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A mass transfer origin for blue stragglers in NGC 188 as revealed by half-solar-mass companions

Aaron M. Geller[1,2] & Robert D. Mathieu[1]

In open star clusters, where all members formed at about the same time, blue straggler stars are typically observed to be brighter and bluer than hydrogen-burning main-sequence stars, and therefore should already have evolved into giant stars and stellar remnants. Correlations between blue straggler frequency and cluster binary star fraction[1], core mass[2] and radial position[3] suggest that mass transfer or mergers in binary stars dominates the production of blue stragglers in open clusters. Analytic models[4,5], detailed observations[6] and sophisticated *N*-body simulations[7], however, argue in favour of stellar collisions. Here we report that the blue stragglers in long-period binaries in the old[8] (7×10^9-year) open cluster NGC 188 have companions with masses of about half a solar mass, with a surprisingly narrow mass distribution. This conclusively rules out a collisional origin, as the collision hypothesis predicts a companion mass distribution with significantly higher masses. Mergers in hierarchical triple stars[9] are marginally permitted by the data, but the observations do not favour this hypothesis. The data are highly consistent with a mass transfer origin for the long-period blue straggler binaries in NGC 188, in which the companions would be white dwarfs of about half a solar mass.

The NGC 188 blue stragglers have a very high binary frequency ($76 \pm 19\%$ for binaries with periods of $<10^4$ d; ref. 10). The orbital period distribution is remarkable; 12 of the 16 blue straggler binaries have periods of order 1,000 d, and all but two of the blue straggler binaries have periods longer than 100 d. The two short-period blue straggler binaries show evidence that binary encounters were involved in their formation[10]. We focus here on the 'long-period' blue straggler binaries, whose orbital solutions yield periods longer than 100 d.

In Fig. 1, we show the companion mass distribution for the twelve NGC 188 blue straggler binaries with periods of order 1,000 d. The orbital solutions are derived from spectroscopic data[11,12] obtained in the WIYN Open Cluster Study. Because we do not detect the flux from the companions to these blue stragglers, the orbital solutions provide mass functions rather than mass ratios. We therefore use a statistical algorithm[13] to convert the mass functions to the companion mass distribution shown here (Supplementary Information). The distribution is narrow and peaked with a mean of 0.53 solar masses ($M_\odot$) and a mode of $0.5M_\odot$.

Predictions for the companions to blue stragglers resulting from mass transfer in solar-type stars are well established by theory. Case-C mass transfer (from an asymptotic giant to a main-sequence star) leaves a carbon–oxygen white dwarf companion in an orbit of order 1,000 d and with a mass of about $0.5M_\odot$–$0.6M_\odot$, dictated by the core mass of the asymptotic giant donor at the end of the mass transfer phase[14–17]. This prediction is qualitatively reproduced by the NGC 188 blue straggler companion mass distribution shown in Fig. 1. To check quantitatively for consistency, we compare the observed mass function distribution (points in Fig. 2) to a theoretical mass function distribution derived assuming that all companions have the typical carbon–oxygen white dwarf mass, $0.55M_\odot$ (solid line in Fig. 2). A Kolmogorov–Smirnov test shows that the theoretical and observed distributions are indistinguishable.

Additionally, NGC 188 contains one blue straggler in a binary with an orbital period of about 120 d, the companion flux of which we also do not detect in our spectra. The observed mass function and orbital period for this system are consistent with the theoretical predictions of Case-B mass transfer (from a giant to a main-sequence star), where a helium white dwarf companion with a mass of about $0.25M_\odot$–$0.5M_\odot$ is expected[14–17]. Thus, the companions to all long-period blue straggler binaries in NGC 188 are consistent with a mass transfer origin.

