Anatomy of the hyper-runaway star LP 40–365 with Gaia

R. Raddi1*, M. A. Hollands2, B. T. Gänsicke2, D. M. Townsley3, J. J. Hermes4†, N. P Gentile Fusillo2, D. Koester5

1 Dr. Remess-Sternwarte, Friedrich Alexander Universität Erlangen-Nürnberg, Sternwartstr. 7, 96049 Bamberg, Germany
2 University of Warwick, Department of Physics, Gibbet Hill Road, Coventry, CV4 7AL, United Kingdom
3 University of Alabama, Department of Physics and Astronomy, Tuscaloosa, AL, USA
4 University of North Carolina, Department of Physics and Astronomy, Chapel Hill, NC - 27599-3255, US
5 Universität Kiel, Institut für Theoretische Physik und Astrophysik, 24098, Kiel, Germany

Accepted 2018 June 6. Received 2018 June 1; in original form 2018 April 25

ABSTRACT

LP 40–365 (aka GD 492) is a nearby low-luminosity hyper-runaway star with an extremely unusual atmospheric composition, which has been proposed as the remnant of a white dwarf that survived a subluminous Type Ia supernova (SN Ia) in a single-degenerate scenario. Adopting the Gaia Data Release (DR2) parallax, \( \sigma = 1.58 \pm 0.03 \) mas, we estimate a radius of \( 0.18 \pm 0.01 R_\odot \), confirming LP 40–365 as a subluminous star that is \( \approx 15 \) times larger than a typical white dwarf and is compatible with the SN Ia remnant scenario. We present an updated kinematic analysis, making use of the Gaia parallax and proper motion, and confirm that LP 40–365 is leaving the Milky Way at about \( 1.5 \) times the escape velocity of the Solar neighbourhood with a rest-frame velocity of \( 852 \pm 10 \) km s\(^{-1} \). Integrating the past trajectories of LP 40–365, we confirm it crossed the Galactic disc \( 5.0 \pm 0.3 \) Myr ago in the direction of Carina, likely coming from beneath the plane. Finally, we estimate that LP 40–365 was ejected from its progenitor binary with a velocity of at least \( 600 \) km s\(^{-1} \), which is compatible with theoretical predictions for close binaries containing a white dwarf and a helium-star donor.

Key words: stars: individual (GD 492) — supernova: general — white dwarfs — subdwarfs — Galaxy: kinematics and dynamics

1 INTRODUCTION

There is general consensus that Type Ia supernovae (SN Ia) are the thermonuclear explosions of white dwarfs (Hillebrandt & Niemeyer 2000). Although a common underlying mechanism makes SNe Ia standardisable candies for distances on cosmological scales (Riess et al. 1998; Perlmutter et al. 1999), their class is rich in peculiar objects, including the subluminous SNe Iax (Foley et al. 2013), the calcium-rich transients (Perets et al. 2011), and SNe Ia (Bildsten et al. 2007).

Less settled is the discussion on the progenitors of SN Ia and their close relatives. Most scenarios assume that SN Ia originate from binary systems, with two fundamentally distinct channels: white dwarfs accreting from a non-degenerate companion (the single-degenerate channel) and mergers of white dwarfs pairs (the double-degenerate channel); for recent reviews, see Wang & Han (2012); Maoz et al. (2014).

The chemically peculiar star, LP 40–365 (aka GD 492), has been recently proposed by Vennes et al. (2017) as a partially burned white that survived a SNe Iax explosion (see Jordan et al. 2012; Kromer et al. 2013, 2015). The detection of a significantly super-Solar manganese-to-iron ratio (Raddi et al. 2018, hereafter Paper I) suggests that LP 40–365 had a non-degenerate companion (Seitenzahl et al. 2013; Cescutti & Kobayashi 2017). In the proposed scenario, LP 40–365 was unbound from the original binary and, due to its initially large orbital speed, it is now travelling at more than \( 500 \) km s\(^{-1} \) (corresponding to the measured radial velocity), becoming therefore a runaway star.\(^1\)

In this Letter, we use the accurate parallax and proper motions available from the recent Gaia Data Release 2 (DR2; Gaia Collaboration et al. 2016, 2018) to carry out the first

