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Supplementary Materials for

The fastest unbound star in our Galaxy ejected by a thermonuclear supernova

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Materials and Methods

Summary

Spectra of US 708 have been taken with the 10m Keck and the 5m Palomar telescopes. From the Doppler shift of the spectral lines we measured the radial velocity using both new and archival data. The tangential velocity components have been determined by measuring the proper motion of the star from multi-epoch position measurements spanning 59 years and its spectroscopic distance performing a full quantitative spectral analysis using state-of-the-art model atmospheres. Using those informations we constrained the kinematics of this star and traced back its origin to the Galactic disk performing a Monte Carlo simulation. The properties of the progenitor binary have been determined mostly based on the derived ejection velocity from the Galactic disc. Binary evolution calculations have then been performed to check the consistency of those properties with theory. The current rotational properties of US 708 have been compared with hydrodynamical models of angular momentum-loss triggered by supernovae explosions.

Observations

US 708 ($\alpha_{2000} = 09^{h}33^{m}20\overset{s}{.}85$, $\delta_{2000} = +44^{\circ}17'05.8''$) was discovered to be a hypervelocity star by Hirsch et al. *(2)*. A medium-resolution ($R \sim 1800$) spectrum was taken by the Sloan Digital Sky Survey (SDSS) on February 20, 2002 *(32)*. Follow-up low-resolution ($R \sim 900$) spectroscopy was obtained with the LRIS instrument at the Keck telescope on May 13, 2005. The reduced spectra from the blue and red channel of the instrument were provided to us by H. Hirsch. A series of 11 consecutively taken medium-resolution ($R \sim 8000$) spectra was obtained with the ESI instrument at the Keck telescope on March 3, 2013. The spectra have been reduced with the ESI pipeline Makee.* One spectrum has been taken

*http://www.astro.caltech.edu/ ˜tb/makee/

with the medium-resolution spectrograph at the 5.1 m Hale telescope on Mount Palomar on May 11, 2013 and another three spectra on June 1, 2013.

Revised radial velocity

Hirsch et al. measured the radial velocity (RV) of US 708 ($708 \pm 15\,\mathrm{km\,s^{-1}}$) from the helium lines in the blue-channel LRIS spectrum. The measured RV exceeded the typical RVs of He-sdOs in the rest of the sample, which is characteristic for halo stars, considerably (see Fig. 5 in *(35)*). We obtained the RV of the SDSS, ESI and Palomar spectra by fitting a model spectrum (see below) to the helium lines using the FITSB2 routine *(33)*. Surprisingly, the most accurate RV measured from the coadded ESI spectrum ($917 \pm 7\,\mathrm{km\,s^{-1}}$) turned out to be significantly higher than the one published by Hirsch et al. *(2)*. This velocity is consistent with the RVs measured both from the SDSS[†] ($898 \pm 30\,\mathrm{km\,s^{-1}}$) and the Palomar spectra ($866 - 936\,\mathrm{km\,s^{-1}}$). To investigate this issue, we performed a reanalysis of the LRIS spectra and measured an RV of $709 \pm 7\,\mathrm{km\,s^{-1}}$ for the LRIS blue-channel spectrum perfectly consistent with the published value. However, when fitting the red-channel spectrum we found a significantly discrepant RV of $797 \pm 21\,\mathrm{km\,s^{-1}}$. This was taken as first indication, that those spectra might be affected by systematics. We used the nightsky emission line of O I at 6300 Å (red-channel) and the interstellar absorption line of Ca II at 3934 Å (blue-channel) to quantify

[†]The RV of $793\,\mathrm{km\,s^{-1}}$ given by the SDSS Sky Server Object Explorer tool is based on the fit of an hydrogen rich template to the spectrum. The He II-lines of the Pickering series are misidentified as Balmer lines. This introduces the shift of $\sim -100\,\mathrm{km\,s^{-1}}$ between our result and the template fit.

those systematic shifts (see Fig. S1, left panel). The nightsky emission line, which is supposed to be at zero RV, was blue-shifted by $-33 \pm 10\,\mathrm{km\,s^{-1}}$. The interstellar line showed a significantly higher shift of $-128 \pm 22\,\mathrm{km\,s^{-1}}$. Since the correct RV of the interstellar line is not known a priori, we measured it from a coadded Palomar spectrum to be $-9 \pm 28\,\mathrm{km\,s^{-1}}$. Correcting the RVs for those shifts, the two RV values ($828 \pm 22\,\mathrm{km\,s^{-1}}$ blue-channel, $830 \pm 21\,\mathrm{km\,s^{-1}}$ red-channel) from the LRIS spectra are consistent with each other, but still smaller than the RVs measured from the ESI and Palomar spectra (see Fig. S1, right panel). Due to the low resolution of the LRIS spectra, the remaining shift corresponds to only about one pixel on the CCD and is therefore regarded as systematic as well. We conclude that the RV published by Hirsch et al. was affected by systematics and therefore underestimated. Going back to the original raw data, we performed an independent reduction. However, we were not able to resolve this issue. Given that the uncertainties are at the 1σ level of confidence and that the LRIS spectra are affected by systematics, no significant shifts in RV on both short and long timescales are detected (see Supplementary Fig. 1, right panel).

Proper motion

The proper motion of US 708 has been derived from multi-epoch position measurements of Schmidt plates obtained from the Digitised Sky Survey (DSS)[‡], the Sloan Digital Sky Survey *(32)* and the PanSTARRS survey (PS1) over a timebase of 59 years (see Fig. S2). The positions from the DSS and SDSS images have been

[‡]http://archive.stsci.edu/cgi-bin/dss_plate_finder

measured with respect to a set of compact background galaxies selected from the SDSS images as described in Tillich et al. *(34)*. The positions of the background galaxies and the object are measured. For each image the measured positions of the background galaxies are compared to the reference values from the PS1 catalogue. The average of the deviations from these reference values is adopted as uncertainty of the object position. In the case of the 29 PS1 epochs, we took the calibrated positions from the PS1 catalogue and therefore use the same reference system for all our measurements. We obtained one position per epoch and used linear regression ro derive the proper motion components with their uncertainties.

