The case and fate of HD 75767 – neutron star or supernova?

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ABSTRACT
We report the discovery of the nearby \((d = 24 \text{ pc})\) HD 75767 as an eight billion year old quadruple system consisting of a distant M dwarf pair, HD 75767 C–D, in orbit around the known short-period \(P = 10.25 \text{ d}\) single-lined binary HD 75767 A–B, the primary of which is a solar-like G star. On the reasonable assumption of synchronous orbital rotation as well as rotational and orbital coplanarity for the inner pair, we get \(M_B = 0.96 \text{ M}_\odot\) for the unseen HD 75767 B, that is, the case of a massive white dwarf. Upon future evolution, mass transfer towards HD 75767 B will render the \(M_A = 0.96 \text{ M}_\odot\) G-type primary, now a turnoff star, to become a helium white dwarf of \(M_A \sim 0.33 \text{ M}_\odot\). Depending on the mass accretion rate, accretion efficiency and composition of the massive white dwarf, this in turn may result in a collapse of HD 75767 B with the formation of a millisecond pulsar, i.e. the creation of a low-mass binary pulsar (LMBP), or, instead, a Type Ia supernova explosion and the complete disruption of HD 75767 B. Irrespective of which scenario applies, we point to the importance of the distant M dwarfs as the likely agents for the formation of the inner, short-period HD 75767 A–B pair, and hence a path that particularly avoids preceding phases of common envelope evolution.

Key words: binaries: close – stars: evolution – stars: individual: HD 75767 – pulsars: general – supernovae: general – white dwarfs.

1 INTRODUCTION
While most of the bright stars in the solar neighbourhood seem to proceed along the ordinary paths of stellar evolution, a few instead offer very intriguing prospects on closer inspection. The relatively unknown sixth-magnitude object HD 75767 is certainly among the most distinguished members in this respect.

Discovered as a single-lined, short-period spectroscopic binary by Sanford (1931), the primary HD 75767 A, usually classified as dG1 or G0, is actually a turnoff star that will soon fill its Roche lobe and launch considerable mass transfer towards HD 75767 B. In this paper we will present strong evidence that this unseen companion is most likely a massive white dwarf. As soon as HD 75767 B starts to accrete matter from HD 75767 A, hydrogen–helium shell burning in the outermost layers of the white dwarf may process this material into carbon and oxygen, thereby increasing its degenerate core mass. Depending, among other things, on the rate and efficiency of the mass accretion as well as the white dwarf’s core composition, a variety of interesting outcomes can occur. One major case is certainly that of a thermonuclear explosion of HD 75767 B, that is, we may face a nearby Type Ia supernova (SNIa) progenitor system. Likewise the accretion-induced collapse of HD 75767 B to a neutron star and the creation of a low-mass binary pulsar is another major scenario upon future evolution.

One obvious oddity of today’s HD 75767 system arises from the fact that HD 75767 B must have been a fairly massive object at birth, and this provokes the question of how this short-period binary could sustain its early vigorous phase, or whether, instead, it evolved to a close binary only later on. With respect to the latter possibility, orbital migration in response to permanent gravitational tugs of a more distant companion is generally known as a viable mechanism and an attractive alternative to common envelope scenarios for the formation of close orbits. Indeed, we report in this paper the discovery of a distant and faint common proper-motion companion to HD 75767 A–B. At an approximate angular separation \(\rho \sim 2.5 \text{ arcsec}\) and position angle \(\theta \sim 340^\circ\), this additional component renders HD 75767 a triple system, with an outer orbital period AB–C of at least several hundred years.

We also present follow-up high-resolution spectroscopy of this distant companion that additionally resolves it to a double-lined spectroscopic binary, dubbed here as HD 75767 C–D, and with components that most likely represent fairly equal-mass M dwarfs with a short orbital period. Hence HD 75767 comes out as a nearby

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star system whose multiplicity level is at least quadruple. In this paper we shall discuss each of the four components as well as some possible future outcomes of the inner A–B pair.

2 THE G-TYPE PRIMARY: HD 75767 A

A straight comparison of the high-resolution spectrum of HD 75767 A with that of the Sun immediately provides the principal similarities of both stellar objects, as well as the common thin-disc population status. Figs 1 and 2 show some relevant spectral portions. On closer inspection, the overall impression is that HD 75767 A must be comparatively metal-depleted, and there are also clear signatures for an enhanced chromospheric activity from the cores of Hα and the Ca ii infrared triplet. The latter is most easily explained with the short orbital period \( P = 10.25 \text{ d} \) (Sanford 1931) of the inner A–B system.

