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# A Multiwavelength Study of the Runaway Binaries HD 14633 and HD 15137

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**Abstract:** The runaway O-type binaries HD 14633 and HD 15137 were likely ejected from the cluster of their birth by supernovae explosions in close binaries. Here we present recent optical spectra to update the orbital solutions of the binaries and study the physical parameters of the O star primaries. We also present *XMM-Newton* observations of both systems that attempt to detect hard power-law emission from compact companions. EPIC spectra of HD 14633 at periastron and apastron reveal a non-thermal X-ray flux component that is variable during the orbit. Our EPIC spectra of HD 15137 indicate thermal X-ray emission consistent with an isolated O star. We provide an upper limit on the emission from a compact companion in HD 15137.

## 1 Introduction

There are two accepted mechanisms to explain the origin of runaway O-type stars: close multi-body interactions in a dense cluster environment (Poveda, Ruiz & Allen 1967), or a supernova explosion within a close binary (Zwicky 1957). Binary runaways such as HD 14633 and HD 15137 offer the potential to study the companion star and distinguish between these ejection scenarios, providing valuable insight into the evolution of open clusters and close binary stars.

The optical properties and space velocity of HD 14633 have been studied by Boyajian et al. (2005) and McSwain et al. (2007a). HD 14633 is an ON8.5 V star with effective temperature $T_{\rm eff} = 35100$ K, surface gravity $\log g = 3.95$, and projected rotational velocity $V \sin i = 138$ km s$^{-1}$. The short orbital period ($P = 15.4$ d) and very high eccentricity ($e = 0.70$) suggest a disruptive supernova origin for the runaway. The very low mass function likewise supports a low mass, neutron star (NS) companion. The enriched nitrogen and relatively fast rotation observed in HD 14633 may be due to a mass transfer episode prior to the supernova in a close binary. With a peculiar space velocity $V_{\rm pec} = 71$ km s$^{-1}$ and

[*] Based partly on observations collected at the Observatoire de Haute-Provence (France) and on observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA.

distance of 2040 pc, this runaway single-line spectroscopic binary (SB1) system was likely ejected from the open cluster NGC 654 about 14 Myr ago (Boyajian et al. 2005).

HD 15137 has many optical and orbital properties similar to HD 14633 (Boyajian et al. 2005, McSwain et al. 2007a, McSwain et al. 2010). It is slightly more evolved with spectral type O9.5 III(n), $T_{\rm eff} = 29700$ K, $\log g = 3.50$, and $V \sin i = 234$ km s$^{-1}$. The star may also be N rich, and it is also an SB1 with a highly eccentric orbit and a very low mass function. It is located at a distance of 2420 pc and has $V_{\rm pec} = 63$ km s$^{-1}$. Coincidentally, HD 15137 was also traced back to the open cluster NGC 654, with a travel time of about 10 Myr since its ejection (Boyajian et al. 2005).

In this work, we present updated orbital solutions for HD 14633 and HD 15137 to refine their orbital geometry and study the potential for binary interactions. We also present the results from the first *XMM-Newton* observations of both systems in an attempt to detect compact companions.

# 2 Optical Observations and Radial Velocity Measurements

We obtained 34 spectra of HD 14633 and 44 spectra of HD 15137 at the Observatoire de Haute-Provence (OHP) during several observing runs from 2005 October to 2007 November. We used the 1.52m telescope with the Aurélie spectrograph with grating #3 and the $2048 \times 1024$ CCD EEV 42-20#3 detector with a pixel size of 13.5 $\mu$m. These spectra cover a wavelength range between 4460–4890 Å with a resolving power of $R = \lambda/\Delta\lambda \approx 8000$.

We also obtained 32 spectra of HD 14633 and 47 spectra of HD 15137 at the KPNO coudé feed (CF) telescope over 35 consecutive nights during 2008 October and November. We used grating B in third order with the 4-96 order-sorting filter and the F3KB detector. This instrumental configuration resulted in a wavelength range of 4130–4570 Å with $R \approx 9000$ across the chip.

For both datasets, we obtained ThAr comparison spectra for wavelength calibration shortly before or after each observation. The OHP data were bias corrected, flat fielded, cleaned for cosmic rays, and extracted using the MIDAS software developed at the European Southern Observatory. The CF spectra were reduced using standard procedures in IRAF. Both datasets were rectified to a unit continuum using line-free regions and interpolated onto a log wavelength scale using a common heliocentric wavelength grid. Our observations are described in more detail by McSwain et al. (2010).

