1993PASP..105..588P

Publications of the Astronomical Society of the Pacific
105: 588–594, 1993 June

The Frequency of Binary Stars in the Young Cluster Trumpler 14

LAURA R. PENNY, DOUGLAS R. GIES,[1] WILLIAM I. HARTKOPF,[1] BRIAN D. MASON, AND NILS H. TURNER[1]

Department of Physics and Astronomy, Center for High Angular Resolution Astronomy, Georgia State University, Atlanta, Georgia 30303-3083
Electronic mail: penny@chara.gsu.edu, gies@chara.gsu.edu, hartkopf@chara.gsu.edu, mason@chara.gsu.edu, nils@chara.gsu.edu

Received 1992 December 1; accepted 1993 March 8

ABSTRACT. We present radial-velocity data for the six brightest members of the open cluster Trumpler 14 based on high-dispersion spectra obtained over a five-night interval. None of these O-type stars appear to be spectroscopic binaries with periods of the order of a week or less, and none are speckle binaries. This binary fraction is low for O-type stars, and we suggest that the lack of primordial hard binaries and their dynamical interactions may explain how the cluster has maintained a high spatial density even after several cluster crossing times.

1. INTRODUCTION

Massive O- and B-type stars are often born in compact, dense clusters (for example, R 136: Elson et al. 1992, Walborn et al. 1992, Campbell et al. 1992; NGC 3603: Moffat 1983, Baier et al. 1985; the Orion Trapezium cluster: Herbig and Terndrup 1986). In such environments, dynamical interactions between the stars assume a new importance, and Gies and Bolton (1986) argued that gravitational encounters between binaries could produce high-speed escapees, the so-called OB runaway stars. Leonard and Duncan (1988, 1990) and Leonard (1991) studied this possibility through numerical simulations of parsec-sized clusters that contain a population of primordial massive binaries. They found that these binaries tend to sink to the center of the cluster where they form hierarchical doubles. Gravitational perturbations by other cluster members cause an increase in the eccentricity of such doubles, and eventually a binary–binary collision occurs at periastron. Leonard and Duncan demonstrate that this process can produce runaway stars of sufficient number and speed to account for the observed high-velocity population. Clarke and Pringle (1992) have further explored the cluster ejection model, and they find that the observed runaway star properties can be explained if (1) massive stars form in small clusters of binaries with near unity mass ratios, and (2) the initial mass function is under represented in low-mass stars. The dynamical influence of binaries on cluster evolution is explored in a more general way by Heggie and Aarseth (1992).

The young open cluster Trumpler 14 in the Eta Carinae region is a potential site for binary–binary encounters since it contains many massive stars (including three of type O3) within a region 1 pc in diameter (Feinstein et al. 1973; Walborn 1973; Feinstein 1983; Morrell et al. 1988; Massey and Johnson 1993). In this paper we report on a radial-velocity study of the brighter members of the cluster designed to find the binary content and to determine whether or not conditions favor dynamical ejection. At the outset of the project, only the brightest star in the cluster, HD 93129 A, had been the subject of a significant radial-velocity study by Conti et al. (1979) who found no evidence of orbital variability. Subsequently, a preliminary search for spectroscopic binaries was conducted by Levato et al. (1991), and these authors estimated the binary frequency to be $6/11=55\%$ which is typical for O stars in clusters and associations (26%–55%; Gies 1987). If the Levato et al. results are correct, they imply that Tr 14 does indeed have favorable conditions for dynamical ejection (although no escapees were actually identified by Levato et al.). Here we describe our spectroscopic (Sec. 2) and speckle (Sec. 5) observations of the six brightest members of the cluster, and measurements of their radial velocities (Sec. 3) and projected rotational velocities (Sec. 4). Contrary to the results of Levato et al. (1991), our measurements indicate a low binary frequency, and we argue that this lack of binaries may explain why Tr 14 has maintained a high spatial density over a significant fraction of its dynamical history (Sec. 6).

