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The Massive Runaway Stars HD 14633 and HD 15137[1]

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ABSTRACT

We present results from a radial velocity study of two runaway O-type stars, HD 14633 (ON8.5 V) and HD 15137 (O9.5 III(n)). We find that HD 14633 is a single-lined spectroscopic binary with an orbital period of 15.4083 days. The second target HD 15137 is a radial velocity variable and a possible single-lined spectroscopic binary with a period close to 1 month. Both binaries have large eccentricity, small semiamplitude, and a small mass function. We show the trajectories of the stars in the sky based upon an integration of motion in the Galactic potential, and we suggest that both stars were ejected from the vicinity of the open cluster NGC 654 in the Perseus spiral arm. The binary orbital

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parameters and runaway velocities are consistent with the idea that both these stars were ejected by supernova explosions in binaries and that they host neutron star companions. We find that the time-of-flight since ejection is longer than the predicted evolutionary timescales for the stars, which may indicate that they have a lower mass than normally associated with their spectral classifications and/or that their lives have been extended through rapid rotation.

Subject headings: binaries: spectroscopic — stars: early-type — stars: individual (HD 14633, HD 15137) — supernovae: general — open clusters and associations: individual (NGC 654)

1. Introduction

There are two competing theories to explain the origin of the massive OB-runaway stars. The model first suggested by Zwicky (1957) and Blaauw (1961) proposes that these stars were originally the binary companions of a star that exploded in a supernova and that the linear momentum of a runaway star balances the momentum lost in the explosion. Since mass ratio reversal probably occurs prior to the explosion, many runaways should still be binaries with a neutron star or black hole companion, unless the system was disrupted by an asymmetric kick velocity imparted to the remnant during the supernova (Brandt & Podsiadlowski 1995). A second model proposes that close gravitational encounters during the young, high stellar number density epoch after cluster formation can lead to ejections through encounters with hard binaries (Leonard & Duncan 1988). This model predicts that most runaways will be single stars, although some close binaries can be ejected in exceptional circumstances. Gies & Bolton (1986) made a radial velocity survey of bright, northern sky runaway stars and found that most were indeed radial velocity constant, implying that they were not members of binary systems. More recently Hoogerwerf, de Bruijne, & de Zeeuw (2000) explored the motions and origins of runaways using proper motion data from the *Hipparcos Satellite* (Perryman 1997), and they found examples of ejection by both mechanisms.

Here we present new radial velocity measurements for two northern sky runaway stars, HD 14633 and HD 15137. HD 14633 is classified as a nitrogen strong ON 8V star (Walborn 1972). It appears at Galactic coordinates $l = 140.^{\circ}78$ and $b = -18.^{\circ}20$, indicating a position nearly 800 pc below the the Galactic plane. The spectral lines have a moderate projected

[1]Based in part on observations made at Observatoire de Haute Provence (CNRS), France.

rotational velocity with $V \sin i$ estimates of 111 km s^{-1} (Conti & Ebbets 1977), 110 km s^{-1} (Schönberner et al. 1988), and 134 km s^{-1} (Howarth et al. 1997). Rogers (1974) found that the star was a single-lined spectroscopic binary with a period of 15.335 days and an orbital eccentricity of $e = 0.68$. However, subsequent analysis by Bolton & Rogers (1978) did not confirm the initial orbital parameters, and Bolton & Rogers (1978) suggested that the binary might have a nearby third star that modulates the velocity curve. There is no known visual companion to HD 14633 (Mason et al. 1998). Additional spectroscopic observations by Stone (1982) showed little evidence of velocity variability.

The second target is the star HD 15137 that Gies (1987) categorized as a field O-star, but we show below (§4) that its peculiar velocity is large enough that the star should also be grouped with the runaway stars. It appears in a similar part of the sky as HD 14633 at $l = 137\overset{\circ}{.}46$ and $b = -7\overset{\circ}{.}58$. Walborn (1973) classified HD 15137 as O9.5 II-III (n), where the suffix (n) indicates broad lines. Conti & Ebbets (1977) reported observing partially resolved double lines in their spectrum. However, Howarth et al. (1997) analyzed a single high dispersion spectrum from the *International Ultraviolet Explorer Satellite (IUE)* and used a cross-correlation method to find the projected rotational velocity, $V \sin i = 336$ km s^{-1}. They caution that the cross-correlation function is broad, asymmetric, and difficult to measure. We show below that the star is indeed broad-lined, and it may display rapid line profile variability normally associated with nonradial pulsation (Howarth & Reid 1993; Kambe et al. 1997). Conti et al. (1977) suggest that the stellar radial velocity is variable. There is no evidence of a nascent cluster nearby (de Wit et al. 2004).

Here we present new radial velocities (§2) based upon high S/N CCD spectroscopy of these two runaways. We give new orbital elements for HD 14633 (§3.1) and a tentative binary interpretation for HD 15137 (§3.2). We use radial velocity and proper motion data to calculate the Galactic trajectories of both stars, and we suggest that both originated in or near the open cluster NGC 654 (§4). We argue that both runaways were probably ejected by a supernova in a binary and that their unseen companions are probably neutron stars (§5).