Atmospheric parameters

The atmospheric parameters effective temperature $T_{\rm eff}$, surface gravity log g, nitrogen abundance log $N(\rm N)/N(\rm H)$ and projected rotational velocity $v_{\rm rot} \sin i$ were determined by fitting simultaneously the observed helium and nitrogen lines of an ESI spectrum, constructed by coadding the 11 single exposures, with NLTE models taking into account line-blanketing of nitrogen *(27)* (see Fig. 1) as described in Geier et al. *(35)*. Since no hydrogen lines are visible in the spectrum, we fixed the helium abundance to $\log y = \log N(\rm He)/N(\rm H) = +2.0$. The atmospheric parameters ($T_{\rm eff} = 47200 \pm 400\,\rm K$, $\log g = 5.69 \pm 0.09$) deviate significantly from the results by Hirsch et al. ($T_{\rm eff} = 45600 \pm 700\,\rm K$, $\log g = 5.23 \pm 0.12$) especially in surface gravity. This is caused by the additional line-blanketing of nitrogen *(27)*. The atmospheric parameters as well as the nitrogen abundance $\log N(\rm N)/N(\rm H) = -2.4 \pm 0.2$ are typical for the nitrogen-rich subclass of He-sdOs

(36). The projected rotational velocity $v_{\rm rot}\sin i = 115 \pm 8\,{\rm km\,s^{-1}}$ on the other hand is significantly higher than the ones of both single sdB ($< 10\,{\rm km\,s^{-1}}$) and He-sdO stars ($20 - 30\,{\rm km\,s^{-1}}$) *(26,27)*. Based on our analysis we can rule out objects with similar spectral features like DO-type white dwarfs ($\log g > 7.0$) or luminous He-stars ($\log g < 4.5$), which can be easily misclassified from visual inspection only.

Spectroscopic distance and kinematics

The spectroscopic distance is derived from the atmospheric parameters $T_{\rm eff}$, log g and the apparent visual magnitude as described in Ramspeck et al. *(40)*. The SDSS-g and r magnitudes have been converted to Johnson V magnitude[§], which has been corrected for interstellar reddening ($A_{\rm V} = 0.07\,{\rm mag}$) *(41)*. Based on constraints provided by the supernova ejection scenario (see below) we adopted a mass of $0.3\,M_{\odot}$ for the hot subdwarf. The spectroscopic distance in this case is $8.5 \pm 1.0\,{\rm kpc}$. For this distance the proper motion components are converted to absolute transverse velocities and, combined with the radial velocity, the Galactic restframe velocity of US 708 is calculated to be $1157 \pm 53\,{\rm km\,s^{-1}}$. This is the highest known restframe velocity of any unbound star in our Galaxy. The past trajectory of US 708 in the Galactic potential *(42,43)* has been reconstructed as outlined in Tillich et al. *(34)*. Due to the high velocity of US 708 we found that the trajectory is not changed significantly if alternative model potentials are used *(42)*. US 708 was ejected from the Galactic disc $14.0 \pm 3.1\,{\rm Myr}$ ago and

[§] http://www.sdss.org/dr6/algorithms/sdssUBVRITransform.html the ejection velocity, corrected for the motion of the Galactic disc, was calculated to be $998 \pm 68\,\mathrm{km\,s^{-1}}$. We performed Monte Carlo simulations to trace back the trajectory of US 708 until it intersects with the Galactic disc. The uncertainty in the proper motion measurement dominates the error budget. Assuming no further perturbation of the trajectory an origin from the central kpc around the Galactic centre can be ruled out with a confidence of more than 6σ (see Fig. 2).

Properties of the progenitor binary. Geier et al. *(5)* proposed the ultra-compact sdB+WD binary CD−30°11223 to be a possible progenitor of the hypervelocity sdO US 708. However, based on the new results presented here, the ejection velocity is $\sim 250\,\mathrm{km\,s^{-1}}$ higher than assumed by Geier et al. Hence, it is necessary to reexamine the supernova ejection scenario and to test its consistency with the newly derived parameters of US 708. Similar to the scenario discussed in Geier et al., we assume that the progenitor binary consisted of a compact helium star and a massive carbon-oxygen WD in close orbit. The ejection velocity of the He-star equals the radial velocity semiamplitude of the progenitor binary at the moment of the supernova explosion ($K = 998 \pm 68\,\mathrm{km\,s^{-1}}$) modified by the additional perpendicular velocity component the star received through the SN explosion ($\sim 200\,\mathrm{km\,s^{-1}}$). Since both velocities are added in quadrature, the kick velocity is negligible within the uncertainties. Assuming a mass for the He-star and a circular orbit, the orbital period of the progenitor binary as well as its separation can be calculated from the binary mass function:

$$f_{\mathrm{m}} = \frac{M_{\mathrm{WD}}^3 \sin^3 i}{(M_{\mathrm{WD}} + M_{\mathrm{He}})^2} = \frac{PK^3}{2\pi G} \qquad (1)$$

Since we known the absolute space velocity, the inclination angle can be set to $\sin i = 1$, and the orbital period P of the progenitor binary can be calculated:

$$P = \frac{2\pi G}{K^3} \frac{M_{\mathrm{WD}}^3}{(M_{\mathrm{WD}} + M_{\mathrm{He}})^2} \tag{2}$$