\(^1\) Runaway stars are proposed to gain their momentum via ejection from binary SN explosions (Portegies Zwart 2000). Hyper-runaway stars are the fastest of this class, with velocities comparable to those of traditional hypervelocity stars, which are thought to form via multi-body interactions with super-massive black holes (Hills 1988; Brown 2015).
Figure 1. Hertzsprung-Russel diagram displaying LP 40–365, compared to various classes of stars. We plot the parameters based on our analysis including the Gaia data (green circle) and the Vennes et al. (2017) estimate (light-blue square), hot subdwarfs (blue dots; Lisker et al. 2005), main sequence stars (orange dots; Boyajian et al. 2013), and nearby white dwarfs (black dots; Giannichele et al. 2012). The proto-white dwarf sequence and the cooling tracks (Althaus et al. 2013) are shown for 0.15 and 0.17 M⊙ white dwarfs (brown solid curves). For reference, we draw the canonical-mass white dwarf cooling sequence (beige-coloured strip; Fontaine et al. 2001), the 100 Myr old main sequence (red curve; Choi et al. 2016), and the evolutionary tracks for 0.47, 0.48, and 0.50 M⊙ hot subdwarfs (blue curves; Dorman et al. 1993). The luminosities for given stellar radii are shown as a function of T_{eff} (dotted curves).

Table 1. Physical parameters of LP 40–365. The nominal values of d, R and M correspond to the median of the distributions, and the 1σ uncertainty. The 5–95 per cent range is also given below.

| T_{eff} | log g | d (mas) | R (R⊙) | M (M⊙) | L (L⊙) |
|---------|-------|---------|--------|--------|--------|
| 8960 ± 300 | 5.50 ± 0.25 | 632 ± 14 | 0.18 ± 0.00 | 0.37 ± 0.07 | 0.18 ± 0.01 |
| 610–655 | 0.16–0.20 | 0.14–0.98 | 0.17–0.19 |

1From Paper I.

detailed kinematic analysis of LP 40–365, which provides strong constraints on its physical parameters, its past trajectory, and the properties of the progenitor system.

2 PHYSICAL PROPERTIES

The precision of the Gaia parallax of LP 40–365, σ = 1.58 ± 0.03 mas, ensures a direct conversion between parallax and distance without significant loss of accuracy (Bailer-Jones et al. 2018, and references therein), placing LP 40–365 at 632 ± 14 pc.

Scaling our best-fit model from Paper I to the Gaia magnitude, G_P = 15.58 mag, which we corrected for the sightline interstellar extinction (0.02 mag; Green et al. 2018), we estimate the integrated flux density of LP 40–365 to be f = 1.45 × 10^{-11} erg/cm^2/s. Thus, using the Gaia parallax and the Stefan-Boltzmann law, the radius of LP 40–365 is constrained to R = 0.18 ± 0.01 R⊙, accounting for the parallax and T_{eff} uncertainties. This result contrasts with the estimate of 0.07 R⊙, obtained by Vennes et al. (2017) via interpolation of their T_{eff} and log g with cooling models for low-mass helium-core white dwarfs (Althaus et al. 2013). On the Hertzsprung-Russel diagram (Fig. 1), our new results place LP 40–365 at a cooler and brighter location with respect to the parameters of Vennes et al. (2017).

Combining our radius estimate with the surface gravity derived from the spectral fit in Paper I implies the mass of LP 40–365 is constrained as M = 0.37±0.09 M⊙, with the 5–95 per cent confidence range between M = 0.14–0.98 M⊙. We note that LP 40–365 does not match the radius-luminosity relation of main sequence stars, as it is two orders of magnitude less luminous than stars of similar T_{eff} (A-type stars), while it is hotter than main-sequence stars of similar radii (M-type dwarfs). LP 40–365 also diverges from the mass-radius relation of both canonical white dwarfs (Tremblay et al. 2017) and low-mass helium-core white dwarfs (Althaus et al. 2013), with a composition clearly excluding a membership to the latter class of stars.

We will discuss the present appearance of LP 40–365 with reference to its evolutionary status in Section 4. The physical parameters are summarised in Table 1, while their correlation with σ is shown in Fig. 2.

