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Blue straggler stars: lessons from open clusters

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Abstract. Open clusters enable a deep dive into blue straggler characteristics. Recent work shows that the binary properties (frequency, orbital elements and companion masses and evolutionary states) of the blue stragglers are the most important diagnostic for determining their origins. To date the multi-epoch radial-velocity observations necessary for characterizing these blue straggler binaries have only been carried out in open clusters. In this paper, I highlight recent results in the open clusters NGC 188, NGC 2682 (M67) and NGC 6819. The characteristics of many of the blue stragglers in these open clusters point directly to origins through mass transfer from an evolved donor star. Additionally, a handful of blue stragglers show clear signatures of past dynamical encounters. These comprehensive, diverse and detailed observations also reveal important challenges for blue straggler formation models (and particularly the mass-transfer channel), which we must overcome to fully understand the origins of blue straggler stars and other mass-transfer products.

Key words. open clusters and associations: individual (NGC 188, NGC 2682, NGC 6819) – binaries: spectroscopic – blue stragglers

1. Introduction

Open clusters hold many lessons about the origins of blue stragglers. One important entry-point is through years (and sometimes decades) of multi-epoch radial-velocity monitoring (for instance, as part of the WIYN Open Cluster Study; WOCS, Mathieu 2000). which reveal the blue straggler (and normal star) binary properties. In particular, the open clusters NGC 188 and NGC 2682 (M67) are home to the two most well-studied blue straggler populations. NGC 6819 is also providing important insights. These observations show that the blue stragglers and binaries are intimately linked, and that the blue straggler binary properties (binary frequencies, orbital elements and masses) are key to understanding their origins.

In general, we find very strong evidence that many blue stragglers in these three clusters formed through mass transfer from an evolved star onto a main-sequence star. However, it is very likely that all viable formation channels operate simultaneously to produce the blue straggler populations that we observe here. These blue stragglers offer very important guidance for formation models.

In particular, a few key blue stragglers in NGC 188 and M67, and their binary companions, are incredibly well characterized empirically. These blue straggler binaries are ideal for refining models of binary mass transfer and stellar dynamics (and their interface), and indeed much of this work is already underway. Yet, as I will highlight below, models still fail to reproduce all of the diverse empirical characteristics that we now know about these blue stragglers. The important next step is for equally detailed models to reproduce these observations.

2. NGC 188

NGC 188 is a 6-7 Gyr old open cluster at roughly solar metallicity and with a present-day mass of about 1500 $M_{\odot}$. The cluster is home to arguably the most well-studied population of blue stragglers in any star cluster. Mathieu & Geller (2015) discuss the observations and *N*-body numerical modeling of the cluster in depth. In summary, WOCS radial-velocities complimented by other ground-based observations (e.g Geller et al. 2008, 2009; Geller & Mathieu 2012) show that the NGC 188 blue stragglers have

- a binary frequency of 80% for orbital periods less than 10^4 days,
- typical orbital periods around 1000 days,
- a companion-mass distribution that is narrow and peaked around 0.5-0.6 $M_{\odot}$,
- modestly rapid rotation (faster than normal main-sequence stars of the same spectral type, though slower than predicted by some formation models),
- a bimodal radial spatial distribution,
- at least one blue straggler whose mass is greater than predicted by standard (single star) stellar evolution models, which can also be stated as being under-luminous for its dynamical mass.

The radial-velocity observations provide the first hint that most of the NGC 188 blue stragglers have origins in mass transfer; specifically, the ~1000-day periods and companion-mass distribution suggest Case C mass transfer from an asymptotic giant donor. This hypothesis was later confirmed with *HST* UV observations, that directly detect the predicted white dwarf companions (Gosnell et al. 2014, 2015). This study concluded that at least two-thirds of the NGC 188 blue stragglers formed through mass transfer. Furthermore, some of these white-dwarf companions are surprisingly young; four have cooling ages of <250 Myr.

The only two NGC 188 blue stragglers in short-period binaries each have their own intriguing characteristics that suggest formation through dynamical channels (though do not rule out a previous stage of mass transfer). One (5078) has a significantly non-zero eccentricity, despite having a period of ~5 days, well shorter than that expected to be circularized by tides (of ~15 days), given the cluster age. 5078 also has a blue straggler that is underluminous for its dynamical mass. The other (7782) is in a circular orbit with a period of ~5 days and contains two blue stragglers!

Geller & Mathieu (2011) performed extensive *N*-body modeling of NGC 188 with empirical initial conditions. These models reproduce the bulk properties of the cluster, the detailed characteristics of the main-sequence solar-type binaries (which are also well characterized observationally), and the binary orbital properties of the blue stragglers. However, the models are unable to produce the raw number of blue stragglers that are observed, and we suggest that this deficit stems from incorrect assumptions used in modeling mass transfer in `NBODY6` (and many other) codes. Also, the two short-period blue straggler binaries in the cluster, and particularly the short-period double blue straggler binary, pose serious challenges for the *N*-body model.

In summary, NGC 188 provides a somewhat unique and very valuable blue straggler population. The cluster is close enough that the blue stragglers are not particularly faint, and the blue stragglers are not very blue, which allows for plenty of narrow absorption features for precise ground-based radial velocities, and the possibility for direct detection and characterization of cooler white dwarfs. The conclusions drawn from these comprehensive NGC 188 observations may be useful in understanding the origins of blue stragglers in clusters with less complete observations.

