Astro2020 Science White Paper

Fundamental Astrophysics from Stellar Multiplicity: from Precision Calibrations to Re-Ionization and Gravitational Waves

Thematic Areas:
☐ Stars and Stellar Evolution
☐ Formation and evolution of compact objects
☐ Multi-Messenger Astronomy and Astrophysics

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Abstract

Stellar multiplicity is a storied topic, with an undeserved slightly stale smell to many in astrophysics. But binary stars play a pivotal role for the coming decade, enabling – or limiting – our understanding of star-formation, stellar evolution, stellar death, supernovae and black hole formation, and cosmic re-ionization. In addition, most spectacular gravitational wave events will hail from some form of binary. What physics can be gleamed from multiple systems varies widely with the masses, orbits and evolutionary phases of the stars or stellar remnants involved. Yet, much of it must draw on the coherent joint analysis of precise, time-domain data from imaging, astrometry and spectroscopic surveys across the sky: if – and only if – surveys in all these categories can be put in place, and account for stellar multiplicity in their design and analysis, this crucial set of astrophysical directions can be taken to a whole new level over the coming decade. A wide range of powerful theoretical modeling tools are in place, awaiting far better observational constraints. Precision multi-epoch photometric surveys across the sky are set for the coming decade (TESS, ZTF, LSST, etc..), and an astounding astrometric survey (Gaia) producing data releases throughout the 2020s exists. All-sky, multi-epoch spectroscopy surveys are just as crucial, but those need support to become reality.

Stellar Multiplicity as Key to Fundamentals of Astrophysics

Hardly any stars are single: they have one or more companion star, or brown dwarf or planet. This multiplicity affects the star system's structure and evolution literally from their cradle to their grave. Multiplicity is the dominant or sole channel to produce some of the most spectacular astrophysical phenomena such supernovae or gravitational wave events [1]; and they seem the way to make gold. Multiple systems also have unique and enormous potential to calibrate the stars themselves [2] and serve as laboratories to test a range of other physics.

Qualitatively this potential of "binaries" is well known. Here we just summarize, quasi as an extended bullet list, the main aspects where understanding multiple stellar systems will be crucial in the 2020s. By no means this is intended as a thorough review and we refer the reader to a limited number of key articles and references therein throughout our text. We broadly divide this sketch into aspects of stellar physics and (other) fundamental astrophysics. And we make the case that it takes the *combination* of photometric, astrometric and spectroscopic time-domain surveys across the sky to make good of this potential, by determining the distributions of masses, radii, orbits, evolutionary stages, etc.. of the components in multiple stellar systems. This white paper focuses on optical surveys, mindful of the fact that theoretical models of binaries [3, 4], radio observations of binary pulsars [5] or upcoming X-ray observations deserve similar attention.

Stellar Physics

Star Formation:

Stellar multiplicity is one of nature's answers where to put angular momentum during star formation; but so are the non-exclusive alternatives of stellar and planetary companions. Much of this process remains to be understood: for what primary masses and metalicities is planet system formation the most common mode, for which binary star formation? Why is there a brown dwarf desert? Is the formation of (very) wide binaries a consequence of the clustered birth environment?

Stellar Structure, Evolution and its Calibration

Much of stellar evolution, of both single and multiple stars, is qualitatively understood, but not quantitative enough to form the foundation that the age of 'precision astrophysics' calls for. When it comes to binaries, however, most questions around 'how often does this happen, and how important is it to the rest of astrophysics' remain open, from the mass (transfer) growth of white dwarfs to the greatly altered lifetimes of massive stars in binaries. But even at larger separations tides, and the mixing they may induce, can greatly change the evolution, blunting stars as astrophysical precision tools if not understood. Distant companions to a close binaries may drive their secular evolution decisively; but we do not yet know how (much).