Detailed evolutionary tracks for HD 75767 A are given in Fig. 3. These calculations provide a mass \( M_A = 0.96 \pm 0.07 \text{ M}_\odot \) for the G star, wherein the given uncertainty refers to the combined errors in \( T_{\text{eff}}, M_{\text{bol}}, [\text{Fe/H}] \) and \([\text{Fe/Mg}]\). They introduce HD 75767 A as an old thin-disc member at \( \tau = 8.2 \pm 3 \text{ Gyr} \), close to its turnoff position. Note that this age estimate for HD 75767 A is particularly independent of any former mass overflow scenario from HD 75767 B, since this could only occur within the initial \( \sim 10^8 \text{ yr} \) after star system formation.

The basic stellar parameters for HD 75767 A are summarized in Table 1; for details of the stellar interior calculations, spectroscopic observations and model atmosphere analysis, we refer here to Bernkopf (1998) and Fuhrmann (1998).
3 THE STELLAR REMNANT: HD 75767 B

The fact that there is no obvious trace of a secondary in our spectra of HD 75767 A in spite of Sanford’s enormous mass function, $f(M) = 0.0154 M_{\odot}$, suggests that HD 75767 A might be in orbit around a stellar remnant. Of course, the orbital inclination angle is principally unknown, but provided HD 75767 A is in synchronous orbital rotation, and there is rotational and orbital coplanarity, we can derive the mass of the secondary.

For a 10 d orbit, synchronization time-scales should amount to some 10$^5$ yr. This is only a small fraction of the age of HD 75767 A, such that the condition for synchronization should be no real concern. Thus, if the case of coplanarity for HD 75767 A and B is fulfilled, the above orbital period $P = 10.25$ d and stellar radius $R_A = 1.10 \pm 0.05 R_{\odot}$ result in an equatorial velocity $v_{eq} = 5.43 \text{ km s}^{-1}$. The projected rotational velocity $v \sin i = 2.1 \pm 0.8 \text{ km s}^{-1}$ (2$\pi$) then implies $i = 22.7$ and hence $M_B = 1.01 M_{\odot}$. This is the case of a massive white dwarf and very reminiscent of the nearby $M = 1.034 \pm 0.026 M_{\odot}$ Sirius B (Holberg et al. 1998), except that the latter has an orbital period of about 50 yr and the fact that our formal mass errors of HD 75767 B are about 10 times as high. Although, on the low-mass side, this raises the question as to whether HD 75767 B could be a late-type dwarf, we note that a companion even down to $M_B \sim 0.60 M_{\odot}$ should be detectable in the spectrum of HD 75767 A. However, this requires $v \sin i \gtrsim 3.0 \text{ km s}^{-1}$, which is very unlikely since the projected rotational velocity of HD 75767 A was differentially measured with respect to the very much alike Moon spectrum (cf. Figs 1 and 2). By the same token, the reasonable range of the macroturbulence parameter for HD 75767 A has a negligible impact on the $v \sin i$ measurement.

Taking into account that Sanford’s plate material goes back to the 1920s, there is however the principal possibility that the distant companion HD 75767 C–D could eventually have altered the orbital inclination (and hence the semi-amplitude $K$) and system velocity $\gamma$ of the inner pair, as has already been found for other multiple systems by e.g. Mayor & Mazeh (1987). Because of this, but also because of the above-mentioned SNIa progenitor versus low-mass binary pulsar prospects, there was the need for a modern, more precise set of orbital parameters for HD 75767 A–B.

Our first radial velocity measurements of HD 75767 A were obtained early in the year 2000 at the Calar Alto Observatory. The bulk of the observations however were done in 2004 when HD 75767 A was also one of the stars monitored during the RV search programme of the Thüringer Landessternwarte described by Hatzes et al. (2003). For this programme we used the 2-m Alfred Jensch Telescope of the Thüringer Landessternwarte Tautenburg, which is equipped with an echelle spectrograph with resolving power of $\lambda/\Delta \lambda = 67,000$. During the observations an iodine absorption cell is placed in the optical light path in front of the spectrographs slit. The resulting iodine absorption spectrum is then superposed on top of the stellar spectrum providing a stable wavelength reference against which the stellar RVs are measured. In the first step, the spectra are bias-subtracted, flat-fielded and extracted using standard IRAF routines.