2. Observations and Radial Velocities

Most of the optical spectra were obtained with the Kitt Peak National Observatory 0.9 m Coude Feed Telescope during observing runs from 2000 September 30 to 2000 October 13 and from 2000 December 10 to 2000 December 23. The spectra have a resolving power of $R = \lambda/\delta\lambda = 9500$. They were made using the long collimator, grating B (in second order with order sorting filter OG550), camera 5, and the F3KB CCD, a Ford Aerospace

3072 × 1024 device. This arrangement produced a spectral coverage of 6440 – 7105 Å. Exposure times varied between 20 and 30 minutes, and generally two spectra were taken only a few hours apart each night. The spectra generally have a signal-to-noise ratio of S/N $\approx$ 200 pixel^{-1}. We also observed the rapidly rotating A-type star, ζ Aql, which we used for removal of atmospheric water vapor and O_2 bands. Each set of observations was accompanied by numerous bias, flat field, and Th-Ar comparison lamp calibration frames. One earlier red spectrum of HD 14633 was made with the Coude Feed Telescope on 1999 November 13, but this spectrum was obtained with the short collimator and grating RC181 (in first order with a GG495 filter to block higher orders), which yielded a lower resolving power, $R = \lambda/\delta\lambda = 4000$. Two additional red spectra of HD 14633 were obtained with the Coude Feed on 2004 October 12 and 14, and one final red spectrum of HD 15137 was made on 2004 October 12. These three spectra are similar to the main group, but they were made with the T2KB CCD (2048 × 2048 pixels). The dates of observation are given in Tables 1 and 2. The spectra were extracted and calibrated using standard routines in IRAF[2]. All the spectra were rectified to a unit continuum by fitting line-free regions. The removal of atmospheric lines was done by creating a library of ζ Aql spectra from each run, removing the broad stellar features from these, and then dividing each target spectrum by the modified atmospheric spectrum that most closely matched the target spectrum in a selected region dominated by atmospheric absorptions. The spectra from each run were then transformed to a common heliocentric wavelength grid.

Two spectra of HD 14633 in the blue domain (4550 – 4900 Å) were obtained at the Observatoire de Haute-Provence (OHP) in 2003 October. These observations were carried out with the Aurélie spectrograph fed by the 1.52 m telescope (Gillet et al. 1994). The detector was a 2048×1024 CCD (EEV 42-20#3), with a pixel size of 13.5 × 13.5 μm. We used a 600 lines mm^{-1} grating, offering a resolving power of about 8000 in the blue with a reciprocal dispersion of 16 Å mm^{-1}. The exposure times were 45 and 30 minutes, and the spectra have a S/N = 350 and 480 pixel^{-1}. The spectra were wavelength-calibrated using a Th-Ar spectrum taken just after the observation of the star. The data were reduced using the MIDAS software package developed at ESO and were normalized to a unit continuum.

We measured radial velocities for the red spectra of both HD 14633 and HD 15137 by cross-correlating the line profiles of each spectrum with those in one spectrum selected for optimum S/N properties. We measured individually the deepest and best defined absorption lines in this spectral region: Hα, the blend of He I λ6678 and He II λ6683, and He I λ7065.

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[2]IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

There was no evidence of Hα emission in either star's spectrum. We then formed the mean difference between the velocity for each line and that of He I λ7065, and we applied these differences to each line's velocities to place them on the same velocity system as that for He I λ7065 in the reference spectrum. Finally, we made a Gaussian fit of the He I λ7065 profile in the reference spectrum and added this to the mean velocity from all three lines to transform the results to absolute radial velocity. These two stars were observed in conjunction with a program on eight other O-star targets, and we used measurements of the interstellar lines in those spectra to make small corrections (on the order of 1 km s^{-1}) to the velocity measurements from each night.

We determined radial velocities for the two blue spectra of HD 14633 by parabolic fitting of the line cores of He I $\lambda\lambda$4471, 4713 and He II $\lambda\lambda$4541, 4686. Many O-stars exhibit line-to-line radial velocity differences due to subtle blends and atmospheric expansion (Hutchings 1976; Bohannan and Garmany 1978; Gies & Bolton 1986), but we found that the average radial velocity for these He lines matched those based on the red He I λ7065 line quite well (§3.1). Our final radial velocities are presented in Table 1 (HD 14633) and Table 2 (HD 15137).

3. Orbital Elements

3.1. HD 14633

Rogers (1974) found that HD 14633 is a single-lined spectroscopic binary with a period of 15.335 days, a small semiamplitude ($K = 31.3$ km s^{-1}), and a large eccentricity ($e = 0.68$). However, additional spectroscopic analysis by Bolton & Rogers (1978) cast some doubt on the original solution. Our 2000 December run was long enough to cover an almost complete cycle of variations, and the velocities do indeed suggest an orbital period close to the 15 day period found by Rogers (1974).

We made an initial period search using the "phase dispersion minimization" technique of Stellingwerf (1978) that is especially useful for finding non-sinusoidal signals in time series data. We combined our radial velocities (Table 1) with measurements from Bolton & Rogers (1978) and Stone (1982) (for a total of 89 measurements spanning nearly 83 years). We omitted from this sample three velocities from *IUE* (Stickland & Lloyd 2001) and two velocities from Conti et al. (1977) that appeared to be systematically shifted to more positive and more negative velocities, respectively, compared to the rest. We found one strong signal at a period of 15.409 days (with one weaker alias at a period of 15.433 days), and we used this period as the starting value in the non-linear least squares fitting program of Morbey &

Brosterhus (1974) to establish the orbital elements of HD 14633. The results are presented in Table 3 together with the original estimates from Rogers (1974). The two sets of elements are comparable, but the new period is larger and the semiamplitude smaller than that obtained by Rogers (1974). We suspect that Rogers found an alias period that failed to fit the additional data reported later by Bolton & Rogers (1978).

The full sample of historical and new radial velocity data forms a very heterogeneous collection based on different lines, spectroscopic dispersions, and S/N in the spectra. Consequently, we repeated the orbital element fitting procedure with the more homogeneous set of velocities from Table 1, this time fixing the period to the value derived from the full, many-year sample. These elements appear in the final column of Table 3, and indeed the rms residuals from the fit are now much smaller and comparable to our measurement errors. The final fit and observed velocities are illustrated in Figure 1.