We investigate the predicted companion mass distribution from the collision hypothesis using a sophisticated *N*-body model of NGC 188 that incorporates detailed stellar and binary evolution with stellar dynamics, and thereby produces blue stragglers through both collisions and mass transfer processes (Supplementary Information). The

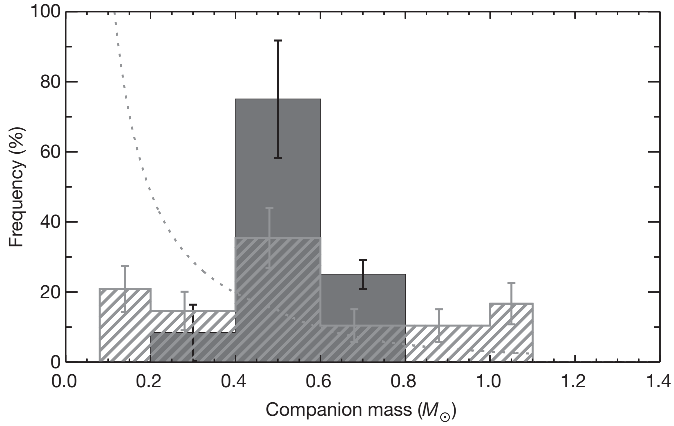

Figure 1 | Companion mass distribution for the 12 blue straggler binaries in NGC 188 with periods of order 1,000 d. The distribution is peaked near the typical carbon–oxygen white dwarf mass, of $0.55M_\odot$, consistent with theoretical predictions from the Case-C mass transfer hypothesis. We use a statistical method[13] to derive the companion mass distribution from the observed mass functions (Supplementary Information). To do so, we first estimate masses for the blue stragglers on the basis of standard stellar evolutionary tracks[29], and assume an isotropic inclination distribution. The shaded histogram shows the resulting companion mass distribution and is normalized to show the frequency. The error bars show the 95% confidence intervals and are converted from the Poisson uncertainties in the mass function distribution using a Monte Carlo analysis. We note that standard evolutionary tracks may underestimate[10] the mass of blue stragglers by up to about 15%. Accounting for this potential bias does not change the results found here (nor in Fig. 2). For comparison, we also plot a standard initial-mass function for single stars[30] (dotted grey line) for companion masses between $0.08M_\odot$ and $1.1M_\odot$ (from the hydrogen-burning limit to the current main-sequence turn-off mass in NGC 188). The grey hatched histogram shows the observed tertiary mass distribution[26] evolved to 7 Gyr in isolation[28]. The error bars on the tertiary mass distribution show the standard Poisson counting uncertainties for each bin. The lowest-mass bin extends from $0.08M_\odot$ to $0.2M_\odot$ and the highest-mass bin extends from $1.0M_\odot$ to $1.1M_\odot$. Both of these bins are renormalized to reflect the different bin sizes.

[1]Department of Astronomy, University of Wisconsin–Madison, Wisconsin 53706, USA. [2]Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA) and Department of Physics and Astronomy, Northwestern University, 2145 Sheridan Road, Evanston, Illinois 60208, USA.

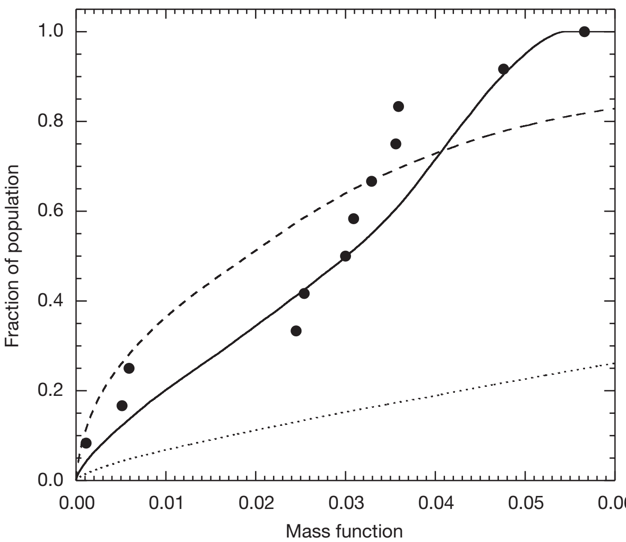

Figure 2 | Cumulative distribution of mass functions of the NGC 188 blue straggler binaries with periods of order 1,000 d. The black points show the observed mass functions derived directly from the kinematic orbital solutions[12], defined as