3 KINEMATIC ANALYSIS

The high precision of Gaia parallaxes enables measuring the total rest-frame velocity of LP 40–365 with no a priori assumption. Taking into account the correlation between the astrometric quantities, and using the radial velocity from Paper I, v_{rad} = 499 ± 6 km/s, with the Galactic parame-
Vallée 2008 (Schönrich 2018) (Bovy & Rix, or Williams et al. 2017). In this Kenyon et al. 2014). We set up the Galactic po-
ters described below, we estimate the rest-frame velocity as

\[ v_{\text{rf}} = 852 \pm 10 \text{ km s}^{-1}, \] making it the fastest known hyper-
runaway star that is the nearest to the Sun. At this re-
markably large speed, LP 40–365 exceeds the Galactic es-
cape velocity (520–533 km s\(^{-1}\)) in the Solar neighbourhood; Piiff et al. 2014; Williams et al. 2017, or \( \approx 550 \text{ km s}^{-1} \) as for the
adopted Galactic model), thus it is confirmed as gravi-
tationally unbound from the Milky Way.

To investigate the space motion of LP 40–365, we used the Galactic orbit integrator implemented in the PYTHON package GALPY\(^2\) (Bovy 2015). We set up the Galactic po-
tential described in Bovy & Rix (2013), which consists of three components (bulge, disk, and halo), to which we added
a central black hole of \( 4 \times 10^6 M_\odot \) (Bovy 2015). In this
model, following Schönrich (2012), the Sun is placed at
\[ R_0 = 8.27 \pm 0.29 \text{ kpc from the Galactic centre and the Milky 
Way rotation speed at the Solar circle is } \] \( v_c = 238 \pm 9 \text{ km s}^{-1}, \)
while the peculiar motion of the Sun in the Local Standard of
Rest is \( (U_\odot, V_\odot, W_\odot) = (11.1, 12.24, 7.25) \text{ km s}^{-1}, \)
from Schönrich et al. (2010). Our simulations take into account
the statistical and systematic uncertainties quoted in the
original works. The boundary conditions correspond to the
Gaia DR2 observables, \( \alpha, \delta, \mu_\alpha, \mu_\delta, \) and \( \pi, \) along with \( v_{\text{rad}} \) from
Paper I. We sampled the boundary conditions via a
Monte Carlo method, taking into account the Gaia covari-
ance matrix and assuming Gaussian distributions for the
Galactic model parameters. We back-traced the trajectories
for 250 Myr in the past, i.e. the timescale of one Solar orbit
around the Milky Way at the Galactocentric distance of the
Sun. We display a representative set of trajectories in Fig. 3.

\[ \frac{v_{\text{rf}}^2}{v_{\text{rad}}^2} = \frac{v_c^2}{v_{\text{rad}}^2} + 2 v_{\text{ej}} V_c \cos \beta \cos \gamma, \] (1)

From this simulation, we find that LP 40–365 crossed the
Galactic plane in the inter-arm region between the Crux-
Centaurus and the Carina spiral arms, at \( 4.2 \pm 0.5 \text{ kpc from the 
}
present position of Sun, corresponding to a Galactocen-
tric radius \( R_\odot = 6.0 \pm 0.3 \text{ kpc } \) at its speed, LP 40–365 has
travelled for \( 5.0 \pm 0.3 \text{ Myr } \) to reach its current location after
it crossed the Galactic disc. We do not attempt to associate
LP 40–365 to any known Galactic structure along its tra-
jectory (e.g. clusters, spiral arms, or stellar streams),
given that its age is not sufficiently well constrained. However, we
note that the flight time from a Galactocentric distance of
100 kpc \( (Z \approx -7.3 \pm 0.5 \text{ kpc }) \) is \( \approx 140 \text{ Myr } \), setting an upper
limit on the cooling age, if LP 40–365 was ejected from the
Galactic halo. We speculate that its membership to known
structures could be investigated in future, when evolutionary
models will become available. An origin in Galactic centre
or in the Magellanic Clouds can definitely be excluded.

