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Forming the Progenitors of Explosive Stellar Transients

INVITED TALK

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Abstract. Explosive stellar transients arise from diverse situations, including deaths of massive stars, a variety of thermonuclear outbursts, and compact-object mergers. Stellar interactions are heavily implicated in explaining the observed populations of events, and not only those where binarity is obviously involved. Relationships between these classes probably help to elucidate our understanding; for example; the production of double neutron-star mergers from field binaries is thought to be heavily biased towards routes involving stripped core-collapse supernovæ. As we gain an ever more synoptic view of the changing sky, theorists should be mindful of developing an ability to take robust quantitative advantage of the available *population* information to help constrain the physics. This is complementary to aiming for deep understanding of individual events.

Keywords. Stars: binaries: close, blue stragglers, evolution, novæ, cataclysmic variables, binaries: general, supernovæ: general, X-rays: binaries.

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1. Introduction

Time-domain astronomy goes back into antiquity, and still the diversity of observed explosive stellar transients continues to increase. Our knowledge of the extent of the universe indicated to Baade & Zwicky (1934) that the *novæ stellarum* contained a class of intrinsically more luminous 'super-novæ'. Those supernovæ (SNe) were soon themselves *provisionally* divided into 'Type I' and 'Type II' by Minkowski (1941). Standard core-collapse SNe and thermonuclear explosions, both terminal and repeating, have been joined by a great menagerie of events. Even during the week before this Symposium, Arcavi *et al.* (2017) published their discovery of an extraordinary new explosive transient.

Understanding the formation of these events does not only require understanding single-star physics. Stellar interactions are self-evidently required when modelling transients involving accretion from mass transfer, or stellar mergers, e.g., X-ray binaries, Type Ia SNe, LIGO gravitational-wave merger sources, and novæ (classical, dwarf or recurrent). Moreover, massive stars are so commonly members of interacting binaries that understanding core-collapse SN populations requires taking into account binary effects (see, e.g., Podsiadlowski *et al.* 1992). Given the predominance of massive interacting binaries – for modern work see, e.g, Kobulnicky & Fryer (2007) or Sana *et al.* (2012) – it should be obvious that the fraction of non-interacting massive stars is much smaller than the fraction of *'normal'* Type II-P SNe. For massive-star populations, binary effects should not be ignored until single-star models do not work.

Using population information to constrain physics. We wish to understand the physics involved in producing these explosive transients. However, there is no realistic prospect that we will be able to solve that fully through first-principles simulations. Interpretation

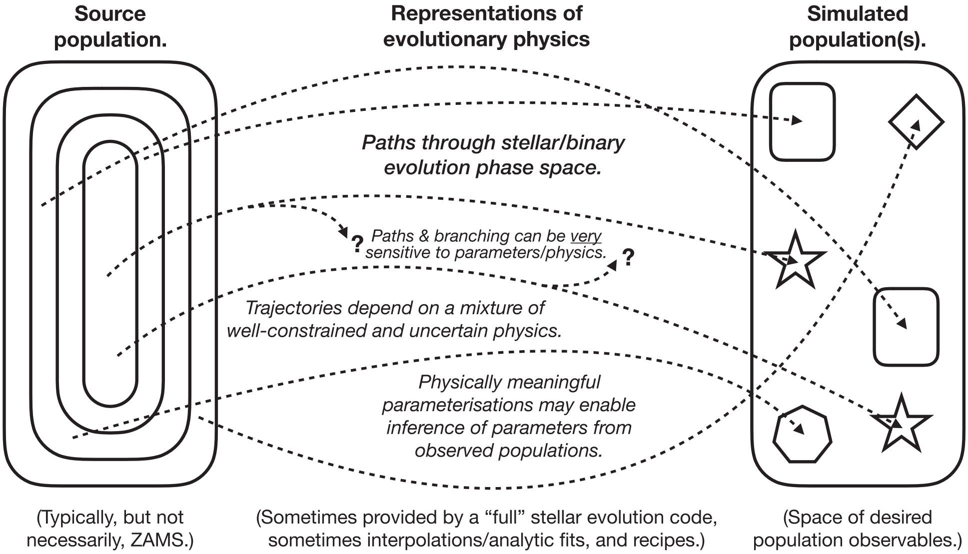

Figure 1. Each trajectory describes schematically the evolution of an individual system. Physics makes some of those configurations more commonly accessible than others. Binary population synthesis methods simulate the evolution of many systems, often to make predictions in a space of population observables, or to try to infer physical parameters from observations.

of observations will be required. Much of the information from the sky is *population* information – typical evolutionary time-scales are too long for us to watch changes happen, so we often constrain evolutionary processes by connecting different observed populations. We are familiar with interpreting systematic changes in host galaxy populations for different explosive transients in terms of differences in their progenitors.