$$f(M_1,M_2,i)=\frac{M_2^3}{(M_1+M_2)^2}\sin^3(i)$$

where M_1 is the mass of the primary star (here the blue straggler), M_2 is the mass of the companion star and i is the inclination of the orbit to our line of sight. (Orbits that are edge-on have inclinations of 90°.) To test the blue straggler formation hypotheses, we compare this observed distribution with three theoretical mass function distributions, all derived using our blue straggler mass estimates and assuming isotropically distributed inclination angles. The solid line shows the resulting distribution assuming that all companions have masses of $0.55M_\odot$, the typical carbon–oxygen white dwarf mass predicted by the Case-C mass transfer hypothesis. The dotted line shows the mass function distribution of the predicted companion masses for blue straggler binaries formed by collisions in the NGC 188 *N*-body model. Finally, the dashed line shows the distribution derived by drawing companion masses from the evolved tertiary mass distribution shown in Fig. 1. A Kolmogorov–Smirnov test rules out the collisional hypothesis at the >99% confidence level. Such a test does not rule out the merger hypothesis. However, there is only a 6.6% chance that all companions would be undetected in our spectra if drawn from the evolved tertiary mass distribution, and only a 1.8% chance that these companions would also realize the observed mass function distribution shown here. The observed mass function distribution is statistically indistinguishable from that predicted by the mass transfer hypothesis, and all white dwarf companions would be undetectable in our spectra, given their low luminosities.

resulting distributions of companion mass, eccentricity and period for the blue stragglers in binaries that respectively formed through the collision and mass transfer mechanisms (Fig. 3) show marked differences. We focus here on the simulated blue stragglers in binaries with periods of 100–3,000 d (matching the period range of our NGC 188 long-period blue straggler binaries).

The very narrow distribution and mean mass of $(0.58\pm0.01)M_\odot$ for companions to the mass transfer blue stragglers in the *N*-body model are in good agreement with the population synthesis predictions discussed above. However, the mean mass of companions to collisionally formed blue stragglers is $(1.11\pm0.02)M_\odot$, nearly twice that of the mass transfer blue stragglers. This result demonstrates the finding that dynamical exchanges are more likely to insert a higher-mass member of the encounter into the binary[18].

These differences in companion mass reflect profound differences in the evolutionary states of the companions resulting from each process. All of the simulated blue straggler binaries that formed through mass transfer processes have white dwarf companions, the remnants of the giant donor stars. Fewer than 1% of the blue stragglers in binaries that formed through collisions have white dwarf companions, whereas 80% have main-sequence companions (and the remaining have giant or blue straggler companions).

A Kolmogorov–Smirnov test rules out at the >99% confidence level the hypothesis that the observed mass functions for the long-period NGC 188 blue straggler binaries are drawn from a parent population of collisional origin (dashed line in Fig. 2). Additionally, collision products are predicted to have significantly higher eccentricities and longer periods than are observed for the NGC 188 blue stragglers (both at the >99% confidence level). We therefore rule out the hypothesis that the long-period NGC 188 blue straggler binaries have a collisional origin.

Three of the long-period NGC 188 blue stragglers have measured orbital eccentricities consistent with circular orbits. By contrast, no NGC 188 solar-type main-sequence binaries in this period range have circular orbits. These blue straggler circular orbits are suggestive of a mass transfer origin. Rapid tidal circularization of the orbit during mass transfer has been a long-held expectation, as is seen in the predicted eccentricity distribution for mass transfer products in the NGC 188 model (Fig. 3b).

