# Ejection of Runaway Massive Binaries

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## Abstract

The runaway O-type stars HD 14633 and HD 15137 are both SB1 systems that were probably ejected from the open cluster NGC 654. Were these stars dynamically ejected by close gravitational encounters in the dense cluster, or did the binaries each receive a kick from a supernova in one member? We present new results from our investigation of the optical, UV, X-ray, and radio properties of these binary systems to determine the probable ejection scenarios.

## Introduction

Most O-type stars form in open clusters and stellar associations, but a small fraction are observed at high galactic latitudes and with large peculiar space velocities. These runaway stars were likely ejected from the clusters of their birth – either by close multi-body interactions in the dense environment or by supernovae explosions in close binaries. Identifying the dominant scenario producing runaway stars can offer important clues to the evolution of close binary stars and open clusters.

Spectroscopic investigations of HD 14633 and HD 15137 have found relatively short orbital periods and low mass companions (Boyajian et al. 2005; McSwain et al. 2006). HD 14633 was ejected from the open cluster NGC 654 about 14 Myr ago, and HD 15137 was ejected from the same cluster about 10 Myr ago (Boyajian et al 2005).

Presumably, HD 14633 and HD 15137 each obtained their high runaway velocities during a supernova explosion in a close binary, and the O stars remain bound to the stellar remnant. In this work, we test this hypothesis using a collection of new observations and archival data across the electromagnetic spectrum.

Table 1: Summary of Orbital and Stellar Parameters

| | HD 14633 | HD 15137 |
|---|---|---|
| *P* (d) | 15.407 | 30.35 (?) |
| *e* | 0.69 | 0.48 |
| *f(m)* | 0.0041 | 0.004 |
| $T_{eff}$ (K) | 35100 | 29700 |
| log *g* | 3.95 | 3.5 |
| *R* ($R_{\odot}$) | 8.3 | 13.2 |
| *d* (pc) | 2040 | 2420 |

## Dynamical Ejection vs. Supernova Ejection

- Both scenarios produce mostly isolated runaway stars
  - Difficult to identify the ejection scenario from a single star
- Dynamical ejection will produce about 10% binaries (Leonard & Duncan 1990)
  - Companion will be an optical star
  - System may be observed as an SB2 or SB1
  - A cool companion can be nearly impossible to detect
- Supernova in a close binary will produce 20-40% runaway binaries (Portegies Zwart 2000)
  - Companion will be a neutron star (or black hole, less likely)
  - Observed as SB1 system with high eccentricity, low mass function
  - Should be observable as an X-ray binary or radio pulsar

## Predicted X-ray Flux

We use a simple model of stellar wind accretion onto the presumed neutron star companion to predict the X-ray flux from each binary (Lamers et al. 1976). This method uses the Bondi-Hoyle accretion rate, $S_a$, which depends on:

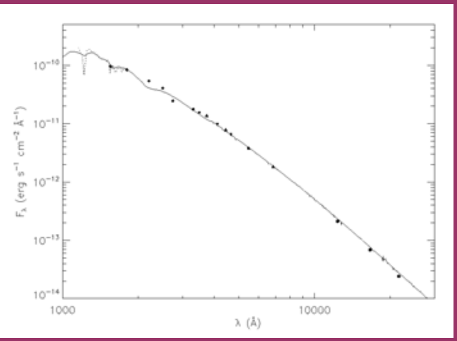
- the system separation, *a*, and eccentricity, *e*;
- the relative wind and orbital velocities, $V_{rel}$;
- the stellar mass loss rate, $\dot{M}_{star}$;
- the mass of the companion, $M_X$;
- the distance to the system, *d*.

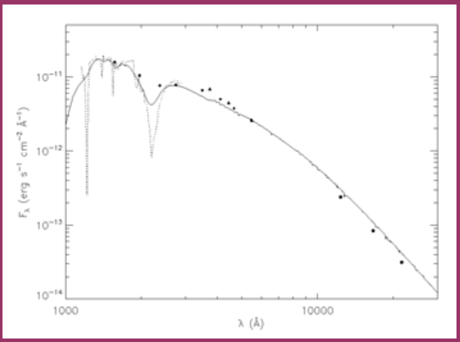
$$S_a = \frac{\pi R_a^2 \dot{M}_{\rm star}}{4\pi a^2}$$

$$V_{\rm wind}(r) = V_\infty \left(1 - \frac{R_{\rm star}}{r}\right)^\beta$$

$$R_a = \frac{2GM_{\rm X}}{V_{\rm rel}^2}$$

$$L_{\rm X} = 3\times10^{13} L_{\rm Sun} \frac{\zeta S_a M_{\rm X}}{M_{\rm Sun}}$$




Figures 1 and 2: The spectral energy distributions of HD 14633 (above) and HD 15137 (below). We compare the observed UV, optical, and IR fluxes to a smoothed TLUSTY model spectrum in each case. **Neither binary shows signs of an IR excess from an accretion disk around a compact companion.**

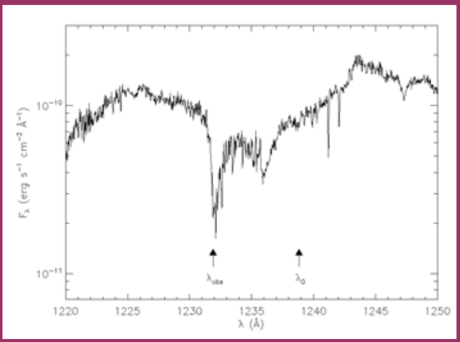



Figure 3: Measuring the terminal wind velocity ($V_\infty$) of HD 14633. From co-added *IUE*/SWP spectra, the blue saturated edge of the N V λ1238.821 line provides $V_\infty$ = 1677 km/s.