In the second step the RVs are calculated by modelling the observed spectra with a high signal-to-noise ratio template of the star (without iodine) and a scan of our iodine cell taken with the Fourier Transform Spectrometer of the McMath–Pierce Telescope at Kitt Peak (Braut 1978). The latter enables us to compute the relative velocity shift between stellar and iodine absorption lines as well as to model the temporal and spatial variations of the instrumental profile. See Valenti, Butler & Marcy (1995) and Butler et al. (1996) for a description of the principles behind this technique.

The radial velocities and the merged and improved orbital parameters for the HD 75767 A–B system are given in Tables 2 and 3, respectively; the velocity curve is displayed in Fig. 4. Compared to Sanford’s early results from the 1920s, we notice indeed small changes for the system velocity $\gamma (+3.5 \text{ km s}^{-1}$ versus $+4.6 \text{ km s}^{-1}$) and semi-amplitude $K (24.5 \text{ km s}^{-1}$ versus $23.5 \text{ km s}^{-1}$), which appear to be significant, although Sanford did not explicitly tabulate the error bars. The revised orbital parameters corroborate the existence of a massive white dwarf, $M_B = 0.96 M_{\odot}$, around HD 75767 A.

4 THE DISTANT COMPANIONS: HD 75767 C–D

Since HD 75767 B may have been a formerly bright and massive star of say $\sim 6 M_{\odot}$, one immediately wonders how HD 75767 A could have survived any formerly close orbit, or, likewise, how the bulk of the mass of HD 75767 B was ultimately lost from the system.

An obvious solution to this question is to consider the existence of an initially much wider pair that however underwent a common envelope evolution with a considerable loss of mass and orbital angular momentum as soon as HD 75767 B ascended the giant branch. In

*Figure 3.* Evolutionary tracks for the nearby G-type star HD 75767 A: the star is significantly older than the Sun, more evolved and slightly less metal-enriched and less massive compared to our parent star. At an age of $\tau = 8.2$ Gyr, HD 75767 A is also among the oldest thin-disc members.

| $T_{\text{eff}}$ | 5802 ± 60 K |
| log $g$ | 4.37 ± 0.10 cgs |
| [Fe/H] | $-0.11 \pm 0.06$ dex |
| [Fe/Mg] | $-0.04 \pm 0.05$ dex |
| $\xi_t$ | 1.00 ± 0.20 km s$^{-1}$ |
| $\xi_{RT}$ | (fixed) 4.0 km s$^{-1}$ |
| $v \sin i$ | 2.10 ± 0.80 km s$^{-1}$ |
| $V$ | 6.570 ± 0.005 mag |
| $M_{\text{bol}}$ | 4.52 ± 0.08 mag |
| $BCV$ | $-0.13 \pm 0.05$ mag |
| Radius | 1.10 ± 0.05 $R_{\odot}$ |
| Mass | 0.96 ± 0.07 $M_{\odot}$ |
| Age | 8.2 ± 3.0 Gyr |
Table 2. Record of the radial velocity measurements of HD 75767 A at the Thüringer Landessternwarte Tautenburg and the Calar Alto Observatory in the years 2000–2004.

<table>
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<tr>
<th>JD</th>
<th>Radial velocity (km s(^{-1}))</th>
<th>Uncertainty (m s(^{-1}))</th>
<th>Observatory</th>
</tr>
</thead>
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<tr>
<td>245 3043.4376</td>
<td>+28.086</td>
<td>65.62</td>
<td>TLT</td>
</tr>
<tr>
<td>245 3075.4932</td>
<td>+24.060</td>
<td>45.29</td>
<td>TLT</td>
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<td>245 3076.3411</td>
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<td>245 3079.3375</td>
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<td>245 3080.3518</td>
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</tr>
<tr>
<td>245 3134.3394</td>
<td>+17.554</td>
<td>66.64</td>
<td>TLT</td>
</tr>
</tbody>
</table>

Table 3. Orbital parameters of the HD 75767 A–B system.