3.2. HD 15137

The photospheric lines in HD 15137 are much more rotationally broadened and shallower than those of HD 14633. The half-width near the continuum of the two He I lines is 309 ± 4 km s^{-1}, which is comparable to the projected rotational velocity of $V \sin i = 336$ km s^{-1} found by Howarth et al. (1997). The He I profiles show significant night-to-night variations in shape that are similar to those observed in the nonradial pulsators HD 93521 (Howarth & Reid 1993) and ζ Oph (Kambe et al. 1997), which are also rapidly rotating, late O-type stars. The profiles appear with a central inversion on a few occasions, giving the impression of a partially resolved, double-lined binary (as claimed by Conti & Ebbets 1977). An investigation with a finer time resolution would clearly be rewarding, but the rapid and complex changes observed in the spectra available indicate that the profile variations are probably due to photospheric modulations rather than the blending of components of a short period binary. These variations do, unfortunately, introduce an additional component of scatter into our radial velocity measurements. Nevertheless, there is a clear indication that the velocity is variable on timescales of a month or so. The mean velocity from the 2000 October run was -57.1 ± 1.9 km s^{-1} compared with -41.6 ± 1.0 km s^{-1} for the 2000 December run (where the errors are the standard deviation of the mean). We again used the phase dispersion minimization technique to search for possible periods, and we found candidate periods of 21.2, 28.6, and 43.4 days (with acceptable periods in a large range surrounding the latter two). This target has unfortunately been largely ignored by observers, and the only two measurements made in the last forty years are single velocities from *IUE* (Stickland & Lloyd 2001) and from Conti et al. (1977). Once again, the *IUE* measurement appears to be much more positive than any of the other observations, while the measurement from Conti et al. (1977) is lower than any of ours. The best fit period for our data is 28.61 days, but there are numerous and almost equally good alias periods at intervals of $+0.62n$ days (where n is an integer) spanning the range from 28.6 to 31.1 days in addition to the other periods mentioned above. We caution that the current data set samples essentially only the velocity extrema at two epochs, so the periodic nature of the variations remains to be verified. Nevertheless, the velocity variations are consistent with those expected for a long period and small semiamplitude binary.

The limited timespan of the available data rules out the determination of an accurate period, but we used the candidate period to find a preliminary set of orbital elements. These elements are presented in Table 4 and the radial velocity curve is illustrated in Figure 2. Although the period is poorly known, tests with other trial periods showed that the resulting semi-amplitude and eccentricity were not too different from the values reported in Table 4. Thus, the current set of velocities suggests that the star is a spectroscopic binary with a low semiamplitude and an eccentric orbit.

4. Ejection from the Galactic Plane

Both HD 14633 and HD 15137 are found well outside the plane of the Galaxy, and *Hipparcos* proper motions indicate that both stars are moving away from the plane (Perryman 1997). Here we present numerical integrations of their motion in the Galaxy made in order to estimate their possible site of origin and their time-of-flight since ejection.

The integration of motion was made using a cylindrical coordinate system (r, ϕ, z). We first determined the position and resolved velocity components of the star in this system using the Galactic coordinates (l, b), proper motion, distance estimate, radial velocity, the velocity of the Sun with respect to the local standard of rest (LSR) (Dehnen & Binney 1998a), and the Sun's position relative to the plane (Holmberg, Flynn, & Lindegren 1997). We then performed integrations backward in time using a fourth-order Runge-Kutta method and a model for the Galactic potential from Dehnen & Binney (1998b). We adopted the model (#2) from Dehnen & Binney (1998b) that uses a Galactocentric distance of 8.0 kpc and a disk density exponential scale length of 2.4 kpc. We used time steps of 0.01 Myr over a time span of 20 Myr. The procedure compared the Sun's and the star's position to find the distance and Galactic coordinates l and b for each time step. We determined when and where the star's trajectory crossed the Galactic plane, and we then integrated forward in time to find the current position and distance of the LSR of the intersection site. We then inspected a list of Galactic open clusters (Leisawitz 1988) to search for candidate birthplace clusters.

We calculated a trajectory for HD 14633 using an adopted current distance of 2.15 kpc (van Steenberg & Shull 1988), the weighted mean of the proper motions from *Hipparcos* (Perryman 1997) and from *Tycho 2* (Høg et al. 2000), and the systemic radial velocity from Table 3. According to this model, the star crossed the plane of the Galaxy about 13 Myr ago, in agreement with prior estimates (Hobbs 1983). We found that the closest cluster to this trajectory was NGC 654, an open cluster in the Cas OB8 association in the Perseus spiral arm. We calculated the trajectory of NGC 654 based on proper motions and a mean radial velocity from Chen, Hou, & Wang (2003) and a distance from Huestamendia, del Rio, & Mermilliod (1993), and the spatial separation between HD 14633 and NGC 654 is plotted as a function of time in Figure 3. This shows that the closest approach occurred about 14.6 Myr ago. The greatest uncertainty in the calculation comes from the errors in spectroscopic parallax for HD 14633 (approximately $\pm 28\%$), so we also calculated closest separations for a grid of current distances to find the minimum separation possible with all the other parameters fixed. We found that the minimum separation was 11 pc for a test value of current distance of 2.24 kpc (well within the error range), and Figure 3 also shows the temporal variation in cluster – star separation for this case. This minimum occurred 13.9 Myr ago when the relative velocity of the cluster and star was 69 km s^{-1}. If the star was actually ejected at this time from this cluster, then this relative velocity is the ejection velocity.