However, observational and theoretical evidence suggests that mass transfer will not always lead to circular orbits. Proposed 'eccentricity-pumping mechanisms' address this issue and are under development[19–21]. Thus, the theoretical eccentricity distribution for blue stragglers formed by mass transfer is uncertain.

Fortuitously, the blue stragglers of the Galactic field provide a basis for empirical comparison[22]. Specifically, we compare the NGC 188 blue stragglers with a blue straggler sample identified within the population of metal-poor thick-disk stars and halo stars, which is found to be coeval[23]. These field blue stragglers probably formed in isolation, presumably through mass transfer processes[22]. In fact, the field blue stragglers are observed to have a high binary frequency, a period distribution that peaks near a few 100 to a few 1,000 d (dotted line in Fig. 3c) and a mean companion mass consistent with $0.55M_\odot$, all again consistent with a mass transfer origin.

These long-period field blue straggler binaries show a range of non-circular eccentricities (dotted line in Fig. 3b). Enhancement of eccentricity through subsequent dynamical encounters cannot explain the non-circular orbits of field blue stragglers, owing to the low stellar density of the Galactic field. Therefore, if the long-period binaries among the field blue stragglers were formed through mass transfer, this is further evidence for the existence of an eccentricity-pumping mechanism.

The eccentricity distribution of the long-period NGC 188 blue straggler binaries is shifted to higher eccentricities than that of the long-period field blue straggler binaries. However, owing to the higher densities in the cluster core, dynamical encounters may have increased the eccentricities of the NGC 188 blue stragglers. If we exclude from the analysis blue stragglers in NGC 188 within 1.5 core radii from the cluster centre, the two eccentricity distributions are statistically indistinguishable. The similarity in periods, companion masses and eccentricities would be a natural consequence of both the field and the NGC 188 long-period blue straggler binaries being formed by mass transfer processes.

Finally, we investigate the possibility of blue straggler formation through mergers in hierarchical triples[9,24]. The potential progenitors of the blue stragglers produced by this mechanism would be triples with short-period (≲10-d) inner binaries[9] having a total mass of $1.2M_\odot$–$2.2M_\odot$. ($2.2M_\odot$ is twice the turn-off mass in NGC 188). The frequency of dynamically formed triples in the NGC 188 model with these orbital parameters is never high enough to contribute considerably to blue straggler production through this mechanism. If the merger mechanism is important, triples must form primordially with suitable orbital parameters in cluster environments.

Observationally, the triple population in open clusters is poorly known, but triples are common in the field[25]. Field triples in the Multiple Star Catalogue[26] with measured masses indicating inner binaries with masses between $1.2M_\odot$ and $2.2M_\odot$ and inner orbital