The binary separation a can be derived using Keplers laws:

$$a = \frac{G}{K^2} \frac{M_{\mathrm{WD}}^2}{M_{\mathrm{WD}} + M_{\mathrm{He}}} \tag{3}$$

Another crucial assumption is that stable mass-transfer from the He-star to the WD triggered the SN, which means that the He-star must have filled its Roche lobe before ejection. To calculate the Roche lobe radius we used the equation given by Eggleton *(44)*, where $q = M_{\mathrm{He}}/M_{\mathrm{M_{WD}}}$:

$$R_{\mathrm{L}} = \frac{0.49 q^{2/3} a}{0.6 q^{2/3} + \ln(1 + q^{1/2})} \tag{4}$$

The radius of the He-star can be calculated as a function of the mass and the surface gravity g:

$$R_{\mathrm{He}} = \sqrt{\frac{M_{\mathrm{He}} G}{g}} \tag{5}$$

To compare the Roche radius with the possible radius of the He-star we have to take into account that US 708 has already evolved away from the EHB (see Fig. S3), which led to an increase in radius. To calculate the radius at the time of ejection we therefore adopt the highest reasonable values for $\log g \simeq 6.1$ close to the ZAEHB and the He-MS. Calculating Roche lobe and He-star radii for different He-star and WD masses, we explored the parameter space and put constraints on possible progenitor systems. Fig. S4 shows the Roche radii for WD masses from $1.0\,M_{\odot}$ to $1.2\,M_{\odot}$. The He-star radii for $\log g = 6.1$ are plotted for comparison. Consistent solutions are only found for low He-star masses ($\sim 0.3 - 0.35\,M_{\odot}$) and high WD companion masses ($\sim 1.0 - 1.2\,M_{\odot}$). The orbital period of the progenitor binary can be constrained to $\sim$ 10 min. Following the method described in Geier et al. *(5)* we calculated the mass-transfer rates for binaries with similar orbital parameters and component masses. The rates of $\sim 10^{-8}\,M_{\odot}\mathrm{yr}^{-1}$ are consistent with the helium double-detonation scenario. Figs. S5-S7 show as an example the evolution of a close binary ($P = 26$ min) that starts mass-transfer with an initial He-star mass of $0.45\,M_{\odot}$ and a WD mass of $1.05\,M_{\odot}$. After about 5 Myr the orbital period becomes as short as 13 min and the component masses change to $0.3\,M_{\odot}$ and $1.2\,M_{\odot}$, when the WD explodes as SN Ia. The helium donor has to be a helium-burning star rather than a He-WD without ongoing nuclear burning in its core, because those objects consist of degenerate matter and as soon as the small non-degenerate envelope is transferred, the mass-transfer rate becomes too high for the double-detonation scenario. Such systems will experience He-flashes on the surface of the WD companion without igniting the carbon in the core *(45)*. This is consistent with the observational evidence. Since the ejection already happened $\sim$ 14 Myr ago, we can also assume that US 708 is a helium-burning star. The minimum mass for such objects is $\sim 0.3\,M_{\odot}$. Even less massive He-stars without nuclear burning, which are the progenitors of He-WDs, exist

(46). However, according to evolutionary tracks, their effective temperatures are much lower than the one of US 708. The most massive He-WD progenitors on the other hand, which can reach such temperatures, are cooling within a few Myr, too fast to be consistent with the position of US 708 in the $T_{\rm eff} - \log g$-diagram (see Fig. S3) *(47)*. EHB-tracks for masses as low as $\sim 0.3\,M_{\odot}$ are also not consistent with the position of US 708 in the $T_{\rm eff} - \log g$-diagram *(6)*. However, since the He-star was significantly more massive before the mass-transfer started, its further evolution might not depend on its current total mass. Especially, if the helium in its core was already exhausted towards the end of the mass-transfer phase, the further evolution would depend on the core mass rather than the total mass. The position of US 708 in the $T_{\rm eff} - \log g$-diagram is, for example, perfectly consistent with post-EHB model tracks for an original mass of $0.45\,M_{\odot}$ (see Fig. S3). Based on these simple calculations we can rule out the sdB+WD binary CD−30°11223 ($0.51\,M_{\odot} + 0.76\,M_{\odot}$, $P = 72$ min) as direct progenitor of US 708. However, systems like CD−30°11223 remain progenitor candidates of other high velocity sdB stars *(34)*. There is no binary known yet, which fulfills all the criteria for a progenitor system to US 708. But evidence is growing, that such objects exist. A whole population of close binaries consisting of He-WDs and CO-WDs has been discovered recently *(46)*. They form in almost exactly the same way as sdB+WD binaries. The only difference is that core helium-burning was not ignited before the hydrogen envelope has been stripped off in the common envelope phase of unstable mass-transfer. The ultracompact, eclipsing He-WD+CO-WD ($0.25\,M_{\odot} + 0.55\,M_{\odot}$) binary SDSS J065133+284423 with an orbital period of only

12 min sticks out *(23)*. Its period is similar to the one expected for the progenitor of US 708, but the component masses are too small. In the double-lined WD+WD binary SDSS J125733+542850 ($0.2\,M_\odot + 1.2\,M_\odot$) on the other hand, the masses are very similar to the ones predicted, whereas the orbital period is much longer (274 min) *(48)*. These discoveries as well as binary evolution calculations indicate the existence of binaries fulfilling the criteria for a progenitor of US 708 as well *(18)*. We therefore conclude that the double-detonation supernova ejection scenario is still able to explain the observed properties of US 708 as ejected donor remnant.