We illustrate the trajectories of the star and cluster as viewed from the Sun in Figure 4. Tick marks along each trajectory mark intervals of 1 Myr before the current time (*diamonds*). We also show the trajectories for the $\pm 1\sigma$ errors in the proper motions (*dotted lines*). The errors in proper motion probably introduce a ± 2 Myr error in the estimated time of closest approach.

We performed the same kind of calculation for HD 15137 using a nominal distance estimate of 2.65 kpc (van Steenberg & Shull 1988), the weighted mean of the *Hipparcos* and *Tycho 2* proper motions, and the systemic radial velocity from Table 4. We found the star crossed the plane of the Galaxy some 8 Myr ago for this assumed distance. We searched for possible clusters of origin, and we were surprised to find that NGC 654 once again presented the closest approach of trajectories. The separation between HD 15137 and NGC 654 is plotted in Figure 3, and we found that the smallest separation was 328 pc for the nominal distance estimate. However, we tested a grid of trajectories for different values of the assumed current distance, and the minimum star – cluster separation occurred for an assumed current distance of 2.29 kpc (again within the errors associated with the spectroscopic parallax). The minimum separation was 27 pc at a time 10.2 Myr ago when the relative velocity was 50 km s^{-1} (Fig. 3). The paths of the star and cluster for the past 20 Myr are illustrated in Figure 4, where we see that errors in the proper motion contribute an uncertainty of ± 2 Myr in the estimate of the ejection time.

5. Discussion

OB runaway stars are probably ejected by one of two mechanisms, sudden mass loss during a supernova explosion in a binary or a close gravitational encounter involving binaries (Gies & Bolton 1986; Hoogerwerf et al. 2000). The supernova theory predicts that runaways will either be single stars (in which the binary was disrupted due to a large, asymmetric kick velocity imparted during the supernova) or binaries with neutron star or black hole companions (such as the high mass X-ray binaries). On the other hand, the gravitational encounter theory suggests that most runaways will be single objects, although in rare cases hard binaries of mass ratio near unity are ejected.

Our radial velocity study has demonstrated that HD 14633 and possibly HD 15137 are binary stars with low mass companions. If we suppose that the masses of the primary are 23 $M_\odot$ for HD 14633 (Keenan & Dufton 1984) and 24 $M_\odot$ for HD 15137 (Vacca, Garmany, & Shull 1996), then the minimum masses of the companion derived from the orbital mass function (Tables 3 and 4) will be 1.3 $M_\odot$ and 1.5 $M_\odot$, respectively (for an orbital inclination of 90°). These masses are close to the 1.35 $M_\odot$ value found for most neutron stars in binaries (Thorsett & Chakrabarty 1999). These runaways may be the first examples of the long sought "quiet" massive X-ray binaries, i.e., those with wide separations in which wind accretion is too weak to power an accretion disk X-ray source (van den Heuvel 1976). We searched for evidence of a companion spectrum in both cases using a Doppler tomography algorithm (Bagnuolo et al. 1994), but no spectral features were found. A faint, low mass, main sequence star could easily remain hidden in the glare of an O-star (for example, the magnitude difference is $\triangle V \approx 8$ between such O-stars and a F3 V companion of mass 1.4 $M_\odot$). Nevertheless, we doubt that these systems are extreme mass ratio binaries containing an O- and F-type star, since no such systems are known among the O-stars and since such systems would probably be disrupted in close gravitational encounters leading to ejection.

Both HD 14633 and HD 15137 have many characteristics in common with the massive X-ray binary and microquasar, LS 5039 (McSwain et al. 2004). All are runaway objects with very eccentric orbits and small orbital mass functions. LS 5039 has a much shorter period (4.4267 days) and the smaller semimajor axis results in a modestly dense wind in the vicinity of the orbiting neutron star, so that LS 5039 is a weak X-ray source. In contrast, the longer period systems HD 14633 and HD 15137 will have very rarefied winds close to their neutron star companions, and consequently their accretion fluxes are expected to be extremely faint (perhaps also as the result of centrifugal inhibition of accretion; Stella, White, & Rosner 1986). Neither system is listed in the ROSAT All-Sky Survey Faint Source Catalogue (Voges et al. 2000). Furthermore, neither system appears to be associated with an *EGRET* γ-ray source (Hartman et al. 1999), nor are they known radio sources (Vallee & Moffat 1985; Wendker 1995; Sayer, Nice, & Kaspi 1996). Thus, wind accretion onto a neutron star in these systems must be too feeble to produce the high energy phenomena associated with other massive X-ray binaries.

McSwain et al. (2004) found that the supernova mass loss prediction for LS 5039 was different depending on whether the calculation was based on orbital eccentricity or runaway velocity, and they argued that both the eccentricity and runaway velocity can be explained if a significant asymmetric kick velocity was imparted to the neutron star during formation. A similar conclusion can be derived for HD 14633 and HD 15137. If we use the expressions for supernova mass loss given by Nelemans, Tauris, & van den Heuvel (1999) and adopt the primary masses given above and secondary masses of 1.4 $M_{\odot}$, then the predicted supernova mass loss is 17 $M_{\odot}$ and 13 $M_{\odot}$ for HD 14633 and HD 15137, respectively, based upon their observed eccentricities. On the other hand, the supernova mass loss estimates are 6.9 $M_{\odot}$ and 6.4 $M_{\odot}$, respectively, based upon the relative runaway velocities between star and cluster from the models given in §4. These significant differences suggest that both systems suffered kick velocities at birth that substantially altered the eccentricity. The supernova mass loss estimates from the runaway velocities should be more reliable since the runaway velocities are less affected by kicks (Brandt & Podsiadlowski 1995).