In Fig. 4, we show the evolution of positional and kinematic
parameters of LP 40–365. We note the asymptotic be-
behaviour of \( Z, R_\odot, \) and \( d, \) which is typical of open tra-
jectories. We also note that LP 40–365 was accelerated while
crossing the Galactic disc \( \approx 5 \text{ Myr ago } \) and it is slowing down
while leaving the Milky Way. All the future trajectories reach
\( R_\odot = 100 \text{ kpc } \) (not plotted in Fig. 4) in \( \approx 130 \text{ Myr}. \)

The simulated trajectories have small pitch angles with
respect to the plane, \( \gamma \approx 5.6 \deg, \) potentially implying a
boost from the Galactic rotation (see Kenyon et al. 2014)
if the ejection occurred in the Galactic disc. The ejection
velocity from the putative progenitor system, \( v_{\text{ej}}, \) could be
estimated from \( v_{\text{rf}} \) via:

\[ v_{\text{ej}}^2 = v_{\text{rf}}^2 + 2 v_{\text{ej}} V_c \cos \beta \cos \gamma, \]
where \( v_z \) is the rotational velocity of the progenitor in the Milky Way at the moment of the explosion, and \( y \) is the angle between \( v_z \) and \( v_{ej} \) in the Galactic plane. However, we stress that Eq. 1 only holds if LP 40–365’s progenitor exploded close to the Galactic plane. In this case, we would have that \( v_{ej} \sim 600 \, \text{km s}^{-1} \). Given that evolutionary timescales of a peculiar white dwarfs such as LP 40–365 are yet unconstrained, it cannot be excluded with certainty that the progenitor exploded at several kiloparsecs from the Galactic centre. Hence, the contribution to \( v_{Rf} \) due to the Galactic rotation would be negligible for a halo progenitor, so that \( v_{ej} = v_{Rf} \).

4 PROPERTIES OF THE BINARY PROGENITOR

Given that LP 40–365 is a single star (Vennes et al. 2017; Raddi et al. 2018), if it is the partly-burnt remnant of a SN Iax, the progenitor system must have been separated as consequence of mass loss caused by the SN explosion.

Following Hills (1983), under the assumption of instantaneous mass loss, a binary system breaks apart if it experiences a minimum mass loss, \( \delta M \), defined as:

\[
\left( \frac{\delta M}{M_{\text{prog}} + M_{\text{donor}}} \right)_{\text{min}} = 0.5 \times \left[ 1 - \left( \frac{v_{\text{kick}}}{v_{\text{orbit}}} \right)^2 \right],
\]

where \( M_{\text{prog}} \) and \( M_{\text{donor}} \) are the mass of progenitor and donor stars, respectively, and \( v_{\text{kick}} \) is a velocity kick that could arise from e.g. asymmetric explosions (Jordi et al. 2012).

In Paper I, we brought evidence in favour of a single-degenerate scenario via the detection of a super-Solar manganese-to-iron ratio, which requires a \( M_{\text{prog}} > 1.2 \, M_\odot \) to synthesise manganese (Seitenzahl et al. 2013). Thus, considering the simplest case, with negligible mass-loss from the donor star (as shown by Marietta et al. 2000; Pan et al. 2012; Liu et al. 2012, 2013, for non-giant companions) and no birth kick (\( v_{\text{kick}} = 0 \)), we have that the minimum possible mass of the donor star is \( M_{\text{donor}} = 0.86^{+0.34}_{-0.15} \, M_\odot \). Hence, the donor star can be constrained to \( \leq 1.32 \, M_\odot \) at the 95 per cent confidence limit. Numerical simulations of subluminous SN explosions that form partly-burnt remnants also produce \( v_{\text{kick}} \) of up to a few hundred km s\(^{-1}\), although debated (Jordan et al. 2012; Kromer et al. 2013), that would enable to unbind binaries with even more massive donors.