Rotational velocity

Only two out of more than 100 single hot subdwarf stars are fast rotators. Both objects are sdB stars with hydrogen-rich atmospheres and might have been formed by a common-envelope merger *(49,50)*. US 708 on the other hand belongs to the population of He-sdOs, which are hotter and show no or only some hydrogen in their atmospheres. They are regarded as a distinct group of stars, that might have been formed in different ways as the sdBs. US 708 is the only single He-sdO rotating faster than $20-30\,\mathrm{km\,s^{-1}}$ indicating a close-binary origin *(27)*. Due to the short orbital period and high companion mass, the rotation of the He-star in the proposed progenitor binary is expected to be synchronised to its orbital motion *(22,24,25)*. Assuming the angular momentum is unchanged after the SN, the ejected donor remnant should remain a fast rotator. The rotational velocity can be calculated as follows:

$$v_{\rm rot} = \frac{2\pi R_{\rm L}}{P} \tag{6}$$

The expected rotational velocity of the ejected He-star is only weakly dependent on the masses of the binary components and of the order of $600\,{\rm km\,s^{-1}}$. This is much higher than the measured $v_{\rm rot}\sin i = 115 \pm 8\,{\rm km\,s^{-1}}$. The significant difference between the expected rotational velocity and the measured $v_{\rm rot}\sin i$ comes unexpected. In a synchronised binary system the rotational axes of both components are perpendicular to the orbital plane. As soon as the He-star is ejected, the rotation axis should be perpendicular to the flight trajectory, which means that $\sin i \simeq 1$. The impact of the supernova shockwave on main sequence (MS) companions in the standard single-degenerate scenario has recently been studied with hydrodynamic simulations. Due to stripping of matter, the star may lose up to $\sim 90\%$ of its initial angular momentum. A subsequent increase in radius due to stellar evolution is also predicted to lower the rotational velocity at the surface *(28-31)*. However, simulations of more compact helium stars show that much less mass is stripped *(28,51)*. The loss of angular momentum is also expected to be smaller in this case. Taking into account evolution on the extreme horizontal branch (EHB), the radius of the sdO increased by about a factor of ~ 1.6 since the ejection. Assuming conservation of angular momentum, the rotational velocity should now be of the order of $400\,{\rm km\,s^{-1}}$. Whether the rest of the angular momentum was lost in the SN impact or later is still unclear. Pan et al. *(28)* predict an increase of the helium star's radius by a factor of up to four right after the impact. This phase should last for a few tens of years. Due to the high initial rotational velocity of the star, another episode of mass and angular momentum loss may be possible in this phase. Another possibility might be a tilting of the stars rotation axis by the SN impact. The projected rotational velocity of the star measured from the line broadening would then be smaller than the true rotational velocity. However, simulations show that this effect is negligible for MS stars and most likely also for the more compact He stars studied here.

Supplementary Text

Discussing alternative acceleration scenarios

Any scenario for the acceleration of US 708 must explain four key properties of this star simultaneously: (I) US 708 is a compact He-sdO, which most likely formed via close binary interaction. Either it is the stripped core of a red giant or the result of a He-WD merger. (II) The star has the highest Galactic restframe velocity ($\sim 1200\,\mathrm{km\,s^{-1}}$) ever measured for any unbound star in the Galaxy. (III) The past trajectory of the star is not consistent with an origin in the Galactic centre. (IV) In contrast to all other known single He-sdOs, US 708 has a projected rotational velocity exceeding $\sim 100\,\mathrm{km\,s^{-1}}$. We now want to review other scenarios for the acceleration of hypervelocity stars in this way. In the classical runaway scenario a massive star in a binary system explodes as core-collapse supernova, while the companion is kicked out of the system *(52)*. However, the ejection velocity scales with the binary separation and because a massive and hence large star is involved, the binary separation cannot become small enough to reach an ejection velocity like the one of US 708. The disruption of a hierarchical triple system consisting of a normal star in wide orbit around a close He-WD binary by the SMBH is regarded as very unlikely as well, because an origin in the GC where the SMBH is located is very unlikely. The subsequent merger of a He-WD binary ejected in this way has been proposed as formation scenario for US 708 *(2,16)*. The ejection of a He-WD binary star by a hypothetical binary black hole in the GC is very unlikely for the same reason *(16)*. Other formation channels for hypervelocity stars invoke dynamical interactions in dense stellar clusters *(53)*. Interactions of two close binaries can lead to the ejection of a star with the appropriate velocity. However, the binary-binary interaction is not affecting the angular momentum of the ejected star. We can therefore assume that the observed $v_{\rm rot}\sin i = 115 \pm 8\,{\rm km\,s^{-1}}$ resembles the rotational velocity in the tidally-locked progenitor binary. To reach such a high rotational velocity, the separation of this binary is constrained to $\sim 1\,R_{\odot}$ *(24)*. The interaction probability of two such binaries even in a very dense cluster is expected to be extremely small.

Another idea to explain HVS not originating from the GC is the origin in a nearby, low-mass galaxy *(15)*. Since the escape velocities from those smaller galaxies are smaller as well, it is easier for stars to escape and travel trough the intracluster medium. Some of those neighbouring galaxies also have quite high velocities with respect to our own Galaxy. However, this scenario is also unlikely for US 708. Although the star might have lived long enough on the main sequence ($\sim$ 10 Gyr) to travel all the way from a satellite or small neighbouring galaxy, its current state of evolution is quite short compared to its total lifetime (only about 0.1%). Furthermore, only about 2% of all main sequence stars undergo an EHB phase. This means that for each single HVS sdO coming from the intracluster medium there should be about 50 000 HVS main sequence stars travelling through our Galactic halo. However, only a few tens of them have been reported so far. While faint, high proper motion objects are still not easy to identify, it is very easy to discover stars with high RVs in big survey like SDSS or RAVE. Palladino et al. *(15)* list more exotic mechanisms like interactions in globular clusters, with intermediate mass black holes or between galaxies (*54)*. In addition to that, combinations of several scenarios are imaginable. If for example a hierarchical triple system would be disrupted by the SMBH and one component of the ejected binary would explode as core-collapse SN, the trajectory of the surviving companion would not point back to the GC. However, we also regard all those scenarios as very unlikely to explain the object presented here.