Two other features of these stars also link them to supernova ejections. First, HD 14633 is a well known nitrogen rich ON star (Walborn 1972; Schönberner et al. 1988), and McSwain et al. (2004) have shown that massive X-ray binary LS 5039 also shares this trait. McSwain et al. (2004) suggest that the nitrogen enrichment is the result of mass transfer of CNO-processed gas from the supernova progenitor prior to the explosion, although rotationally induced mixing may also play a role. Second, HD 15137 is a very rapid rotator, a characteristic shared with many other OB runaway stars (Blaauw 1993). Mass transfer prior to the supernova may lead to a spin up of the mass gainer, and this process may be responsible for the largest class of massive X-ray sources, the rapidly rotating, Be X-ray binaries (Coe 2000).

Both runaways appear to have been ejected from the Perseus spiral arm, and our analysis of their motions in the Galaxy (§4) indicates a probable origin in the open cluster NGC 654 in the Cas OB8 association. The cluster's age is approximately 14 Myr (Huestamendia et al. 1993), and the cluster contains a number of early B-type stars and two massive supergiants

(HD 10494, F5 Ia, and BD+61°315, A2 Ib). Garmany & Stencel (1992) include the nearby O-star BD+60°261 (O7.5 III(n)((f)); Walborn 1973) as a cluster member. The Cas OB8 association has a diameter of approximately 85 pc and contains several other clusters including NGC 581, 659, and 663 (Garmany & Stencel 1992), which have slightly greater ages of 22, 35, and 16 Myr, respectively, according to the Webda database[3] (Mermilliod & Paunzen 2003). The time-of-flight for HD 15137 (10 Myr) suggests that the star was ejected from NGC 654 when the cluster was approximately 4 Myr old, which may be consistent with the evolutionary timescale required for a supernova progenitor. However, the main sequence lifetime of a star of 24 $M_\odot$ is approximately 6.7 Myr (Schaller et al. 1992), which is less than the time-of-flight for HD 15137. The situation is even more discrepant for HD 14633 which has a time-of-flight of at least 12 Myr (see also the extreme case of the runaway star HD 93521; Howarth & Reid 1993). It is difficult to reconcile these long travel times with the expected short lifetimes of O-stars. There are several possible explanations. First, the runaways may have been rejuvenated by mass transfer just prior to the supernova explosion, which would reset their effective zero-age times to an epoch just prior to ejection. Second, at least HD 15137 is a rapid rotator, and fast rotation may help to mix gas and extend the main sequence lifetime of massive stars (Heger & Langer 2000; Meynet & Maeder 2000). Third, these stars may be over-luminous for their mass in same way as found for some massive X-ray binaries (Kaper 2001), so that their masses are lower and evolutionary lifetimes longer than simple estimates suggest.

The orbital properties of these two runaway binaries, their small mass functions, and their probable origin in a cluster containing evolved, massive stars all indicate that these stars were ejected during a supernova explosion in a binary. They are not known X-ray sources, due presumably to their large semimajor axes and low wind accretion rates, but it is possible that they exhibit transient X-ray emission when their neutron stars pass through the densest stellar wind regions near the periastron orbital phase. It is important to pursue radial velocity studies of other OB runaway stars to search for additional instances of such low amplitude binary systems. Only then will we determine the relative importance of the supernova and close encounter ejection processes for the kinematics of massive stars.

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Table 1. HD 14633 Radial Velocity Measurements

HJD (−2,400,000)	Orbital Phase	V_r (km s^{-1})	$O-C$ (km s^{-1})
51495.903	0.741	−31.6	−1.8
51818.807	0.698	−29.3	1.0
51819.741	0.758	−29.4	0.2
51820.786	0.826	−28.5	0.6
51821.746	0.888	−29.6	0.1
51822.797	0.957	−35.6	1.6
51822.963	0.967	−41.0	0.1
51823.738	0.018	−66.5	0.5
51823.899	0.028	−66.1	−0.9
51824.732	0.082	−51.8	1.4
51824.928	0.095	−50.3	1.1
51830.758	0.473	−31.4	2.6
51830.889	0.482	−34.5	−0.6
51889.828	0.307	−39.5	−1.4
51890.749	0.367	−36.2	0.3
51892.727	0.495	−32.9	0.8
51893.753	0.562	−32.2	0.2
51895.688	0.687	−29.9	0.6
51895.777	0.693	−30.0	0.4
51896.617	0.748	−30.8	−1.0
51896.750	0.756	−28.7	0.9
51897.613	0.812	−28.1	1.1
51897.751	0.821	−29.6	−0.4
51898.620	0.878	−30.8	−1.4
51898.754	0.886	−29.7	0.0
51899.624	0.943	−34.8	−0.8
51899.757	0.951	−35.9	−0.2
51900.619	0.007	−67.7	−1.6
51900.751	0.016	−65.2	2.0
51901.604	0.071	−58.7	−3.6
51901.737	0.080	−52.4	1.3
52930.558	0.851	−30.3	−1.1
52934.413	0.101	−50.4	0.2
53290.840	0.233	−41.5	−0.6
53292.825	0.362	−38.2	−1.6