Considering possible ejection velocities at the moment of explosion, \( v_{ej} \lesssim v_{Rf} \approx 600–800 \, \text{km s}^{-1} \), the orbital period of a near-Chandrasekhar mass white dwarf with a donor star between 0.3–1.2 \, M_\odot \ is in the range of 30 min to 1 hr. Binaries leading to such tight configurations have been theoretically identified in the helium star donor channel of the single-degenerate scenario (Wang et al. 2009, 2014). These systems are proposed as a leading mechanism behind subluminous SNe Iax (Jha 2017; McCully et al. 2014), which could also have an important contribution to the population of Galactic hyper-runaway stars (Justham et al. 2009; Wang & Han 2009). They include either massive helium core- or shell-burning donor stars (up to 2.5 \, M_\odot \), down to canonical mass hot subdwarfs (\( \approx 0.47 \, M_\odot \), Heber 2016). As already noted by Vennes et al. (2017), the hypervelocity hot subdwarf US 708 (Geier et al. 2015) and LP 40–365 could represent two sides of the same coin: a donor star and an unburnt remnant surviving a SN Ia in a close binary. US 708 is suggested to have a mass of 0.3 \, M_\odot \, and it is proposed to have originated as the donor in an ultra compact 10-min binary exploded as sub-Chandrasekhar mass SN, LP 40–365, instead, is unique in its kind, as it is the first surviving white dwarf fitting with this scenario. Gaining a speed as large as that of US 708 (\( \sim 1200 \, \text{km s}^{-1} \), Geier et al. 2015), the subdwarf donor of LP 40–365 could have escaped the Milky Way long time ago.

However, we note that the hot subdwarf donor scenario may not entirely fit with LP 40–365, because low-mass donors (\( \lesssim 0.8 \, M_\odot \)) are not expected to lead to near-Chandrasekhar mass SN Ia, due to unstable helium-shell burning (Piersanti et al. 2014; Brooks et al. 2015). More massive donors (0.8–1.7 \, M_\odot \), Piersanti et al. 2014; Brooks et al. 2017), instead, could lead to near-Chandrasekhar mass explosions, after accreting sufficient mass on to the white dwarf. While such progenitors could be identifiable as helium-novae, or super soft X-ray sources, some detached candidates of this SN channel have been proposed, e.g. KPD 1930+2752 (Maxted et al. 2000; Geier et al. 2007). Although this scenario is theoretically appealing, very compact systems like these remain, so far, rare (just three are known with \( P_{\text{orb}} \leq 90 \, \text{min} \), Vennes et al. 2012; Kupfer et al. 2017a,b) and their fate is still debated.

In this context, Shen et al. (2018) have recently identified three hyper-runaway stars classified as “expanded” white dwarfs, which are proposed as former donor stars in double-degenerate systems. These stars would now have larger luminosities than normal white dwarfs due to several effects, such as dynamical interactions within the progenitor binary, impact of the SN ejecta, and accretion of radioactive \(^{56}\)Ni-rich material, all of which contributed to (partially) lift the core degeneracy and expand the envelope. Although having larger \( v_{Rf} \), redder colours, and a likely carbon-oxygen atmosphere, Shen et al. (2018) proposed these new stars and LP 40–365 to form a short-lived heterogeneous class of...
stars that would eventually re-join the white dwarf cooling sequence. As the peculiar atmospheric composition of LP 40–365 remains the strongest connection to the partly-burned remnants of SN Iax, we note that such objects would also expand due to internal adjustments of the stellar structure after the explosion (Kromer et al. 2013; Shen & Schwab 2017). Further theoretical investigations concerning the evolutionary timescales are crucial, given the small parameter space tested in the literature.

Finally, another physical constraint worth comparing is the rotational velocity of LP 40–365 to that of US 708. The hot subdwarf shows a high rotational velocity (115 km s$^{-1}$; Geier et al. 2015), consistent with it being tidally locked at an orbital period before detonation of roughly 10 min. US 708 is best explained as the donor to an exploded system whose rotation would have synchronized the rotation of both components of such short orbital periods (Fuller & Lai 2012).

The rotation velocity of a 0.18 R$_\odot$ star rotating faster than 1 hr would exceed 200 km s$^{-1}$, which we would be able to detect in LP 40–365 for all inclinations higher than roughly 20 deg. However, if the progenitor of LP 40–365 were a massive white dwarf rotating at the previous orbital period, its radius will have increased more than a factor of 20 to match the size we observe today; its rotation would have likely slowed considerably to conserve angular momentum. Therefore the relatively slow rotation velocity adds another line of evidence to LP 40–365 being the partly burnt remnant of a sub-luminous supernova and not the donor.