Extracting information about physics from population information is an important task, but the value of population synthesis methods is sometimes doubted.† Fig. 1 illustrates schematically how binary population synthesis combines individual stellar and binary evolution trajectories into ensembles, appropriately weighted by the initial conditions. It would be valuable to improve our ability to constrain quantitatively the underlying evolutionary physics by comparison to the available observables – as long as that inference can be done robustly, without forgetting the implicit and explicit assumptions. This would be complementary to attempts to simulate directly the relevant physics.

2. Formation Models, Processes and Population

2.1. *Regulus*

Regulus (α Leonis) provides a beautiful introductory illustration to binary-star evolution pathways, including whether a given initial system will eventually produce an explosive transient. This bright star was found only recently, by Gies *et al.* (2008), to be a probable binary with an orbital period of ~40 d. Rappaport *et al.* (2009) interpreted the discovery in terms of the prior and future evolution of this naked-eye star, on which the following is based. The observed B-type star ($\sim$3.4 $M_\odot$) is best understood not as a main-sequence star of age ~150 Myr, but as a blue straggler of age ~1 Gyr. The present-day companion is probably a low-mass white dwarf (WD; $\sim$0.3 $M_\odot$), formed after the

† E.g., http://online.kitp.ucsb.edu/online/stars17/mandel/

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core of the star which was initially the more massive component was exposed during stable Roche-lobe overflow (RLOF).

Branching at the common-envelope phase. Since the Regulus system has a mass ratio of order 10, it is expected to undergo dynamically unstable RLOF after the present-day primary fills its Roche-lobe when crossing the Hertzsprung Gap, and will enter a common-envelope (CE) phase. Section 3 addresses CE phases in general. This particular CE phase leads to a merger, and presumably to an atypical single giant star. Alternatively, successful CE ejection may leave behind a binary system containing the present-day WD companion and a hot sub-dwarf companion (since Regulus is sufficiently massive for non-degenerate core helium ignition). For sufficiently *long* post-CE orbital periods, the sub-dwarf will have finished helium burning by the time the gravitational-wave radiation brings the components into a *third* phase of mass transfer, in which case the less massive of the two degenerate components will be the donor star. If the post-CE orbital period is less than approximately 80 minutes, the helium-burning star will fill its Roche lobe and transfer mass onto the WD; see Rappaport *et al.* (2009) for further details of all of the above. The future of Regulus is thus directly relevant to understanding the formation of transient populations, including thermonuclear transients from explosive ignition of thick helium layers.

The divergent potential outcomes from that CE phase exemplify the branching depicted schematically in Fig. 1. Small differences in parameter choices or initial conditions can lead to large differences in the predicted outcome. For similar types of branching we do not average away the uncertainties by simulating large ensembles in a population.

2.2. *Double neutron-star mergers*

One potential future for Regulus given by Rappaport *et al.* (2009) leads to a WD–WD merger. The path to that outcome is similar qualitatively to the canonical formation channel to double neutron-star mergers (DNS) – see, e.g., Dewi *et al.* (2006); for recent work, see Tauris *et al.* (2017). In both cases the primary star is stripped by stable mass transfer; a later phase of RLOF is unstable, leading to a CE ejection; a third phase of RLOF before the merger occurs from the CE-stripped secondary onto the remnant of the initial primary. This route for the DNS case is described at the foot of Fig. 2.

Branching at SN kicks. Unlike the Regulus case, this route to a DNS merger involves the possibility of a SN kick when each NS is formed, which might disrupt the system. The SN kicks illustrate a kind of branching in binary evolution phase space (Fig. 1) which is different from the CE-related branching to which we referred above. At our current level of understanding, individual SN kicks are not predictable deterministically in direction and magnitude. Population synthesis codes therefore split one pre-SN binary system typically into multiple notional post-SN systems via different kick realizations. The phase-space density for each such system is spread out at the time of the SN, which is not the case for a CE event where we generally assume a one-to-one mapping between pre-CE and post-CE configurations (even though we are not highly confident in that mapping).