Table 2. HD 15137 Radial Velocity Measurements

HJD (−2,400,000)	Orbital Phase	V_r (km s^{-1})	$O-C$ (km s^{-1})
51817.788	0.985	−59.6	−3.4
51818.797	0.021	−58.5	5.6
51819.758	0.054	−70.8	−5.3
51820.793	0.090	−63.7	−0.2
51821.762	0.124	−59.7	1.3
51822.805	0.161	−57.5	0.9
51822.970	0.167	−54.8	3.3
51823.746	0.194	−60.6	−4.1
51823.907	0.199	−54.6	1.6
51824.739	0.228	−54.3	0.3
51824.935	0.235	−55.3	−1.0
51830.770	0.439	−46.8	0.3
51830.897	0.444	−46.4	0.5
51889.849	0.505	−47.4	−2.0
51890.769	0.537	−41.4	3.2
51892.761	0.606	−46.4	−3.3
51893.788	0.642	−40.7	1.6
51894.790	0.677	−44.2	−2.5
51895.699	0.709	−40.3	0.8
51895.788	0.712	−36.7	4.4
51896.628	0.742	−47.9	−7.3
51896.762	0.746	−42.8	−2.3
51897.627	0.776	−41.4	−1.2
51897.762	0.781	−38.8	1.3
51898.633	0.812	−31.9	8.1
51898.766	0.816	−34.9	5.1
51899.635	0.847	−45.8	−5.7
51899.768	0.851	−43.7	−3.6
51900.630	0.881	−38.9	2.0
51900.762	0.886	−44.1	−3.1
51901.615	0.916	−38.3	4.6
51901.748	0.921	−43.9	−0.5
53290.849	0.482	−45.3	0.6

Table 3. Orbital Elements for HD 14633

Element	Rogers (1974)	Bolton & Rogers (1978) + Stone (1982) + New	New
P (days)	15.335	15.4083 ± 0.0004	15.4083[a]
T (HJD–2,400,000)	42007.3	44227.26 ± 0.21	51854.28 ± 0.05
e	0.68	0.63 ± 0.05	0.698 ± 0.010
ω (deg)	166.3	142 ± 10	140.3 ± 2.2
K (km s^{-1})	31.3	15.9 ± 1.4	19.0 ± 0.4
γ (km s^{-1})	−46.0	-38.8 ± 0.8	-37.9 ± 0.3
$f(m)$ ($M_\odot$)	0.019	0.0030 ± 0.0009	0.0040 ± 0.0003
$a_1 \sin i$ ($R_\odot$)	6.95	3.8 ± 0.4	4.14 ± 0.10
rms (km s^{-1})	···	7.4	1.3

[a]Fixed.

Table 4. Preliminary Orbital Elements for HD 15137

Element	Value
P (days)	28.61 ± 0.09
T (HJD–2,400,000)	51904.0 ± 0.7
e	0.52 ± 0.07
ω (deg)	125 ± 11
K (km s^{-1})	12.9 ± 1.3
γ (km s^{-1})	-49.0 ± 0.7
$f(m)$ ($M_\odot$)	0.0039 ± 0.0013
$a_1 \sin i$ ($R_\odot$)	6.2 ± 0.7
rms (km s^{-1})	3.8

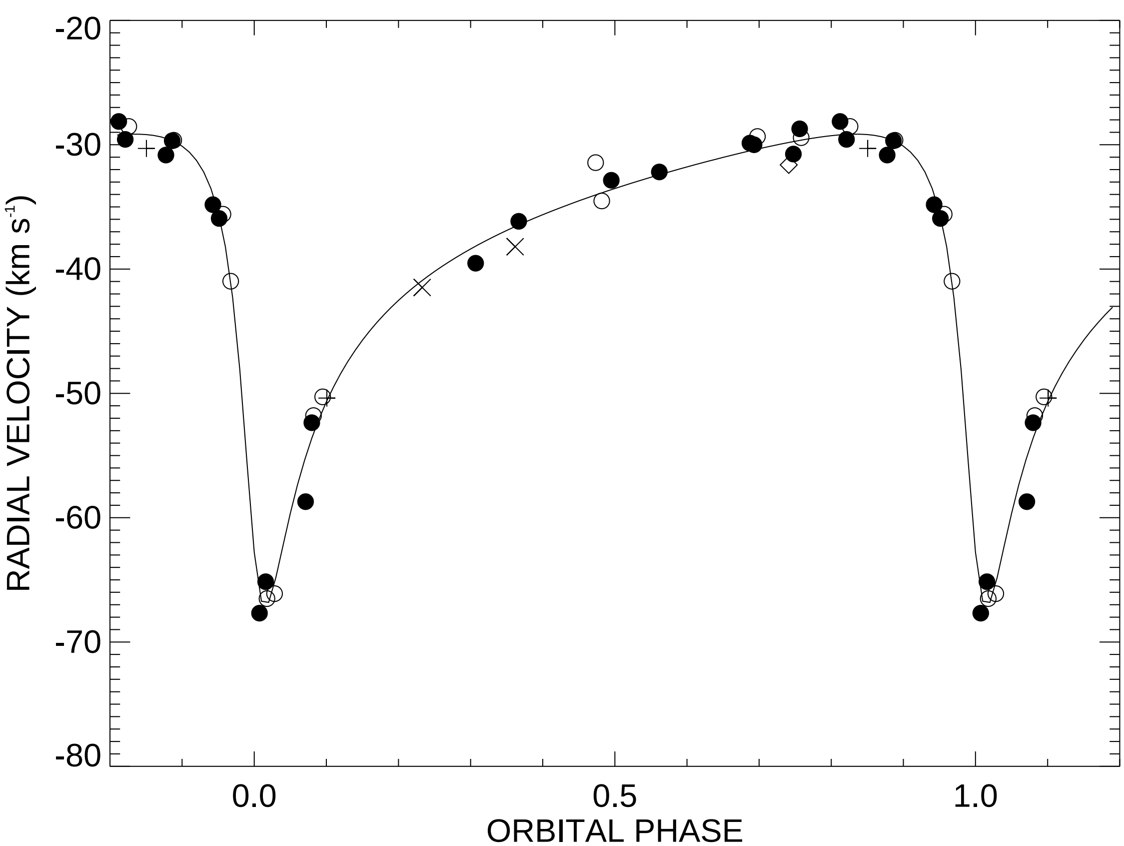

Fig. 1.— Calculated radial velocity curve (*solid line*) for HD 14633. The different symbols indicate observations from 1999 November (*diamond*), 2000 October (*open circles*), 2000 December (*solid circles*), 2003 October (*plus signs*), and 2004 October ($\times$ *signs*).