5 SUMMARY AND CONCLUSIONS

LP 40–365 is a hyper-runaway star, which is the first example of a possible SN Iax survivor, i.e. a partly burnt white dwarf that is enriched with nuclear ashes (Vennes et al. 2017; Raddi et al. 2018). Here, we have presented a detailed analysis of its physical and kinematic properties, making use of the recent Gaia-DR2 astrometry. At a distance of 632 ± 14 pc, LP 40–365 is the nearest hyper-runaway star to the Sun that is unbound from the Galaxy, having a rest-frame velocity of 852 ± 10 km s$^{-1}$. We confirm it as a sub-luminous star, with a radius of $0.18 \pm 0.01$ R$_\odot$ and a mass of 0.37$^{+0.29}_{-0.17}$ M$_\odot$, matching the partly-burnt white dwarf hypothesis.

We simulated the past trajectory of LP 40–365 in the Milky Way potential, finding it crossed the Galactic disc $\approx 5$ Myr ago in the direction of Carina at a Galactocentric radius of $\approx 6.5$ kpc, i.e. $\approx 4.2$ kpc from the Sun’s current position. With a cooling age possibly as large as $\sim 100$ Myr, LP 40–365 could have been ejected from the Galactic halo at a few kpc below the plane. From the constraint we have on LP 40–365’s mass, we suggest its progenitor may have had a short-period (30–60 min) binary with a donor star of 0.8–1.32 M$_\odot$. The ejection velocities from such tight binaries are sufficient to accelerate LP 40–365 and similar objects to and beyond the Galactic escape velocity.

With the high quality data of Gaia DR2, we expect that more candidates of partially burned remnants and/or donor stars ejected from SN Ia will be identified, helping to fill in the gaps between theoretical predictions and unusual stars such as LP 40–365 and those found by Shen et al. (2018).

ACKNOWLEDGEMENTS

We thank U. Heber for useful discussions. R.R. acknowledges funding by the German Science Foundation (DFG) through grants HE1356/71-1 and IR190/1-1. The research leading to these results has received funding from the European Research Council under the European Union’s Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement n. 320964 (WDTracer). Support for this work was provided by NASA through Hubble Fellowship grant #HST-HF2-51357.001-A, awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Incorporated, under NASA contract NAS5-26555.