Estimating supernova rates

Another sanity check for our scenario is to provide a rough estimate of the double-detonation SN Ia rates we would expect based on our observations and binary population synthesis models. So far US 708 is unique among the known He-sdO stars and this estimate is based on very small number statistics. The star was drawn from a sample of hot subdwarfs selected from SDSS. The full sample contains 1369 hot subdwarfs in total, 262 of them or roughly 20% are He-sdOs *(55)*. Binary population synthesis models by Han et al. *(9)* predict a birthrate of $5 \times 10^{-2}\,\mathrm{yr}^{-1}$

for hot subdwarfs in general and therefore $1 \times 10^{-2}\,\mathrm{yr}^{-1}$ for He-sdOs. One of the observed He-sdOs (US 708) might be an ejected donor remnant ($\sim$ 0.4%). This translates into a double-detonation SN rate of roughly $4 \times 10^{-5}\,\mathrm{yr}^{-1}$. This has to be regarded as lower limit only, because a few He-sdOs with smaller RVs, but rather high proper motions might still be hidden in our sample.

The predicted rates of double-detonation SN Ia are around $3 \times 10^{-4}\,\mathrm{yr}^{-1}$ and the observed rates of all types of SN Ia around $3 \times 10^{-3}\,\mathrm{yr}^{-1}$ *(56)*. Since all those numbers have quite significant uncertainties, they are regarded as broadly consistent. The most important point for this sanity check is, that our estimates from observations do not deviate from the predicted or observed rates by orders of magnitude.

Yu & Tremaine *(57)* calculated the ejection rates of hypervelocity stars expected from interactions with the Galactic centre black hole (or a binary black hole in the GC). The rates are of the order of $\sim 10^{-5}\,\mathrm{yr}^{-1}$ to $\sim 10^{-4}\,\mathrm{yr}^{-1}$. However, these numbers correspond to the simplest case, the ejection of single main sequence stars. Since stars as peculiar as US 708 and their progenitors are very rare compared to normal main sequence stars, the close encounter and ejection rates of such stars have to be orders of magnitude smaller. It is therefore very unlikely to find one He-sdO along with the about 20 other hypervelocity stars assuming that they are all accelerated in the GC.

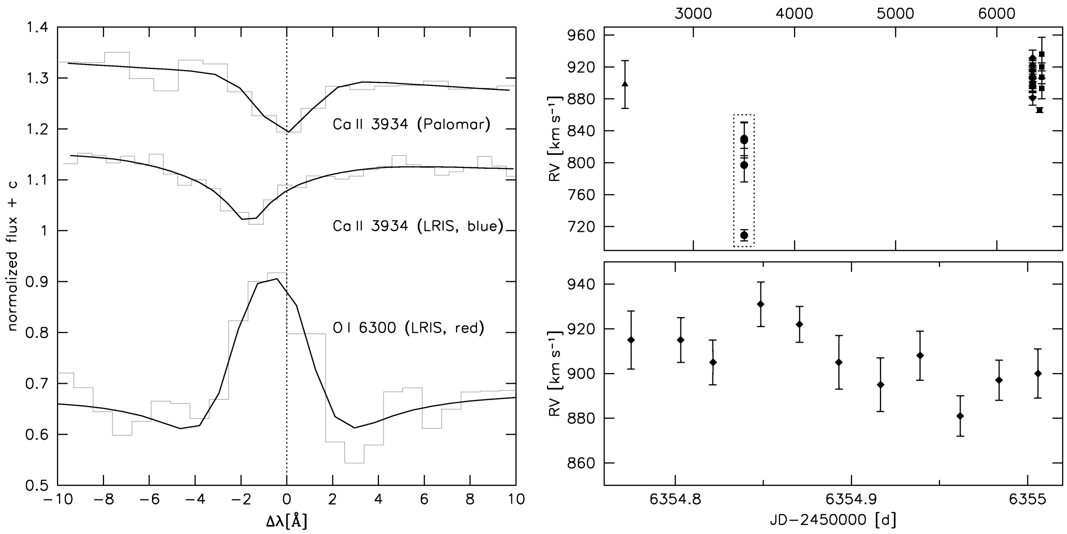

Fig. S1: Revised radial velocity. *Left panel:* Interstellar Ca II line of US 708 in the Palomar (upper plot) and blue-channel LRIS spectra (middle plot). In contrast to the Palomar spectrum, the LRIS spectrum is significantly blue-shifted. Night-sky emission line of O I in the LRIS red-channel spectrum (lower panel). The blue-shift is smaller than in the red-channel spectrum. *Right panel:* Radial velocities of US 708 plotted against Julian date. Upper panel: SDSS (triangle), LRIS blue- and red-channel uncorrected (grey circles), LRIS blue- and red-channel corrected (black circles), ESI (diamonds), Palomar (squares). The dotted box marks the LRIS RVs, which are affected by systematics. Lower panel: Close-up of the ESI RVs taken within one night.