To measure the radial velocities, $V_r$, of both stars, we used a cross correlation procedure described by McSwain et al. (2010). The orbital period of HD 14633 is well known at $P = 15.4$ d from our previous spectroscopic studies (Boyajian et al. 2005, McSwain et al. 2007a), and our new $V_r$ measurements allow us to refine the orbital parameters of this system here. For HD 15137, we initially proposed an orbital period $P \sim 30$ d for the system, but our new $V_r$ measurements exclude this value. From our new period search, there was no one clear signal that stands out from any of the resulting periodograms, so we inspected each candidate frequency carefully. We used each proposed period to solve for the resulting orbital elements. After ruling out all resulting $V_r$ curves with poor fits and extremely large scatter, any $P < 35$ d, and an alias frequency, we adopt an orbital period $P = 55.4$ d for HD 15137.

We present the final orbital solutions for HD 14633 and HD 15137 in Table 1, and the corresponding radial velocity curves in Figure 1. Both orbits are highly eccentric with low velocity semiamplitudes and very low mass functions, suggesting low mass companions. Based on the runaway nature of the binaries and their orbital parameters, Boyajian et al. (2005) proposed a supernova ejection scenario and a NS companion for both stars, even though they were not known X-ray sources. They proposed that HD 14633 and HD 15137 may be “quiet” HMXBs, too widely separated for the NS to accrete a significant mass of stellar winds to produce the bright X-ray flux commonly associated with X-ray binaries (Liu, van Paradijs & van den Heuvel 2006). To investigate this scenario, we describe *XMM-Newton* observations of both systems below.

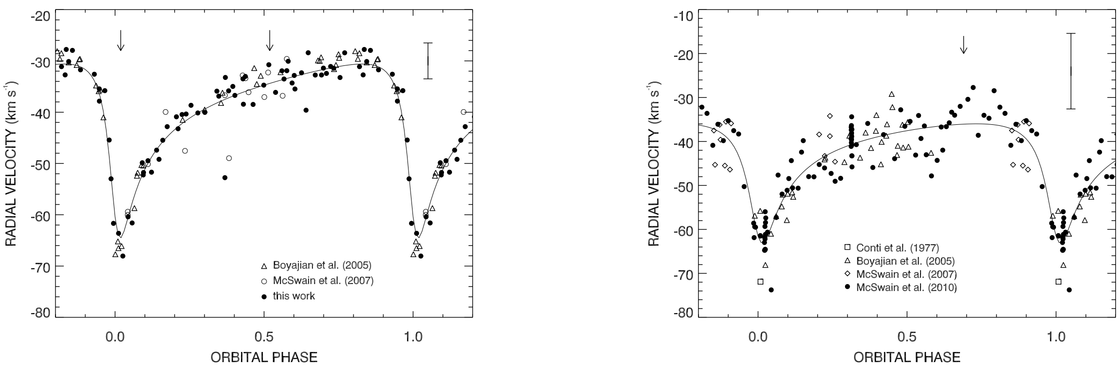



Figure 1: *Left:* Radial velocity curve of HD 14633. A typical error bar assuming the standard deviation $\sigma = 4.3$ km s$^{-1}$ is also shown. Arrows mark the orbital phases of our *XMM-Newton* observations of HD 14633. *Right:* Radial velocity curve of HD 15137. The error bar includes $\sigma = 7$ km s$^{-1}$ in addition to the intrinsic $V_r$ error of $\pm 5$ km s$^{-1}$ due to rapid line profile variations. The arrow marks the orbital phase of the single *XMM-Newton* observation of HD 15137.