Connections between populations; slices in evolutionary time. Fig. 2 shows how paths to the formation of one type of system contain subsets of other populations. For the route to the DNS formation outlined there, both of the SNe are stripped (Type Ibc), so there is an automatic connection between understanding DNS populations and (a subset of) stripped SN populations. Furthermore, the approach to the unstable RLOF phase in the DNS case involves wind mass transfer, so the system spends time as a high-mass X-ray binary. The lifetime of one system can produce multiple distinct explosive transients.

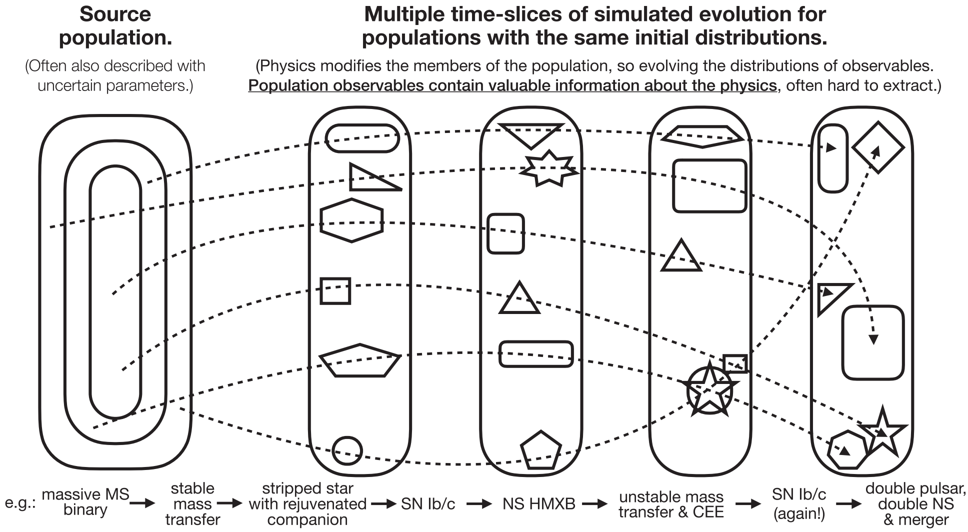

Figure 2. Individual systems may be members of different transient populations at different times, as illustrated by the canonical binary formation channel of a DNS merger. Different populations can often be seen as representing slices in evolutionary time. Connections between populations give information about evolutionary processes which we cannot observe directly.

3. Common-Envelope Evolution and Events

We might regard CE phases as temporary mergers, during which two stellar cores orbit inside one envelope. Some of the binary systems which enter a CE episode are expected to be able to eject their shared envelope, along with orbital energy and angular momentum, and to emerge as a tighter binary, as suggested by Paczynski (1976); others would merge. This process is thought to enable the formation of close compact binaries from relatively widely-spaced interacting binaries. Wide initial orbits help in allowing the cores of one or both stars to grow in mass before their respective stellar envelope is removed, which is favourable for the formation of relatively massive WDs and black holes, for example.

Simulations of CE phases have become increasingly impressive, but are still far from being able to claim that they include all the potentially relevant physics at all the potentially relevant scales of space and time. Empirical evidence will therefore remain important for drawing conclusions about the outcome of CE events. However, interpreting population evidence relies somewhat on our adopted parameterizations of the physics. First-principles theory and simulations should continue to guide those parameterizations.

Transients from mergers and CE ejections. An important recent development in the study of CE events is the recognition that they produce observable transients. Stellar mergers have long been suggested as potentially being responsible for some transients – see Tylenda & Soker (2006) and Ivanova *et al.* (2013a), and references therein. However, the key modern observation in understanding transients from CE events was provided by OGLE – itself a legacy of Paczyński. Tylenda *et al.* (2011) presented the orbital decay of a binary system which then apparently merged and produced the V1309 Sco transient. Ivanova *et al.* (2013a) used the initial conditions provided by OGLE to simulate the merger, and combined it with a semi-analytic treatment of emission from the ejecta. That explained specific characteristics of the event, and also the collective characteristics of several other unusual transients. The group of similar known transients is now growing relatively rapidly, as is the theoretical interest.