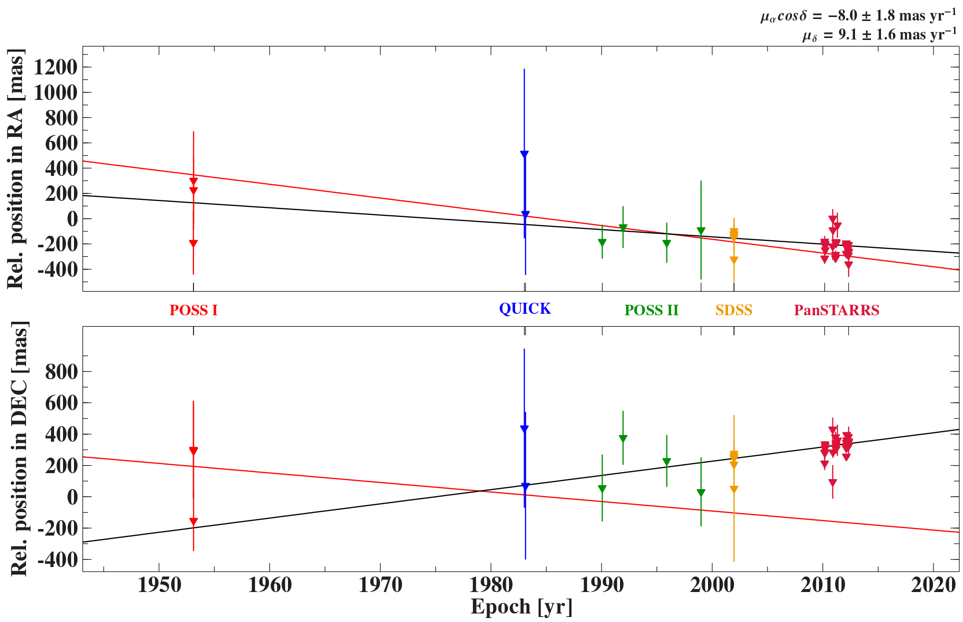

Fig. S2: Proper motion of US 708. Relative positions of US 708 in right ascension (upper panel) and declination (lower panel) plotted against time. The POSS I, QUICK and POSS II positions are measured from scanned photographic plates provided by the Digitised Sky Survey. SDSS and PanSTARRS positions are measured from CCD images. The black solid lines mark the best fits, from which we derive the proper motion components. The solid red lines mark the proper motion components required for the star to originate from the Galactic centre.

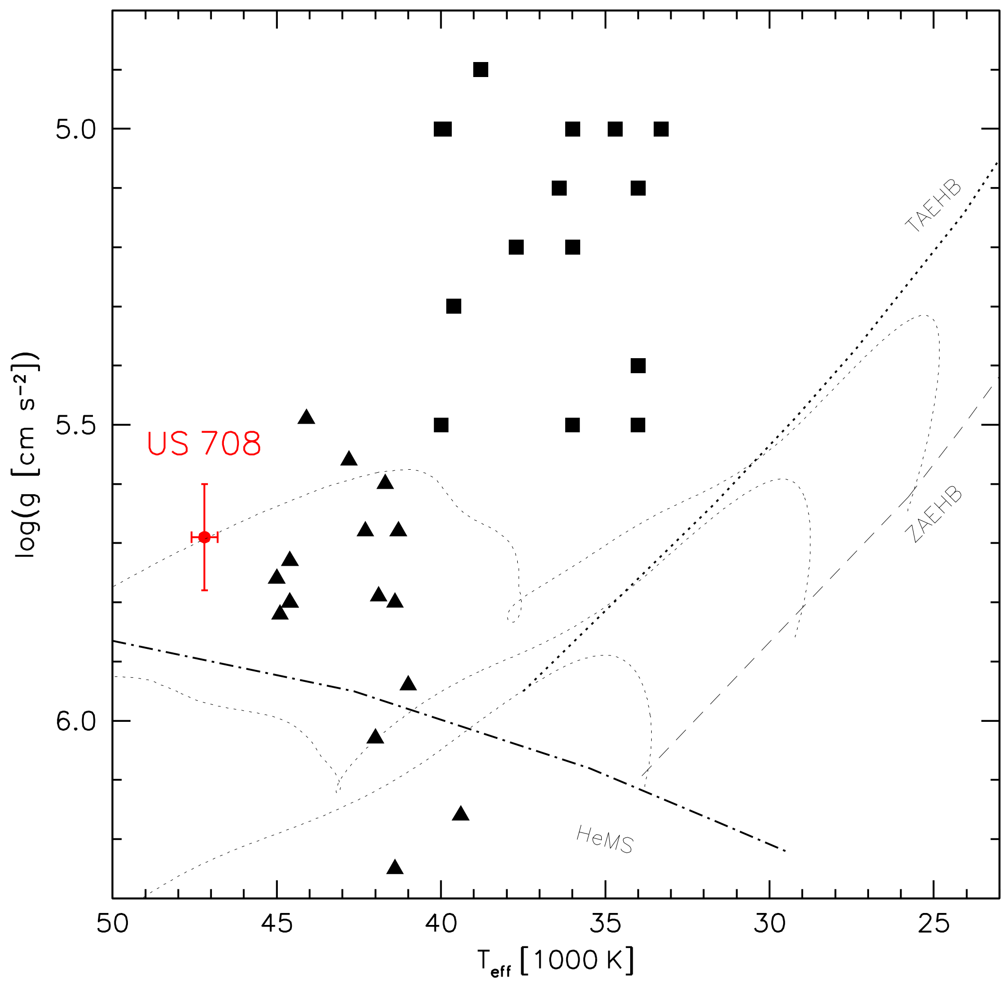

Fig. S3: Evolutionary status of US 708. $T_{\rm eff}$ − $\log g$ diagram. Evolutionary tracks (solar metallicity) of core helium-burning stars with a mass of 0.45 $M_{\odot}$ and different masses of their hydrogen envelopes (for bottom to top, 0.0 $M_{\odot}$, 0.001 $M_{\odot}$, 0.005 $M_{\odot}$) are plotted *(6)*. The positions of both the Zero Age and the Terminal Age Extended Horizontal Branch (ZAEHB, TAEHB) are indicated as well as the helium main sequence (He-MS). The filled black symbols mark known He-sdBs

(37,38) (squares) and He-sdOs*(39)* (triangles) from the literature.