Table 1: Orbital Elements

| | HD 14633 | HD 15137 |
|---|---|---|
| $P$ (days) | $15.40825 \pm 0.00024$ | $55.3957 \pm 0.0038$ |
| $T$ (HJD–2,400,000) | $44227.297 \pm 0.099$ | $54421.991 \pm 0.064$ |
| $e$ | $0.677 \pm 0.035$ | $0.6239 \pm 0.0088$ |
| $\omega$ (deg) | $139.2 \pm 6.5$ | $152.17 \pm 0.86$ |
| $K_1$ (km s$^{-1}$) | $17.0 \pm 1.3$ | $13.56 \pm 0.15$ |
| $\gamma$ (km s$^{-1}$) | $-38.88 \pm 0.55$ | $-42.06 \pm 0.11$ |
| $f(m)$ ($M_\odot$) | $0.00312 \pm 0.00080$ | $0.00685 \pm 0.00030$ |
| $a_1 \sin i$ ($R_\odot$) | $3.80 \pm 0.33$ | $11.60 \pm 0.17$ |
| $\sigma$ (km s$^{-1}$) | 7.13 | 4.28 |

# 3 XMM-Newton Observations

We observed HD 14633 twice with *XMM-Newton* on 2009 July 23 and July 31. We denote these two observations as A and B, respectively, and further details are summarized in Table 2. We observed HD 15137 once on 2008 August 3, observation ID 0553810201, for approximately 20 ks. Based on the orbital solution above, these observations took place at orbital phase $\phi = 0.69$. The EPIC Observation Data Files and event lists were provided by the standard XMM Pipeline Processing System, and we filtered the event lists and extracted the source spectra using standard analysis threads.

## 3.1 Spectral Fits of HD 14633

For each observation of HD 14633, we fit the two MOS spectra simultaneously over the range 0.5–5.0 keV by grouping the data to a minimum of 5 photons per energy bin. Obs. A was fit using two absorption components: the ISM (model *tbabs* with Wilms abundances; Wilms, Allen & McCray 2000) and a second warm absorber from the N-rich stellar wind (model *vphabs*). The *tbabs* component

Table 2: XMM-Newton Observations and Spectral Fits of HD 14633

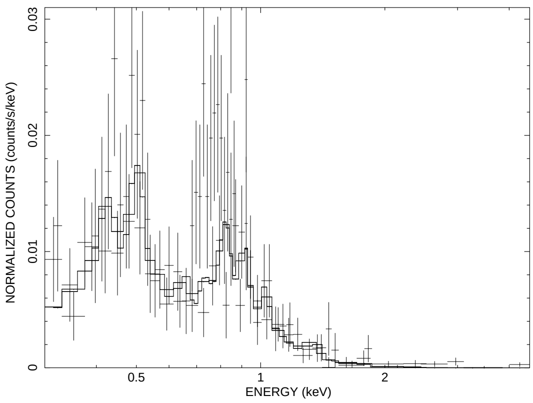
| Parameter | Obs. A | Obs. B | Notes |
|---|---|---|---|
| Observation ID | 0603570301 | 0603570401 | |
| Good time interval | 27 ks | 33 ks | |
| Orbital phase, $\phi$ | 0.519 | 0.019 | |
| $nH_{\rm tbabs}$ (cm$^{-2}$) | $7.50 \times 10^{20}$ | $7.50 \times 10^{20}$ | a |
| $nH_{\rm vphabs}$ (cm$^{-2}$) | $2.2^{+0.09}_{-1.0} \times 10^{21}$ | $2.20^{+0.13}_{-0.07} \times 10^{21}$ | |
| N abundance ($\times$ solar) | $15^{+12}_{-11}$ | 15 | b |
| $kT_{\rm vapec,1}$ (keV) | 0.27 | 0.27 | b, c |
| norm$_{\rm vapec,1}$ (cm$^{-5}$) | $8.2^{+13}_{-3.6} \times 10^{-3}$ | $8.2 \times 10^{-3}$ | b, d |
| $kT_{\rm vapec,2}$ (keV) | 0.56 | 0.56 | b, c |
| norm$_{\rm vapec,2}$ (cm$^{-5}$) | $1.2^{+2.0}_{-0.8} \times 10^{-3}$ | $1.2 \times 10^{-3}$ | b, d |
| $\Gamma$ | – | $1.46^{+0.75}_{-0.83}$ | |
| norm$_{\rm power}$ (keV cm$^{-2}$ s$^{-1}$) | – | $3.3^{+2.7}_{-2.0} \times 10^{-6}$ | |
| Reduced $\chi^2$ | 1.33 | 1.29 | |
| Degrees of Freedom | 78 | 103 | |
| Absorbed flux (erg cm$^{-2}$ s$^{-1}$) | $5.7^{+9.4}_{-3.4} \times 10^{-14}$ | $7.9^{+11.1}_{-4.7} \times 10^{-14}$ | |
| Unabsorbed flux (erg cm$^{-2}$ s$^{-1}$) | $9.4^{+15.5}_{-5.4} \times 10^{-14}$ | $1.1^{+1.7}_{-0.7} \times 10^{-13}$ | e |
| $L_X/L_{\rm bol}$ | $1.3 \times 10^{-7}$ | $1.5 \times 10^{-7}$ | |

a: Fixed, see text. b: The value for Obs. B was fixed using the value from Obs. A. c: Not constrained according to *steppar*. d: The $nH_{\rm vphabs}$ and N abundances were frozen to determine errors with *steppar*. e: The unabsorbed flux neglects only the interstellar absorbing column.