3. NGC 2682 (M67)

M67 is also old (4 Gyr) and rich, with solar metallicity and has a very well-studied population of blue stragglers through a diverse set of observations. Again, the multi-epoch radial velocities are the cornerstone of our understanding of these stars (e.g. Latham 2007; Geller, Mathieu & Latham 2015), and thus far, the available binary characteristics of the M67 blue stragglers are strikingly similar to those of NGC 188. The M67 blue stragglers have a binary frequency of ~80% (11/14; again within periods of $\lesssim 10^4$ days), most with orbital periods near 1000 days, and two with short orbital periods. The similarities to the NGC 188 blue stragglers suggest that the long-period blue straggler binaries in M67 may also come from mass transfer, and a more thorough analysis of these M67 blue stragglers is underway.

M67 also has a population of well-studied "yellow giants", in between the blue straggler region and the normal red-giant branch on a color-magnitude diagram (CMD). These stars also have a high binary frequency (all those within a 30 arcmin radius from the cluster center are in binaries). One such binary, S1040, is known to have a He white-dwarf secondary, likely left behind after Case B mass transfer (Landsman et al. 1997, 1998). This star, and indeed the other yellow giants, may be blue stragglers caught evolving toward their giant branch (Mathieu & Latham 1986).

M67 is also home to one of the most well-studied and intriguing individual blue stragglers (S1082), which arguably provides our best evidence that blue stragglers form dynamically, or at least actively participate in cluster dynamics (Sandquist et al. 2003). This blue straggler lives in a triple system with an inner orbital period of about 1 day and an outer orbital period of about 1200 days (with an eccentricity of about 0.6). The inner binary is eclipsing and also a double-lined spectroscopic binary; the component masses are found to be 2.5 $M_\odot$ and 1.6 $M_\odot$. However, the turnoff of the cluster is only 1.3 $M_\odot$, and when decomposing the light of the system, the secondary appears to be underluminous for its mass (like 5078 in NGC 188). Further, the tertiary may also live in the blue straggler region of the CMD. So this system contains at least two, and possibly three, blue stragglers (defined by photometry and/or mass), which implies that at least five, and possibly six, stars must have been involved in forming this system!

Hurley et al. (2005) developed an *N*-body model of M67, using a similar code to that of the Geller et al. (2013) NGC 188 model but with different (less empirically motivated) initial parameter distributions for the binary stars. The M67 model succeeded in matching the general cluster characteristics (similar to the NGC 188 model) and managed to reproduce roughly the correct number of blue stragglers in the cluster (unlike the NGC 188 model). However the M67 model did not reproduce the observed binary properties of the blue stragglers or normal stars. Likely related, hardly any of the blue stragglers present in the M67 model at the cluster age were produced through Case B or C mass transfer. The M67 model provides a cautionary message: (*i*) The choices for initial conditions of the binaries impact the resulting production rates, dominant formation mechanisms and observable characteristics of exotic stars like (but not confined to) blue stragglers, and (*ii*) it is critical to know and match the true binary properties of both the normal and blue straggler populations in order to trust the predictions of a given model.

M67 and NGC 188 have arguably the most well-studied main-sequence and blue straggler binary populations and have the most targeted direct *N*-body models. Yet, both *N*-body models struggle to reproduce the detailed observations of both the normal and blue stragglers binaries simultaneously (both use a similar code, but different assumptions for the initial conditions). The next challenge is to improve the treatment of binary mass transfer in such models, in hopes that a future *N*-body model may truly succeed in reproducing the available observations of the binaries and blue stragglers in a star cluster.

Finally, I remind the reader that M67 is within the *Kepler/K2* survey; data for the M67 blue stragglers, and other exotic stars, are currently being analyzed.

4. NGC 6819

NGC 6819, an intermediate (2.5 Gyr) aged open cluster, tells an interesting story about Barium abundance enhancements amongst blue straggler stars (Milliman, Mathieu & Schuler 2015). Mass transfer from an asymptotic giant branch donor star should enhance the surface abundances of *s*-process elements, such as barium, whereas other formation channels do not predict an enhancement. Of the 12 blue stragglers in the Milliman, Mathieu & Schuler (2015) study, five show significant barium enhancement, indicative of a mass-transfer origin. However, four of these five have no detectable radial-velocity variations, implying orbital periods of >15,500 days for any possible companion. At these large orbital separations, models predict that only $\lesssim 0.1\mathrm{M}_\odot$ of material can be transferred (according to BSE; Hurley et al. 2002). Furthermore, the one blue straggler with enhanced barium that is known to be in a binary has a luminous companion (i.e., not a white dwarf) that could not have been responsible for the observed barium enrichment. These observations, and particularly the four barium enriched blue stragglers without detectable companions are additional important challenges for binary mass transfer models.

5. Conclusions

As is often the case in science, more comprehensive, precise and diverse observations give us both new empirical insights, but also highlight parts of our models that require improvements. These observations of open cluster blue stragglers suggest that many, and maybe most, blue stragglers in open clusters likely come from mass transfer. Yet, models are unable to produce as many mass-transfer blue stragglers per unit mass as is observed, or to match the detailed observations of key individual blue straggler stars, both through mass transfer and dynamical processes. Importantly, the improvements that are clearly needed in the binary mass-transfer models may also impact the predicted production rates of all progeny of mass transfer, not limited only to blue straggler stars.

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