Binary stars are in many ways the ideal self-calibrators and probes of evolution models [6]: when widely separated (and Gaia has given us a million examples now) they offer us observables for two stars born at the same time from the same material, but with different masses. When the components are close in they offer us dynamical mass measurements that can compliment stellar evolution estimates, e.g. from asteroseismology. The power to test models gets yet amplified if the system is eclipsing, which provides numerous geometric constraints [7]. Such tests are of particular importance for massive stars ($\geq 3\ M_{\odot}$), where asteroseismology has shown us that current models are a poor description of reality.

Understanding Stellar Death: It is becoming increasingly clear that close binary systems play a central role for supernovae, especially for the cosmologically crucial type Ia [8]. Merging, possible hierarchical merging, or mass transfer from a companion must play a role in leading to a SN Ia. Yet, which channels matter most, and whether they can provide quantitative explanations is not understood yet: we need to know the distribution of multiple white dwarfs better. And whenever close, or even merging, binaries are involved, as for SN Ia, the question of distant companions driving the evolution of the close pair returns.

We basically know of no single stellar-mass black hole in our Galaxy: the few known cases are in X-ray binaries. Yet, there may be vastly more stellar mass black holes (BH) in binaries that are not accreting. Understanding the distribution of their masses would matter for understanding the relation between precursor and BH masses; understanding their separation distribution would teach us about any recoil during black hole formation [9]. Finding BH companions to massive stars would teach us about possible future BH-BH mergers, and so would a census of neutron stars (NS) in binaries around normal stars. In all these systems, dark companions would only be apparent from the effect on their visible companion: ellipsoidal light-curves induced by tidal distortion, astrometric wobble and radial velocity variations. But those are rare circumstances, with some of their signatures mimicked by far more boring circumstances (unseen M-dwarf or white-dwarf companions etc..): only the combination of upcoming photometric, astrometric and spectroscopic across the sky can tackle them.

Cosmology and Fundamental Physics

The impact of stellar multiplicity, however, goes well beyond stellar physics *per se*. It has immediate bearing in the physics of degenerate matter, on the epoch of re-ionization, on testing gravity, and of course on gravitational waves.

Equations of State for Dense Matter: Both WDs and NSs are extremely valuable laboratories to study dense matter. But e.g. our empirical understanding of maximum NS and minimum BH masses is still limited [10] by the dirth of examples: GW170817 is currently expected to have formed a low mass ($2.7 M_{\odot}$) BH, putting one (!) observational constraints on this limit. Expanding the parameter space of known BHs in binaries will be central to understand this crucial limit.

Cosmic Re-Ionization: Our understanding of what sources re-ionize the universe has somewhat stalled: single massive stars and AGNs seem insufficient, and other frequent sources of copious and quite hard UV emission that can escape from galaxies is needed. The fact that so many massive stars are in close binaries with other massive stars may offer the solution: their common evolution, the possible repeated mass transfer between them, the ensuing exposure of very hot Helium stars, and the effective tidal mixing that extends their lifetimes may all just come together to explain re-ionization [11]. If massive binaries indeed end up effecting cosmic reionization, any quantitative inference at $z \sim 8$ must be founded on understanding the population properties of present-day binaries exquisitely.

Testing Dark Matter and Gravity: Binaries with separations approaching a parsec are marginally bound systems, where very small accelerations can make a large difference, making them sensitive probes of gravity. The enormous astrometric precision of Gaia has just made it possible to identify such ultra-wide binaries in great numbers and measure them in great detail. Such systems can constrain the presence of macroscopic dark matter constituents, such as black holes (which would destroy wide binaries), and they can serve as tests of the acceleration law itself [12]. Such tests require multi-epoch spectroscopy to make sure that unresolved binarity in one of the components does not mimick long-distance accelerations.

