 2019 Ap&SS 364. 171).

Because many of the binary- and multiple results were connected with space- and ground-based surveys, results are spread across many conferences on many subjects. The binary/multiple meeting territory, in contrast, was rather sparse. Universe of Binaries took place 7-11 September 2019 in the Czech Republic, with its web site still perhaps alive at https://binaries.physics.muni.cz. And, similarly, Exploring the Importance of Binary Stars through the Universe graced September 18, 2019 at the University of Warwick, UK via the fairly memorable site name https://www.uksolphyserg/conference/one-day-science-meeting-the-importanct-of- binary-stars-through-the-universe/. In contrast, ESO decided to postpone The Binary Effect on Stellar Wind (BINAGB2020)
https://www.eso.org/sci.meetings/2020/binagb2020.html.

It has been a while since an IAU Symposium focused on binary and/or multiple systems of stars, nor are we conscious in the items selected, or even proposed, for the upcoming IAU General Assembly. Clearly the next regime must try harder, and in this respect it would be wonderful if we were allowed to have Junior Members on Commission Committees! Per aspera ad Binastro!

Near the end of the triennium, we lost perhaps the most persistent binary star astronomer in the history of the subject, Roger Francis Griffin (23 August 1935 - 12 February 2021). A fine obituary appears on the web site of St. Johns College, Cambridge (www.joh.cam.ac.uk), and another is planned for Observatory Magazine, where he published so very many of his papers. From the G-1 point of view, he developed and built the first photoelectric radial velocity spectrometer (1967 Astrophys. J. 148, 165), a paper that had about 10 citations (excluding self-citations) in the triennium, including two in Nobel Prize Lectures by the discoverers of 51 Peg b. Griffin himself used the device and later incarnations thereof for a series of 265 numbered papers (1 - 265, he having wisely eschewed the use of Roman numerals in this context), the last eight appearing during the triennium. Each presented an orbit or orbits for one or more spectroscopic binaries (often SB1s), many of unprecendently long periods. The 1967 description was his second-most cited paper, the most cited being J.E. Gunn & R.F. Griffin (1967 Astron. J. 84, 752) on velocities of individual stars in the globular cluster M3. The data came from a radial velocity spectrometer constructed specifically for use on the 200-inch telescope on Palomar Mountain. A much shorter series of papers with R. Elizabeth Griffin on stars with composite spectra (often unresolved binaries) came to an end with XXIII in 2020. The earlier ones appeared in the *Journal for Astrophysics and Astronomy*, the later ones in *Astronomische Nachrichten*. As early as 1992, a workshop (A. Duquennoy & M. Mayor Eds. Binaries as Tracers of Stellar Formation, Cambridge Univ. Press, ISBN 0521433584) had been organized in his honor in Bettmeralp. A focus was the correlation of orbital eccentricities with period, an effect particular conspicuous in the long-period systems explored by Griffin. He sanctioned, but did not vet, a statistical analysis of the 559 systems in those 265 papers by H. Boffin & V. Trimble (Observatory 140, 1-10)

The author is grateful to the (subset of) members of the 2018-2021 Committee of G-1 and candidates for the next triennium who provided input on their favorite binary and multiple star events of the past three years.

Virginia Trimble
Department of Physics and Astronomy
University of California
Irvine CA 92797 USA
vtrimble@uci.edu