\[
P = 10.2485 \pm 0.0013 \text{ d}
\]
\[
a_1 \sin i = 3.2897 \pm 0.0078 \times 10^6 \text{ km}
\]
\[
\epsilon = 0.016 \pm 0.007
\]
\[
\omega = 356 \pm 2^\circ
\]
\[
\gamma = +4.6 \pm 0.2 \text{ km s}^{-1}
\]
\[
K = 23.5459 \pm 0.081 \text{ km s}^{-1}
\]
\[
f(M) = 0.01371 \pm 0.00010 \text{ M}_\odot
\]

this case an observable characteristic might be an enhanced helium abundance on HD 75767 A. Yet, inspection of the chromospheric He I D3 transition at \(\lambda 5876\) provides no convincing clue in this respect: the weak helium absorption that one notices in Fig. 5 ties in with the chromospheric activity level of HD 75767 A as deduced from H\(\alpha\) and Ca II \(\lambda 8542\) in Figs 1 and 2. This is also corroborated from a comparison with \(\pi 1\) UMa below, a young G star of the Ursa Major Association with characteristics similar to HD 75767 A (cf. Fuhrmann 2004, for details) but a rather equator-on perspective and a rotational period of only \(\sim 5\) d.

Another argument that one may put forward against a former common envelope phase is that HD 75767 A should have accreted rather large amounts of mass from the \(\sim 6\) M\(_\odot\) reservoir of its B-type primary and hence emerge as, for example, a massive A-type star on its own.

Thus, while the case for a former common envelope evolution remains inconclusive, a competing scenario for the formation of the inner, short-period A–B pair arises from the fact that a remarkable number of close binaries do originate from higher-level star systems (e.g. Tokovinin & Smekhov 2002). The likely impact of any distant companion is here to change the eccentricity of the inner system in cycles that scale with \(P_2^2/P_1\) out such that tidal friction at periastron passages gives rise to a secular evolution towards even closer, circularized orbits (cf. Kiseleva, Eggleton & Mikkola 1998).

Indeed, our first pointing towards HD 75767 in the early hours of 2000 January 24 revealed an approximately 6 mag fainter companion at a projected angular separation of about 2.5 arcsec on the sky. This discovery was possible basically as a result of good seeing conditions, in combination with the ‘coronographic’ properties of the spectrograph’s entrance diaphragm that absorbed essentially all the light of the much brighter G star. The resulting enhanced sensitivity of the attached guiding camera then immediately revealed the faint companion.

On that particular night this was of course only a first hint of a physical companion to HD 75767. Four years later however, in 2004 February, we returned to HD 75767, and in view of the considerable...
proper motion of this nearby star, the first observation under good seeing conditions confirmed beyond doubt that the relative orientation and angular distance were essentially unchanged. This circumstance sparked our interest in the distant companion and the desire to obtain a high-resolution spectrum. In the third night of this observing run, on 2004 February 13, good atmospheric conditions were met and we took a 30-min low signal-to-noise ratio, high-resolution spectrum of the faint companion of HD 75767 A. Two small portions of this are reproduced in Fig. 6. In the left-hand panel of this figure two outstanding features are of interest: (i) a radial velocity of the faint companion that is essentially in keeping with that of HD 75767 A, i.e. confirmation of a physical companion as already implied from the common proper motion; and (ii) an Hα line that shows up in emission. This, of course, needs some explanation, and an answer is immediately found in the companion’s near-infrared spectrum, from which it is clear that it is a binary on its own. The right-hand panel of Fig. 6 shows the relevant data and a comparison to the bright and nearby K7 dwarf 61 Cyg B. Evidently, both components, ‘HD 75767 C and D’, are of similar spectral type and the relative velocity displacement of ~21 km s\(^{-1}\) leads to the suspicion that, as with the inner A–B system, we are dealing with a short-period system in bound rotation.

To estimate the combined spectral type of the C–D pair we have applied the criteria for low-resolution spectra described in Kirkpatrick, Henry & McCarthy (1991) to classify the combined spectra of the stars. We derive a spectral type of M3–M4. To double check the results we have also compared the spectrum of HD 75767 C–D to those of HIP 34603 (M4.5), HIP 25953 (M3.5) and HIP 110526 A (M3), observed with the same instrument setup and given in Fig. 7.