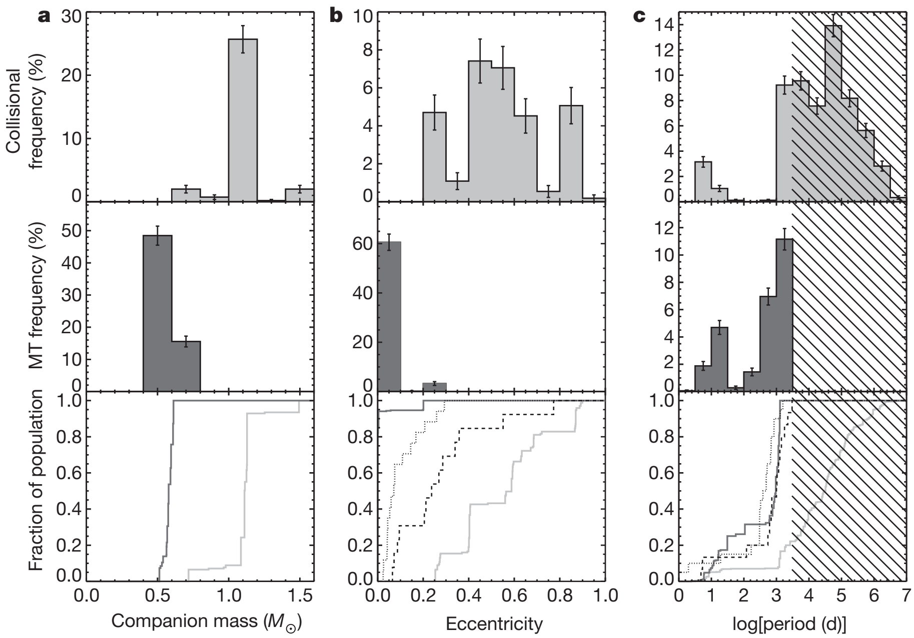

Figure 3 | Distributions of binary orbital elements for the blue stragglers in the NGC 188 *N*-body model. **a**, Companion mass; **b**, orbital eccentricity; **c**, orbital period. The top plots show blue stragglers formed in collisions, and the middle plots show blue stragglers created through mass transfer (MT). The bottom plots compare the cumulative distributions for these two populations, with collision products shown in light grey and mass transfer products shown in dark grey. The sample contains all blue straggler binaries present from 6–7.5 Gyr in the model, spanning the uncertainty in the cluster age. In **a** and **b**, we show only blue straggler binaries with periods between 100 and 3,000 d (the period range of our NGC 188 long-period blue straggler binaries). In **c**, we include blue straggler binaries of all periods (with the hatched regions indicating binaries at periods beyond our detection limit). Each bin is normalized by the total number of blue straggler binaries in the sample, and the error bars show the Poisson counting uncertainties. Additionally, in the bottom panels of **b** and **c** we show the cumulative eccentricity (**b**) and period (**c**) distributions of the blue straggler binaries in NGC 188 (dashed lines) and the field[22] (dotted lines). The *N*-body model predicts that collision products will have significantly more-massive companions, larger eccentricities and longer periods than the blue stragglers in NGC 188. However, the predicted companion masses and periods for mass transfer blue stragglers are consistent with those of the long-period NGC 188 blue straggler binaries. We note that the *N*-body model does not implement proposed eccentricity-pumping mechanisms that are required to reproduce the non-zero eccentricities observed for post-mass-transfer systems, including the field blue stragglers. Thus, the predicted eccentricities of the mass transfer products are uncertain, although they are still likely to be lower than those of the collision products.

periods of less than 10 d have a nearly uniform tertiary mass distribution populated by main-sequence stars. However, the typical age of local field stars is 4×10^9 yr (4 Gyr) (ref. 27). If we evolve the tertiary mass distribution to 7 Gyr in isolation[28], 15% of the tertiaries evolve to become white dwarfs. The grey hatched histogram in Fig. 1 shows the resulting tertiary mass distribution at 7 Gyr. The mass distribution is qualitatively broader than that of the companions to the NGC 188 long-period blue stragglers. However a Kolmogorov–Smirnov test comparing the mass function distributions does not rule out the triple hypothesis.

The fact that we do not detect in our spectra the flux from companions to any of the long-period blue straggler binaries also constrains the companion masses. The higher-mass main-sequence stars in the evolved tertiary mass distribution (Fig. 1) would be easily detected if these were the true companions to the long-period blue straggler binaries in NGC 188. A Monte Carlo analysis yields a 6.6% probability that all companions to the long-period NGC 188 blue straggler binaries would be undetected in our spectra if drawn from the evolved tertiary mass distribution, and only a 1.8% probability that these companions would also realize the observed mass function distribution of the long-period NGC 188 blue straggler binaries (Supplementary Information). Thus, mergers in hierarchical triples are not favoured by the observations, but the data are not sufficient to rule out this hypothesis completely.

We aim to detect directly the flux from the white dwarf companions predicted by the mass transfer mechanism with forthcoming Hubble Space Telescope observations of the NGC 188 long-period blue straggler binaries in the ultraviolet. These observations will be invaluable for distinguishing between the two remaining formation hypotheses: binary mass transfer and mergers in hierarchical triples.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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