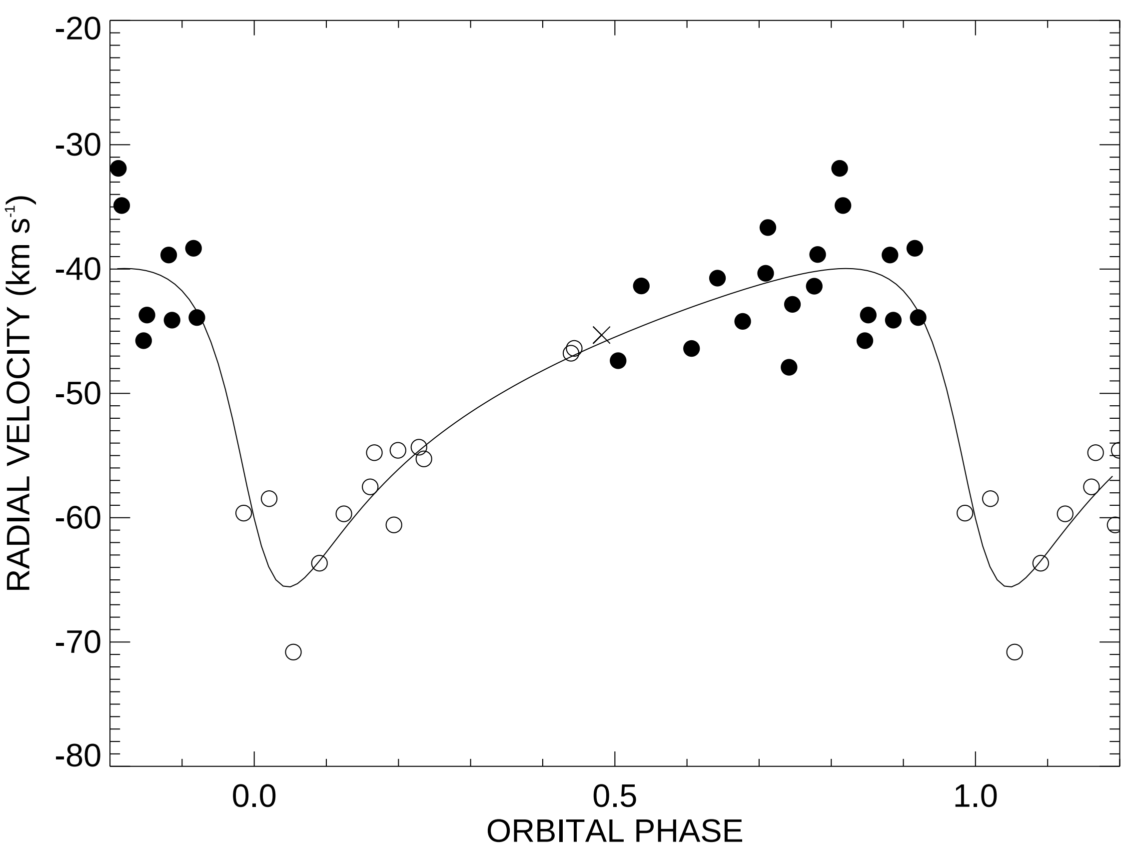

Fig. 2.— Preliminary radial velocity curve (*solid line*) for HD 15137. The different symbols indicate observations from 2000 October (*open circles*), 2000 December (*solid circles*), and 2004 October ($\times$ *sign*).