This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

REFERENCES

Althaus L. G., Miller Bertolami M. M., Cósico A. H., 2013, A&A, 557, A19
Bailer-Jones C. A. L., Rybizki J., Fouesneau M., Mantelet G., Andrae R., 2018, preprint, (arXiv:1804.10121)
Bildsten L., Shen K. J., Weinberg N. N., Nelemans G., 2007, ApJ, 662, L95
Bovy J., 2015, ApJS, 216, 29
Bovy J., Rix H.-W., 2013, ApJ, 779, 115
Boysen T. S., et al., 2013, ApJ, 771, 40
Brooks J., Bildsten L., Marchant P., Paxton B., 2015, ApJ, 807, 74
Brooks J., Schwab J., Bildsten L., Quataert E., Paxton B., 2017, ApJ, 834, L9
Brown W. R., 2015, ARA&A, 53, 15
Cescutti G., Kobayashi C., 2017, A&A, 607, A23
Choi J., Dotter A., Conroy C., Cantillo M., Paxton B., Johnson B. D., 2016, ApJ, 823, 102
Dorman B., Rood R. T., O’Connell R. W., 1993, ApJ, 419, 596
Foley R. J., et al., 2013, ApJ, 767, 57
Fontaine G., Brassard P., Bergeron P., 2001, PASP, 113, 409
Fuller J., Lai D., 2012, MNRAS, 421, 426
Gaia Collaboration et al., 2016, A&A, 595, A1
Gaia Collaboration, Brown A. G. A., Vallenari A., Prusti T., de Bruijne J. H. J., Babusiaux C., Bailer-Jones C. A. L., 2018, preprint, (arXiv:1804.09366)
Geier S., Nussler S., Heber U., Przybilla N., Napiwotzki R., Kudritzki R.-P., 2007, A&A, 464, 299
Geier S., et al., 2015, Science, 347, 1126
Giammichele N., Bergeron P., Dufour P., 2012, ApJS, 199, 29
Green G. M., et al., 2018, preprint, (arXiv:1801.03555)
Heber U., 2016, PASP, 128, 082001
Hillebrandt W., Niemeyer J. C., 2000, ARA&A, 38, 191
Hills J. G., 1983, ApJ, 267, 322
Hills J. G., 1988, Nature, 331, 687
Jha S. W., 2017, Type Iax Supernovae. p. 375, doi:10.1007/978-3-319-21846-5_42
Jordan IV G. C., Perets H. B., Fisher R. T., van Rossum D. R., 2012, ApJ, 761, L23
Justham S., Wolf C., Podsiadlowski P., Han Z., 2009, A&A, 493, 1081
Kenyon S. J., Bromley B. C., Brown W. R., Geller M. J., 2014, ApJ, 793, 122
Kromer M., et al., 2013, MNRAS, 429, 2287
Kromer M., et al., 2015, MNRAS, 450, 3045
Kupfer T., et al., 2017a, preprint, (arXiv:1710.07287)
Kupfer T., et al., 2017b, ApJ, 835, 131
Lisker T., Heber U., Napiwotzki R., Christlieb N., Han Z., Homeier D., Reimers D., 2005, A&A, 430, 223
Liu Z. W., Pakmor R., Röpke F. K., Edelmann P., Wang B., Kromer M., Hillebrandt W., Han Z. W., 2012, A&A, 548, A2
Liu Z.-W., et al., 2013, ApJ, 774, 57
Maoz D., Mannucci F., Nollett G., 2014, A&Arv, 52, 107
Marietta E., Burrows A., Fryxell B., 2000, ApJS, 128, 615
Maxted P. F. L., Marsh T. R., North R. C., 2000, MNRAS, 317, L41
McCully C., et al., 2014, Nature, 512, 54
Pan K.-C., Rickter P. M., Taam R. E., 2012, ApJ, 750, 151
Perets H. B., Gal-yam A., Crockett R. M., Anderson J. P., James P. A., Sullivan M., Neill J. D., Leonard D. C., 2011, ApJ, 728, L36
Perlmutter S., et al., 1999, ApJ, 517, 565
Piersanti L., Tornambé A., Yungelson L. R., 2014, MNRAS, 445, 3239
Piffl T., et al., 2014, A&A, 562, A91
Portegies Zwart S. F., 2000, ApJ, 544, 437
Raddi R., Hollands M. A., Koester D., Gansicke B. T., Gentile Fusillo N. P., Hermes J. J., Townsley D. M., 2018, ApJ, 858, 3
Riess A. G., et al., 1998, AJ, 116, 1009
Schönrich R., 2012, MNRAS, 427, 274
Schönrich R., Binney J., Dehnen W., 2010, MNRAS, 403, 1829
Seitenzahl I. R., Cescutti G., Röpke F. K., Ruiter A. J., Pakmor R., 2013, A&A, 559, L5
Shen K. J., Schwab J., 2017, ApJ, 834, 180
Shen K. J., et al., 2018, preprint, (arXiv:1804.11163)
Tremblay P.-E., et al., 2017, MNRAS, 465, 2849
Vallée J. P., 2008, AJ, 135, 1301
Vennes S., Kawka A., O'Toole S. J., Németh P., Burton D., 2012, ApJ, 759, L25
Vennes S., Nemeth P., Kawka J. R., Thorstensen J. R., Khalack V., Ferrario L., Alper E. H., 2017, Science, 357, 680
Wang B., Han Z., 2009, A&A, 508, L27
Wang B., Han Z., 2012, New Astron. Rev., 56, 122
Wang B., Meng X., Chen X., Han Z., 2009, MNRAS, 395, 847
Wang B., Meng X., Liu D.-D., Liu Z.-W., Han Z., 2014, ApJ, 794, L28
Williams A. A., Belokurov V., Casey A. R., Evans N. W., 2017, MNRAS, 468, 2359

This paper has been typeset from a TeX/ΛTeX file prepared by the author.