Sources of Gravitational Waves: Eventually, continuous sources of gravitational waves may be detectable, such as spinning neutron stars. Yes, arguably, the most exciting and most informative gravitational wave (GW) detections come from merging compact objects, foremost merging binary BHs and NSs [13]. Already the first few events have provided revolutionary insights: nature finds ways to make BH-BH binaries of $\sim 30\mathrm{M}_\odot$ each [14], and neutron stars mergers are the central channel of making heavy (r-process) elements. GW science is poised to become one of the great three themes of astrophysics, next to exoplanets and cosmology/structure formation. Yet, GW science in the 2020s is in good part binary star (or stellar remnant) science. Certainly when the field of GWs moves beyond the immediate excitement of discovery and analysis and turns to the relative frequency of different events, the prehistory of GW events will become crucial. A comprehensive, and precise study of binary star-star, and star-remnant systems will become an indispensable foundation for a wide swath of (rightfully “hot topic”) astrophysics.

Experimental Approaches

Stars have been studied quantitatively since the 19^{th} century, measuring and monitoring their fluxes and with parallaxes luminosities, tracking their positions on the sky (reflecting linear motions or orbits), and taking spectra; all this has been meshed with epochal efforts on modelling both stellar structure and stellar spectra.

All these techniques have taken decisive leaps forward in the last decade: photometry has reached a precision to enable wholesale asteroseismology (COROT, Kepler, TESS). The power of asteroseismology has shown us that we understand much less about stars than we thought: the open issues brought to the surface matter whether one cares about stars themselves, or cares about them merely as precision tools for other questions. Similarly, the Gaia mission through its globally accessible data [15] is enabling breakthroughs in stellar physics even only through its parallaxes. Finally, the last decade has seen stellar spectral surveys reach an ’industrial scale’ (SDSS (SEGUE/APOGEE), RAVE, LAMOST, GALAH, etc..), laying a foundation both for

Galactic archaeology and for understanding stars. The wealth of new opportunities on understanding single stars as a first step has left stellar multiplicity somewhat in the wake. The upcoming decade can and should change this.

Stellar Multiplicity: A Posterchild of Time-Domain Astrophysics

Binaries are systems whose observables inevitably have an explicit time-dependence, making them poster-children of time-domain astrophysics (possibly, but not necessarily, of "transient astrophysics"). To tackle all the above themes, one would need to have a comprehensive, well-characterized distribution of stellar multiplicity. For binaries, that would be a probability distribution describing the most important parameters, e.g. $p_{12}(M_1, M_2, a, e)$, augmented when important by the 'nuisance parameters' of inclination and orbital phase, and additional information about the components' radii, effective temperatures, ages and level of (tidal) deformation. But the general multiplicity function $p_{123..}$ is also critical, if hierarchical systems drive binary structure in important regimes.

The practical challenge lies in the fact that vastly different regimes in (M_1, M_2, a, e) parameter space are of crucial importance: both the $M_i \geq 8\mathrm{M}_\odot$ (future GWs) and the $M_i \leq 1\mathrm{M}_\odot$ (WDs) regime have fundamental physics implications. Separations of ≤ 0.01AU lead to mergers, separations of $\geq 100,000$AU test gravity.

The other practical challenge lies in the fact that no single experimental approach (lightcurves, astrometry, spectra, respectively) can solve most systems uniquely.

Multi-Band Light-Curves: Well-sampled stellar lightcurves, with a precision of 10^{-2} to 10^{-5} mag, are now becoming available across the sky with e.g. TESS, Gaia, ZTF (and soon LSST). They are the first powerful tool in diagnosing binaries, especially for small values of a/R_*, where a is the orbit's semimajor axis, and R_* is the radius of the (larger) star. Illumination effects and ellipsoidal distortions cause sinusoidal variations that can be modelled in detail with established tools, and yield periods and often a joint constraint on R_*/R_{Roche} and $\sin i$. For eclipsing systems, of course, the relative radii (in units of a) become exquisitly constrained. In general, lighcurves become increasingly informative the closer the binary components are, in units of a/R_*.

Astrometry: Astrometry, in particular that from Gaia, often constrains parallaxes permitting the direct conversion of apparent to physical quantities. But starting with Gaia DR3 (2021) there will be direct astrometric orbit solutions for $> 10^5$ stars with orbital periods up to 20 years[1]. From those alone one one can derive P, a[AU], sin(i) and $M_2^3/(M_1+M_2)^2$ with no inclination ambiguity. Given an apparent brightness and a distance D_* from us, the precision of the astrometric inferences scales with a/D_*, as long as an appreciable fraction of the orbit is traced.