Thus, HD 75767 C–D appears to be too late in comparison with the well-known \(P = 5.98\) d short-period BY Dra (Boden & Lane 2001) with masses \(M_A + M_B = 0.59 + 0.52\ M_\odot\), and eventually more like the recently detected (but metal-rich) CU Cnc Aa–Ab with \(M_A + M_B = 0.434 + 0.399\ M_\odot\) (Ségransan et al. 2000). However, while the latter has an orbital period of only \(P = 2.77\) d, the rather similar Hα emission features that we notice for BY Dra and HD 75767 C–D lead us to suspect that both may have similar orbital periods as well. If so, one may not even exclude the case of an eclipsing binary for HD 75767 C–D, which means that additional observations could provide very accurate masses for a nearby M dwarf pair whose metallicity is already known from its G-type primary.

5 THE FUTURE: COLLAPSE OR EXPLOSION?

Today HD 75767 A–B is clearly a detached system. However, once HD 75767 A leaves the turnoff region (cf. Fig. 3) and becomes a subgiant, it will soon thereafter fill its Roche lobe at \(\log g_A \sim 2.5\) or \(R_A \sim 9.4\ R_\odot\), whereupon mass loss towards the massive stellar
remnant will commence. By that time HD 75767 A will be in its hydrogen-shell-burning stage such that a case B mass transfer as defined by Kippenhahn & Weigert (1967) applies. The outcome is then a low-mass helium white dwarf, very similar to the one first described in Kippenhahn, Kohl & Weigert (1967), except that their secondary was a solar-like main-sequence star. For an estimate of the final helium white dwarf mass, we make use of the approximation given in Refsdal & Weigert (1971) wherein we adopt log $K \sim 3.84$ with reference to the chemistry of HD 75767 A; application of their formula then results in $M_A = 0.329 M_\odot$. This appears to be a fairly robust case with an uncertainty of only a few hundreds of a solar mass, as more recent calculations by e.g. Tauris & Savonije (1999) or Podsiadlowski, Rappaport & Pfahl (2002) suggest.

As opposed to this, things are much more difficult to quantify for the fate of the massive white dwarf (e.g. Canal, Isern & Labay 1990). The matter that is transferred to the surface of HD 75767 B may give rise to a recurrence of shell flashes or nova outbursts, which leaves some doubt as to whether conservative conditions for the total mass and orbital angular momentum are a good approximation (e.g. Kovetz & Prialnik 1994). The latter would suggest that, since $M_\text{A}/M_\text{B} \sim 1$ at present, their changing mass ratio should enlarge the semimajor axis from $a \sim 24.7 R_\odot$ now, to $a \sim 76.4 R_\odot$ for $M_\text{A} \sim 0.33 M_\odot$ and $M_\text{B} \sim 1.59 M_\odot$ after mass transfer; in particular for HD 75767 B this implies that it reaches the Chandrasekhar limit even if some non-negligible part of the accreted mass is ultimately rejected. The most pertinent number in this context is of course the mass transfer rate, which may reach up to $M \sim 10^{-7} M_\odot$ yr$^{-1}$ at the initial transfer phase. In that case one possible scenario in e.g. the models of Nomoto & Kondo (1991, their fig. 4) is that of a carbon deflagration for a carbon–oxygen white dwarf, whereas for $M < 10^{-8} M_\odot$ yr$^{-1}$ an off-centre helium detonation might occur – should the critical mass limit be reached at all.

However, with reference to the uncertainty of the white dwarf’s mass, HD 75767 B could instead be an oxygen–neon–magnesium degenerate. Electron captures on $^{24}\text{Mg}$ and $^{20}\text{Ne}$ (the efficiency of which depends in turn on the density) may then induce a collapse of the white dwarf and the formation of a neutron star (cf. Nomoto & Kondo 1991, their fig. 3). This may thereafter emerge as a millisecond pulsar, in which case the nearby HD 75767B would be the progenitor system of a low-mass binary pulsar.

Finally, the evolutionary tracks in Fig. 3 imply that the mass transfer of the inner HD 75767 A–B system will not start before four billion years from now. By that time the present nearby star system will have left the solar neighbourhood. For the supernova scenario, this is certainly no disadvantage. Also, what about the distant M dwarf companions? Unless magnetic braking and/or gravitational radiation has by then provoked their merger, they will continue a low-budget core hydrogen burning such that it is tempting to forget that a good deal of the dramatic changes to the inner A–B system were eventually driven from them.

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