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This is an exciting time. Near-future transient surveys offer the realistic prospect that CE physics will be studied through regular observations of mergers and ejections, both individually and as a population. However, care should be taken in interpreting pre-outburst systems when only photometric colours and luminosities are available. The observations by Tylenda *et al.* (2011) were particularly powerful because the time-domain information meant that the pre-outburst system could be characterized well.

3.1. *The onset of CE phases*

Extended onset of CE phases. One canonical way for mass-transfer phases to become unstable is for the mass transfer to run away on a dynamical time-scale (see Paczyński & Sienkiewicz 1972). However, there are several ways to trigger the onset of CE phases; Ivanova *et al.* (2013b) include a recent review. The approach to such events may take far longer than a dynamical time-scale. Such extended onset of instability could potentially be misleading when interpreting pre-outburst photometry for transients from mergers and CE ejections; comparisons with single-star models may often not be robust.

One important example of this is the 'delayed dynamical instability', or DDI – see Hjellming & Webbink (1987). A donor star with a radiative envelope can respond to RLOF in a way that does not initially cause instability, but as the entropy profile in the outer layers of the envelope flattens the RLOF phase later becomes unstable. During such RLOF phases the appearance of the donor star can change drastically – see, e.g., the DDI example shown in figure 4 of Podsiadlowski *et al.* (2002). The DDI is not expected to be a particularly uncommon route to instability for donor stars; for example, it applies to donors with radiative envelopes and are crossing the Hertzsprung Gap.

Instability due to the response of the donor. Mass-transfer phases may also become unstable after a delay due to the response of the *accreting* star to the mass-transfer episode. The accreting star may itself expand into contact if it accretes faster than it can readjust thermally, as explored by Pols (1994). When both stars are overflowing their Roche lobes it is natural to expect that at least some of those mass-transfer phases will be unstable; see, e.g., Podsiadlowski (2010). A merger following such an instability helps to explain the individual SMC system R4 (see Pasquali *et al.* 2000) and populations of unusual core-collapse SN progenitors (see, e.g., Justham *et al.* 2014). Such an instability following the expansion of an accreting secondary into contact also provides an alternative route for DNS formation via 'double-core' CE evolution, as proposed by Brown (1995); see also, e.g., Dewi *et al.* (2006). Whilst the reasons that double-core CE evolution were proposed are no longer a worry – we expect that the standard CE route works – there is evidence that similar double-core CE evolution does occur, at least in lower-mass stars; see, e.g., Justham *et al.* (2011) and Şener & Jeffery (2014).

Stability and SS 433. Blundell *et al.* (2001) found that SS 433 is ejecting mass at a very high rate in the equatorial plane, probably in excess of 10^{-4} $M_{\odot}$ yr^{-1}. This might be taken to suggest that such extreme phases of RLOF are commonly stable. However, given the prior discussion about extended onset of instability in RLOF, one hopes it is clear that *we do not know* whether this mass-transfer phase will finally be stable for SS 433. Its orbital period is consistent with a Hertzsprung-Gap donor star; depending on the component masses, it is a natural candidate for later DDI, as was noted by King *et al.* (2000) and Podsiadlowski (2001). Alternatively, the equatorial outflow in SS 433 might be overflow from the gradual build-up of a common envelope around the two components, as discussed by Blundell *et al.* (2001). It would be an unhappy outcome (though an educational one) to lose such a beautiful source to the onset of instability.

4. Conclusions & Outlook

Time-domain surveys will provide vast amounts of population information, not only about explosive transients themselves but also about stellar and binary populations which are related to the formation of those transients. The prospect of significantly more information about transients associated with CE events (both mergers and envelope ejections) is particularly exciting, both for individual events and for the related population.

If we wish to take full advantage of the anticipated floods of new survey data for theory, population modellers should also develop good use of statistics. Binary population synthesis can naturally be viewed as producing probability distribution functions of observables across populations, with the model physics as a transfer function from the space of initial conditions to the space of relevant observables. Developing our use of binary population synthesis as a robust statistical tool will help us make best use of the information from the sky for probing the evolution of these systems, taking quantitative insight from connections between related populations, and so help in understanding the physics of processes which occur over time-scales too long to be observed directly.

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