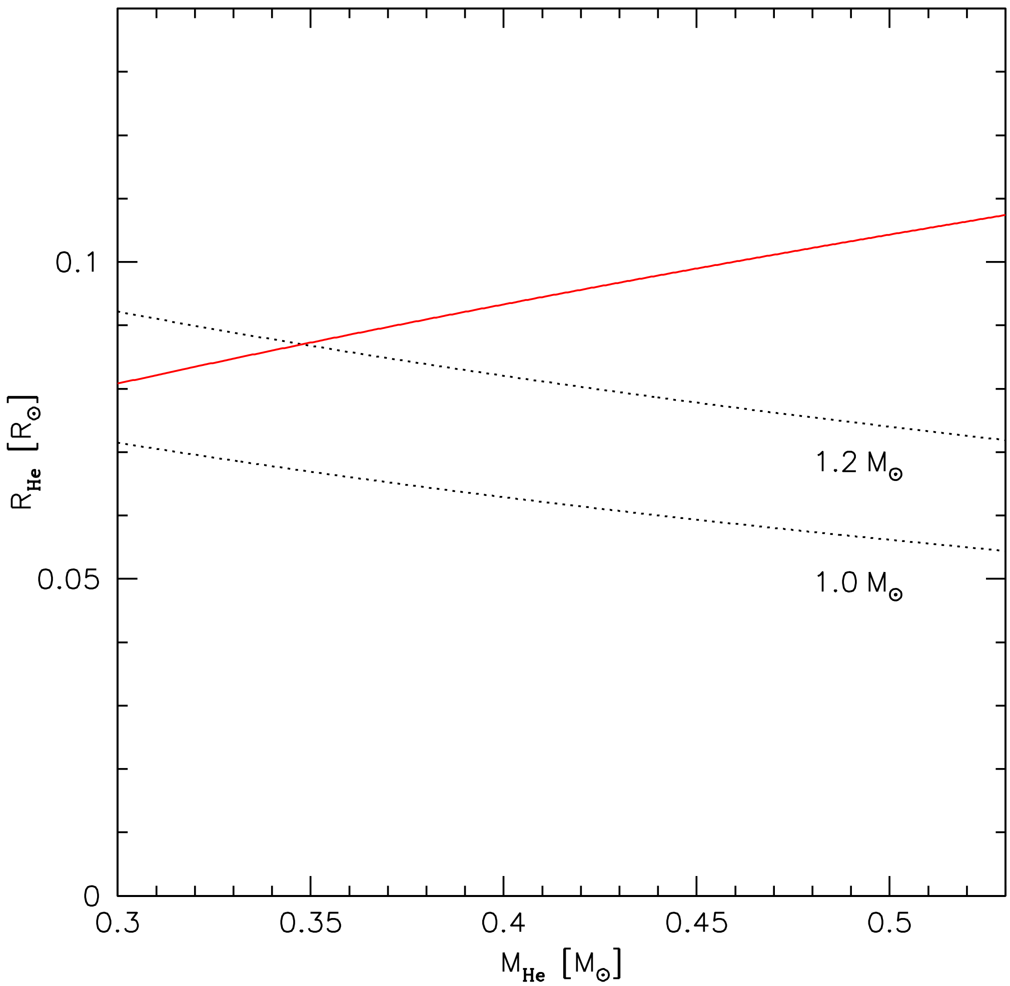

Fig. S4: Mass-radius relation of the compact He-star. The dotted black lines mark the Roche radii for WD companion masses of 1.0 $M_\odot$ and 1.2 $M_\odot$. The red solid line marks the He-star radius assuming $\log g = 6.1$.

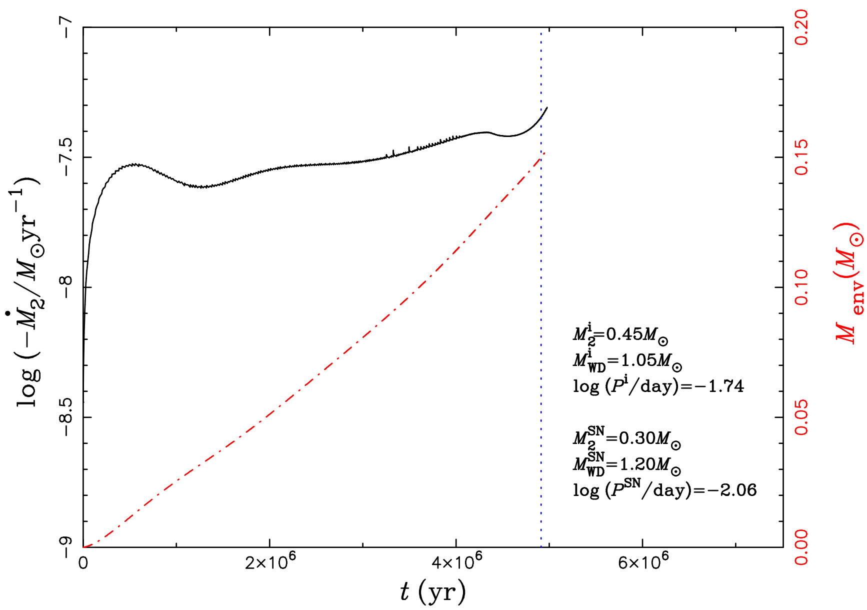

Fig. S5: Mass-transfer rate. The solid and dash-dotted curves show the mass-transfer rate and the mass of the WD envelope (He shell) varying with time after the He star fills its Roche lobe, respectively. The dotted vertical line indicates the position where the double-detonation may happen (the mass of the He shell increases to $\sim 0.15\,M_\odot$). The initial binary parameters and the parameters at the moment of the SN explosion are also given.