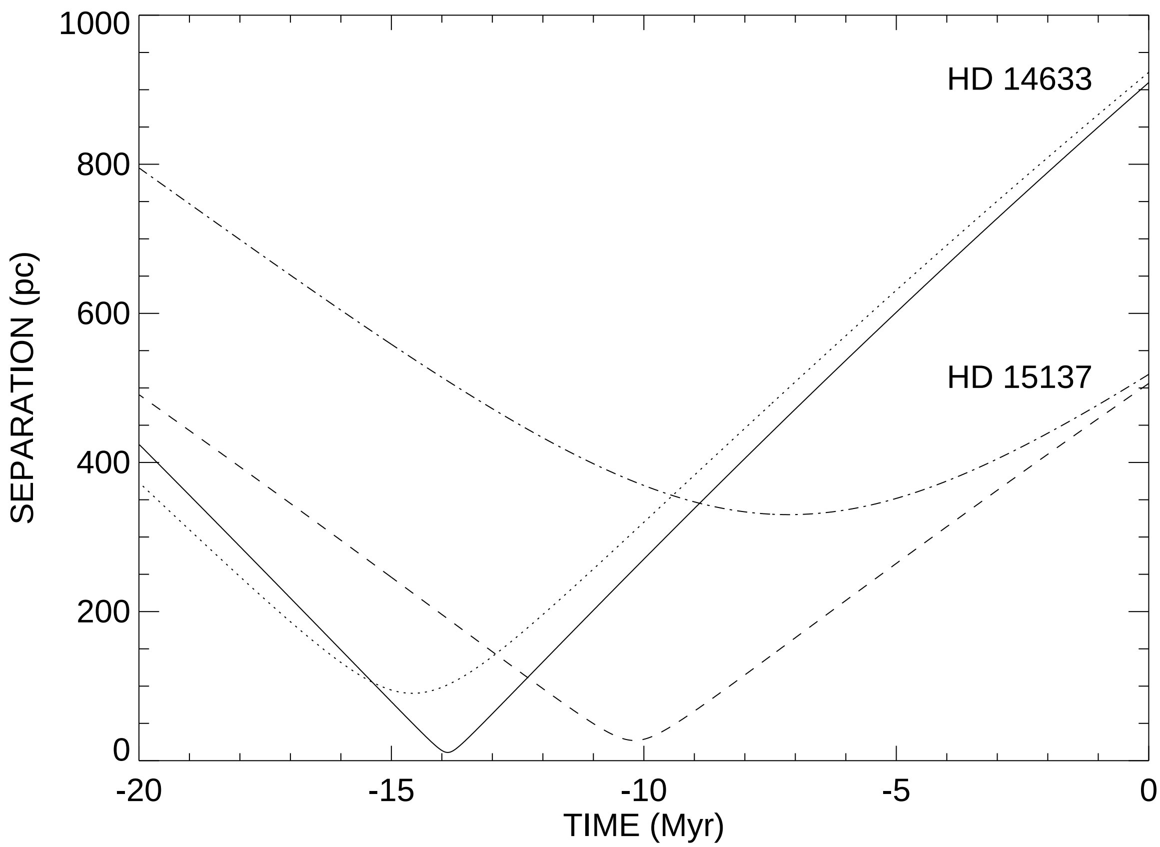

Fig. 3.— The separation between HD 14633 and NGC 654 and between HD 15137 and NGC 654 plotted against time in millions of years relative to the present. The dotted line shows the separation for the nominal current distance to HD 14633 of 2.15 kpc while the solid line shows the separation for a trajectory calculated using a current distance of 2.24 kpc. Likewise the dot-dashed line shows the separation for the nominal distance to HD 15137 of 2.65 kpc while the dashed line shows the same for a current distance of 2.29 kpc.

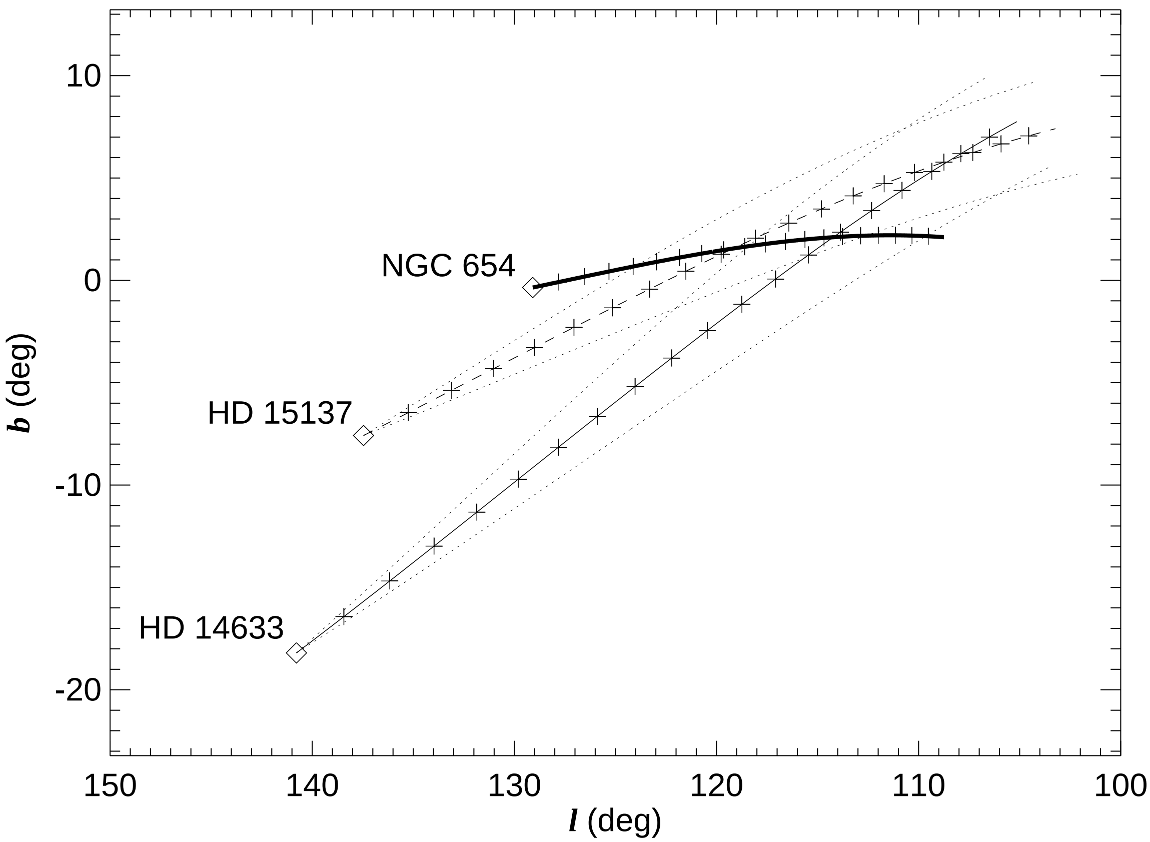

Fig. 4.— The past trajectories of HD 14633 (*thin solid line*), HD 15137 (*thin dashed line*), and NGC 654 (*thick solid line*) in Galactic longitude and latitude. The diamonds mark the current positions and tick marks are placed at 1 Myr intervals along each track. The dotted lines show the tracks for $\pm 1\sigma$ errors in proper motion for the runaway stars.