was fixed using the observed $E(B-V) = 0.13$ (McSwain et al. 2007a) and the relation $nH/E(B-V) = 5.8 \times 10^{21}$ atoms cm$^{-2}$ mag$^{-1}$ (Bohlin, Savage & Drake 1978). For the X-ray source, the best fit was achieved with a two-temperature (2-T) thermal model (*vapec*) with the N abundances fixed to the value from *vphabs*. We used the *steppar* routine separately for each parameter to investigate the 90% confidence limits. No additional components were necessary to fit obs. A, and the fit results are provided in Table 2.

Obs. B has a slightly higher observed count rate than A, especially at higher energies. We attempted to fit obs. B using the same model *tbabs*vphabs(vapec + vapec)* used for A, but none of the results were well constrained with *steppar*. Thus we chose to fix the N abundance and *vapec* values to those from obs. A, and we investigated whether an additional flux component was required. Adding a hard powerlaw component produced a significant improvement according to a statistical F-test. These results are summarized in Table 2, and the spectral fits are shown in Figure 2.

We derived the ratio of the X-ray to bolometric luminosity, $L_X/L_{\rm bol}$, using the unabsorbed flux with the measured effective temperature and distance to HD 14633 ($T_{\rm eff} = 35100$ K, $d = 2.150$ kpc; McSwain et al. 2007a). The compact companion contributes a flux $F_X = 1.6 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ at periastron. Assuming that this flux is due to wind accretion onto a neutron star, we used the stellar wind properties (McSwain et al. 2007b), physical parameters of the optical star (McSwain et al. 2007a), and the orbital elements above to determine the Bondi-Hoyle accretion rate $S_a \sim 9 \times 10^{-11}\ M_\odot$ yr$^{-1}$ near periastron (Lamers, van den Heuvel & Petterson 1976). Given the observed $F_X$, this implies a low efficiency $\zeta \approx 10^{-5}$ of converting accreting matter into X-ray luminosity.



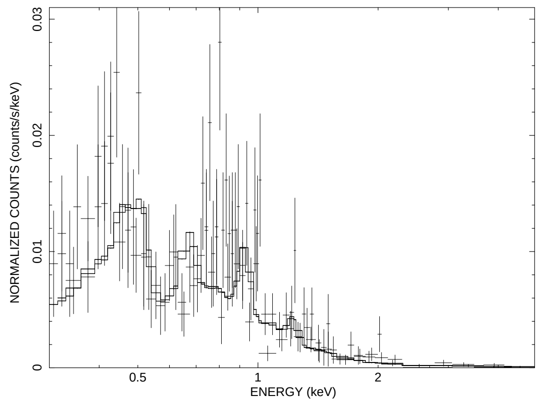




Figure 2: *Left: XMM-Newton* MOS spectra of HD 14633 (obs. A) performed near apastron. *Right: XMM-Newton* MOS spectra of HD 14633 (obs. B) performed near periastron.

### 3.2 Spectral Fit of HD 15137

Our *XMM-Newton* observation of HD 15137 is described in detail by McSwain et al. (2010), and we summarize the key results here. The EPIC spectra of HD 15137 are consistent with a soft thermal source typical of isolated O-type stars (Sana et al. 2006). We fit the MOS spectra simultaneously over the range 0.5–2.3 keV, using a variety of warm absorbed, single temperature (1-T) and 2-T thermal models, and we repeated our fits for the pn spectrum. The resulting fits were equally good for the 1-T and 2-T models, but a statistical F-test reveals that the second temperature does not significantly improve the fits. We also cannot distinguish between the quality of the various 1-T model fits due to the low signal-to-noise. We weakly constrain the temperature to $0.10 \leq kT \leq 0.25$ keV, and the neutral hydrogen column density to $2.8 \times 10^{21} \leq nH \leq 8.6 \times 10^{21}$ atoms cm$^{-2}$. We find an absorbed flux $F_{abs} \sim$ 1–2 $\times$ $10^{-14}$ erg cm$^{-2}$ s$^{-1}$ and unabsorbed flux $F_{unabs} \sim$ 2–4 $\times$ $10^{-14}$ erg cm$^{-2}$ s$^{-1}$ (0.2–10 keV) depending on the model. There is no evidence of any hard X-ray photons.