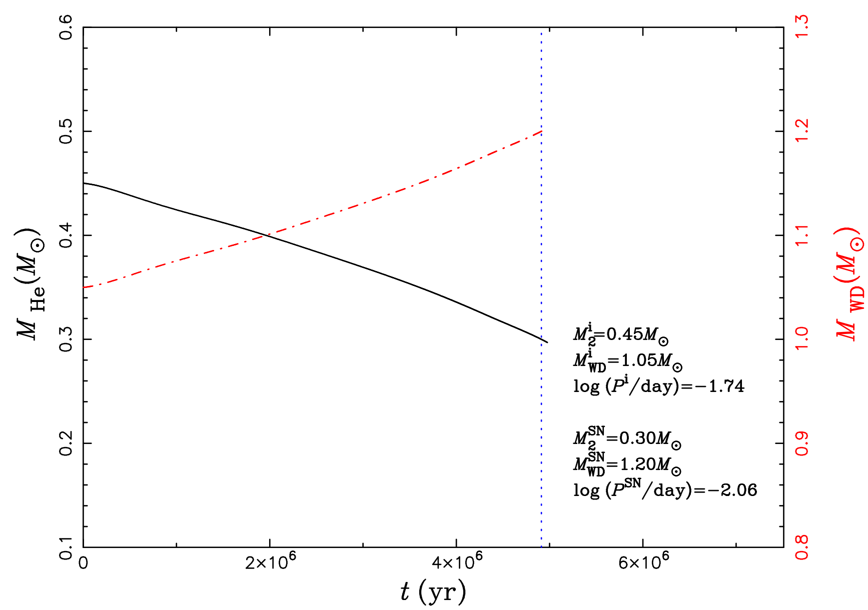

Fig. S6: Change of component masses. Change of He-star (solid line) and WD mass (dash-dotted line) with time. The dotted vertical line indicates the position where the double-detonation may happen (the mass of the He shell increases to $\sim 0.15\,M_\odot$). The initial binary parameters and the parameters at the moment of the SN explosion are also given.

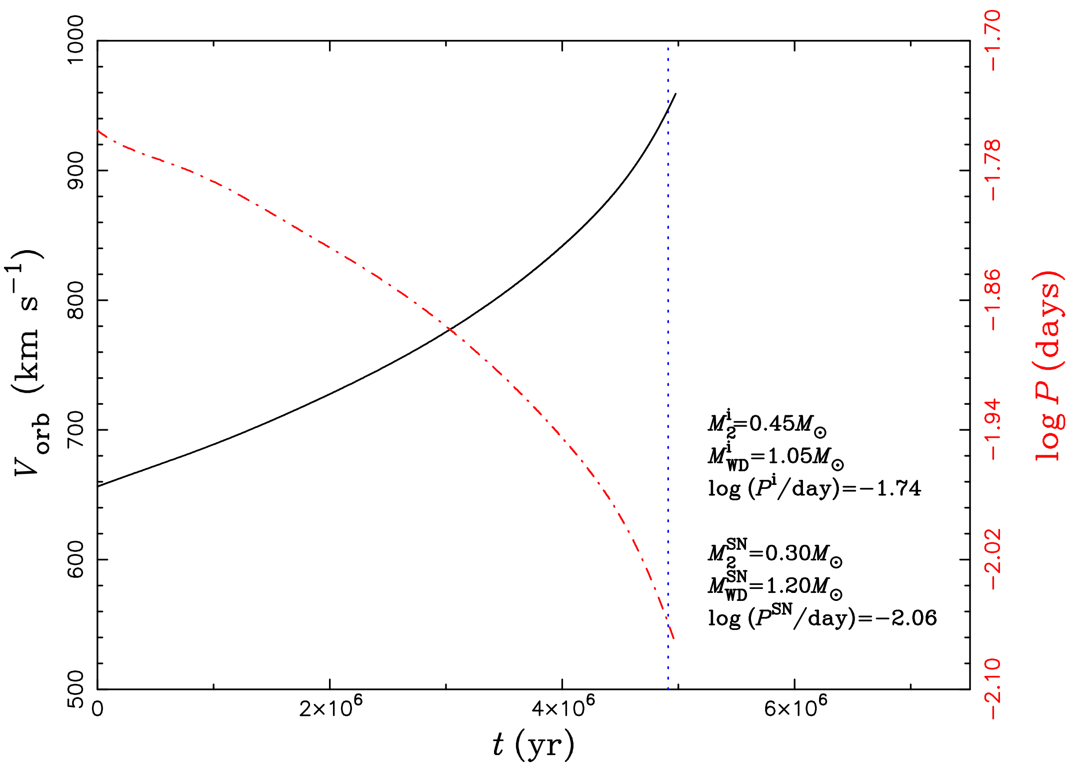

Fig. S7: Evolution of orbital parameters. Time evolution of the radial velocity semiamplitude (solid line) and the orbital period (dash-dotted line) of the binary. The dotted vertical line indicates the position where the double-detonation may happen (the mass of the He shell increases to $\sim$ 0.15 $M_\odot$). The initial binary parameters and the parameters at the moment of the SN explosion are also given.

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