Multi-Epoch Spectroscopy: Even single epoch spectra can be very constraining, as they allow an astrophysical estimate of M_1 if one component dominates the light, breaking many degeneracies of the previous approaches; and they can lead to a spectroscopic determination of the luminosity ratio L_1/L_2, which can astrophysically constrain M_1 *and* M_2. Multi-epoch spectra (whether for so-called SB1 or SB2 binaries) add enormous dynamical information from the velocity curve(s) $v_1(t)$ (and $v_2(t)$). While typically 10 epochs are needed to solve a system fully, even 2 or 3 epochs for many objects are enough to get tight constraints on populations, or to break

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[1] In almost all cases of $P < 20$ yrs the components will be unresolved and Gaia measures the apparent orbit of the light-centroid

degeneracies for well-sampled light-curves or astrometry. Obviously, velocity signals reflected in spectra scale as $\sqrt{m/a}$ independent of distance. In particular, finding 'unseen' companions to normal stars, whether they be the holy grail of BHs, or NSs, or "only" WD's and brown dwarfs, needs extensive sets of velocity curves across the sky; finding candidates, needs only a modest number of epochs.

The Case for Joint Photometric-Astrometric-Spectroscopic Analysis

The only case where any one of the techniques alone can solve a binary/multiple system is when both components are seen separately, yet the orbital periods are short ($<$ few years); these cases are rare. In general, the construction of $p_{12}(M_1, M_2, a, e)$ requires the combination of these techniques. This is particularly true for some of the most interesting cases, where one component is unseen and the phenomena are rare (NS or BH companions, binary WDs, 'brown dwarf desert'). Lightcurve signals typically scale as R_*/a, astrometric signals as a/D_*, and velocities as $\sqrt{M/a}$: different approaches have their strengths simply in different regimes. Bringing this multi-pronged approach to bear is particularly important in trying to find the extremely rare, but extremely informative cases. There, formal redundancy between the different approaches results in robust rejection of interlopers, and may be the only way to find appreciable numbers of stellar mass BHs around normal stars.

Prospects and Needs for the Next Decade

Why is this science case laid out in a white paper for Astro 2020? It is because not all tools are in place for the photometric-astrometric-spectroscopic approach that must be the empirical foundation for unlocking all the above potential of multiple stellar systems. For lightcurves, TESS (to 13mag), Gaia and ZTF to 18mag, LSST to 20mag (an in many bands) will provide superb data; late in the decade, ESA's PLATO mission can provide a new boon. Overall, the time-domain photometry is in great shape.

For astrometry, the Gaia mission with its globally accessible data, and data releases expected through 2027 (depending on mission extensions) provides a giant leap forward. In particular, the Gaia DR3 release with its first orbital solutions will be a game-changer. The fact that the two most highly cited papers in global astronomy 2018 are Gaia data release papers, attest to the missions's profound and instant impact already now.

Gaia has been conceived in the last millenium. Yet, there is no large-scale coherent effort towards a next-level astrophysics space mission. The next years are the time to get going.

Multi-epoch spectroscopy is the third indispensible element in unlocking the power of multiple stellar systems. And while all-sky time-domain photometric surveys abound, all-sky, time-domain spectroscopic surveys do not. The Gaia mission provides such a survey, albeit restricted to spectra in a very narrow wavelength domain (around 8500Å) and to bright magnitudes (G<15). *SDSS-V: Pioneering Panoptic Spectrosopy* is the only all-sky, multi-epoch spectroscopy effort underway; it's implementation is foreseen for the early 2020's, but its success still depends on funding. As for the photometric and astrometric surveys, survey speed and sky coverage matter more for such spectroscopy than great survey depth.

This white paper ultimately argues that the US community needs to ensure that all-sky, time-domain spectroscopic survey capabilities exist, and needs to think about an astrometry space mission beyond Gaia.

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