In order to place an upper limit on any hard power law component that may originate from an accreting compact companion, we repeated the 1-T models with an additional power law component with photon index $\Gamma = 2$ (fixed). All of the best fit parameters from the 1-T fits, including $nH$, $kT$, and their normalizations, were fixed in Xspec. We then refit each model, allowing only the normalization of the power law component to vary. We then used the *steppar* routine to investigate the 90% confidence limit for the power law normalization. Upon removing the thermal component from the models, we used the fixed $\Gamma$ and the upper limit for its normalization in the remaining absorbed power law model to determine the upper limit for the X-ray flux, $F_X$, of the putative compact object. Our fits indicated an unabsorbed $F_X < 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ (0.2–10 keV). At a distance of 2.42 kpc, this corresponds to an X-ray luminosity $L_X < 10^{31}$ erg s$^{-1}$ for any hard power law component.

## 4 Conclusions

We have detected a hard X-ray component from the proposed NS companion in HD 14633. Due to its very high eccentricity, the binary separation in that system varies by a factor of 7 during the orbit. The lack of detection near apastron suggests that stellar wind interactions with the NS produce a modulated X-ray emission during the orbit, and we recommend further observations throughout the orbit to study the interaction region and variability.

The longer orbital period and greater system separation of HD 15137 is not favorable for wind interactions, hence our non-detection of a NS. Our observation was also not performed at an optimal orbital phase. Further observations near periastron may identify a compact companion in this system.

## Acknowledgements

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## Discussion

**L. Oskinova**: Two questions. (1) Did you check the X-ray images for the presence of some diffuse emission? (2) Did you estimate the X-ray luminosity of these objects?
**M.V. McSwain**: Visual inspection of the *XMM-Newton* images did not indicate any diffuse emission. Given the close orbits that should truncate any diffuse gas, we do not expect to resolve any diffuse emission. The unabsorbed X-ray luminosity of HD 14633 ranges from $1.3 - 2.1 \times 10^{32}$ erg/sec. The unabsorbed X-ray luminosity of HD 15137 is about $2 \times 10^{31}$ erg s$^{-1}$.

**I. Antokhin**: I have a question about your fit of the X-ray spectrum of HD 14633. Maybe I missed something, but why do you attribute a lower temperature component of your 2T-fit to the shock?
**M.V. McSwain**: Our initial fits of HD 14633 data with `xspec` suggest a 2 component model: a thermal component associated with the O star, and a plane-parallel shock. The HD 14633 spectra are significantly softer than the HD 15137 spectrum. Therefore our preliminary analysis attributes the soft X-ray excess to the shock component. However, different models of interstellar absorption treat the soft components differently, and we are currently exploring further models to better account for the two components.

**I. Negueruela**: You mentioned that the two objects that you studied were likely runaways from the open cluster NGC 654. How was this determined and how certain is it? The brightest stars in NGC 654 have rather later spectral types than your targets. If they are really runaways, their present day spectral types (O types) would be strong indication of mass transfer in a binary, making them very important objects to test models for the creation of early-type blue stragglers.

**M.V. McSwain**: The cluster of origin was determined by Boyajian et al. (2005), who traced their positions back in time by integrating a model of the Galactic potential. Based on their present day space velocities, the runaways were ejected 10-14 Myr ago, which is no longer than the expected lifetime of these O-type stars. And as you mentioned, the earliest spectral types remaining in NGC 654 are B0 - 1 V. Therefore we suspect that HD 14633 and HD 15137 were rejuvenated by prior mass transfer. HD 15137 does show evidence of CNO-enriched gas at its surface.

**D. Gies**: I'd like to comment on this point. Boyajian et al. (2005) used proper motions and radial velocities to trace back the motion of stars and of cluster NGC 654 in the Galactic potential. A common origin is suggested but not proven.