## Pulsar Search Results

Although previous searches have failed to detect radio pulsars in runaway OB stars (Philp et al. 1996; Sayer, Nice, & Kaspi 1996), we performed a new, more sensitive search to investigate the companions of both HD 14633 and HD 15137. Our search offers several advantages over these earlier searches:

- Our new orbital ephemerides (McSwain et al. 2006) allowed us to schedule observations near the time of apastron, when the radio emission is least dispersed by the O stars' winds.
- We used higher frequencies that are more likely to detect radio pulses dispersed by the stellar winds.
- We obtained a better flux density sensitivity than previous searches.

We observed both targets using the National Radio Astronomy Observatory's 100-m Green Bank Telescope and the Pulsar Spigot back-end (Kaplan et al. 2005). The details of each observation are summarized in Table 1, and the data were reduced using the PRESTO software package (Ransom 2001). **No pulsars were detected in either HD 14633 or HD 15137.**

Table 2: Summary of Green Bank Telescope Observations

| Star | Receiver | Frequency range (freq. resolution) | MJD – 2450000 | Orbital Phase | Exposure time (time resolution) |
|---|---|---|---|---|---|
| HD 14633 | S-band | 1650-2250 MHz (0.78125 MHz) | 3909.4194 | 0.390 | 6300 s (81.92 μs) |
| | 820 MHz | 795-845 MHz (0.0488 MHz) | 3909.5085 | 0.396 | 6300 s (81.92 μs) |
| HD 15137 | S-band | 1650-2250 MHz (0.78125 MHz) | 3897.4847 | 0.482 | 6300 s (81.92 μs) |
| | 820 MHz | 795-845 MHz (0.0488 MHz) | 3897.5753 | 0.485 | 6300 s (81.92 μs) |

## Test for Quiescent Neutron Stars

The conditions for wind accretion onto a neutron star depend strongly upon its spin rate and magnetic field (Lipunov 1992). A young neutron star in the ejector and propeller regimes will not accrete significant amounts of material because its fast rotation and/or large magnetic field sweep material out of the system at a distance larger than the accretion radius, $R_a$. The neutron star spins down over time, and eventually the corotation radius, $R_c$, becomes larger than both the magnetospheric radius, $R_{mag}$, and $R_a$.

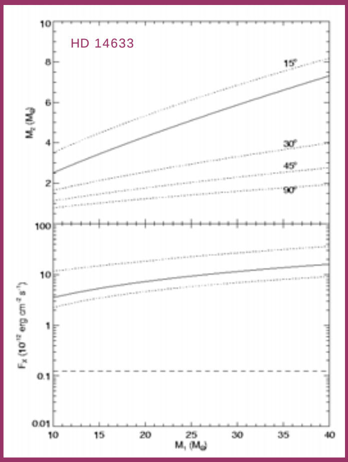
Using our measured stellar and orbital parameters with a few reasonable assumptions for the spin rates of the presumed neutron stars and their magnetic moments, we estimate these critical distances:

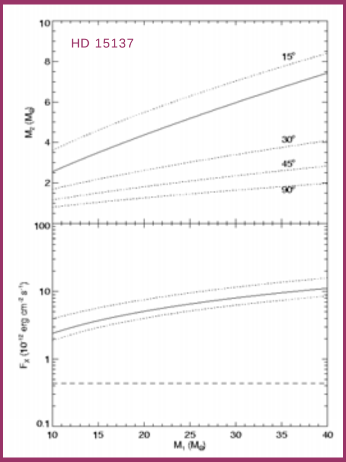
$$R_a = \frac{2GM_{\rm X}}{V_{\rm rel}^2} \sim 10^{10}\,{\rm cm}$$

$$R_c = \left(\frac{GM_{\rm X}}{\omega^2}\right)^{1/3} \sim 10^8 - 10^9\ {\rm cm}$$

$$R_{mag} = \left(\frac{\mu^2}{2S_a\sqrt{2GM_X}}\right)^{2/7} \sim 10^9\,{\rm cm}$$

Unrestrained accretion requires $R_{mag} < R_a$ and $R_{mag} < R_c$, which may be possible in these systems. However, even a non-accreting neutron star could be detected by its thermal or non-thermal spectrum with an X-ray luminosity of $10^{30} - 10^{34}$ erg/s ($F_X \sim 10^{-15} - 10^{-11}$ erg/s/cm$^2$; Lipunov 1992). **Further X-ray observations are required to confirm or refute the presence of neutron stars in HD 14633 and HD 15137.**




Figures 4 & 5:
(top) Mass diagram for a range of inclination angles (*dotted lines*) and the most probable companion mass (*solid lines*), based on the statistical method of Mazeh & Goldberg (1992).
(bottom) **The predicted time-averaged X-ray flux (*solid line*) is at least an order of magnitude greater than the observed upper limits for $F_X$** from *ROSAT*/PSPC observations (*dashed lines*). This prediction assumes the minimum value of $M_X$, and a higher mass companion will produce an even greater $F_X$.

## Conclusions

If HD 14633 and HD 15137 were ejected by supernovae in these close binary systems, they should contain neutron stars detectable as either radio pulsars and/or X-ray sources. Our search for pulsars with the Green Bank Telescope revealed no detections, and the predicted X-ray emission from wind accretion is much larger than the observed limits. Furthermore, neither system exhibits an IR excess from an accretion disk around a compact companion. While a neutron star cannot be ruled out, the probable companion mass supports a higher mass object. Therefore we propose that **these binaries may not contain neutron stars, and we suggest that they may have been ejected from NGC 654 by dynamical interactions in the dense cluster environment.**

## References

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