2. SPECTROSCOPIC OBSERVATIONS

We obtained spectra with the CTIO 4-m telescope and cassegrain echelle spectrograph in the period 1987 February 14–18. We used the 31.6 grooves mm^{-1} echelle grating and a 226 grooves mm^{-1} cross disperser grating blazed at 8000 Å (which we used in second order with a $CuSO_4$ filter to block competing orders). The spectra were made with blue train optics, blue collimator, and long camera. The detector was the RCA4 CCD, a 320×512 array consisting of 30 μm square pixels. We obtained spectra in two regions: on 1987 February 14, we made observations over the range 4406–4688 Å (seven echelle orders with some wavelength gaps between orders), and on the other four nights, we recorded spectra in the range 3915–4234 Å (ten orders

[1]Visiting Astronomer, Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

© 1993. Astronomical Society of the Pacific

© Astronomical Society of the Pacific • Provided by the NASA Astrophysics Data System

1993PASP..105..588P

TABLE 1
Target Stars

Star	Spectral Classification	V	$B-V$	$V \sin i$ (km s^{-1})
HD 93129 A	O3 If*	7.3	0.22	130
HD 93129 B	O3 V((f))	8.9	0.22	112
HD 93128	O3 V((f))	8.84	0.25	116
FMM 20	O6 V((f))	9.61	0.28	56
FMM 8	O6.5 V((f))	9.40	0.17	46
FMM 9	O8 V	9.92	0.21	60
FMM 3	B0.5 IV-V	10.80	0.26	111

with no gaps). The spectra for the first (second) region were made with a 150 (225) μm slit, equal to 1.0 (1.5) arcsec on the sky, and the spectra have a reciprocal dispersion of 0.067 (0.060) Å pixel^{-1} and a resolution (FWHM) of 0.15 (0.18) Å.

The primary targets of our survey are listed in Table 1 which identifies the stars by their designation in the HD catalog or by the cluster member number assigned by Feinstein et al. (1973; noted as FMM). The spectral types are from Walborn (1973, 1982), except for the final two entries (FMM 9, 3) which are types from Morrell et al. (1988). The photometric quantities are derived from Feinstein et al. (1973), with the exception of the measures for the close pair HD 93129 A, B which are taken from Walborn (1973). These measurements are in good agreement with those of Massey and Johnson (1993) for those stars which are free from image blending in their CCD photometry. We also obtained spectra each night of the bright O stars HD 38666 (Mu Columbae) and HD 57682 which are considered constant radial-velocity objects by Garmany et al. (1980), and we used these targets to provide a check on the velocity stability of our observing scheme. We kept the exposure times short (10–20 min) to minimize the effect of cosmic ray hits on the CCD, and we generally obtained three consecutive images that were combined subsequently by median averaging. The S/N ratio (per pixel) of the resulting spectra falls in the range 40–90 depending on the brightness of the target. We also made a series of bias and flat-field frames at the beginning and end of each night, and a Th Ar comparison spectrum was made before and after each stellar spectrum for wavelength calibration.

The spectra were extracted and calibrated using routines in IRAF.[2] In brief, each image was subject to a bias frame subtraction and flat-field division using nightly means of the bias and flat-field frames. One-dimensional spectra were extracted by direct integration of the image orthogonal to the dispersion direction (profile weighting method) using the IRAF routine "apsum." A local background was fit between the interorder regions and subtracted from the spectrum at each wavelength step. The spectra were then transformed to a uniform wavelength grid using "ecdispcor." Each spectrum individually was examined for excessive noise spikes which were replaced by interpolation. Each order was then rectified to a unit continuum (using "eccontinuum") by fitting a parabola (or a straight line in the case of the order recording Hδ for the four cooler stars since this feature occupies most of the order) to line-free regions. Finally, the heliocentric Julian dates and solar corrections were calculated using "rvcorrect," and velocities were measured using rectified intensity versus heliocentric wavelength format spectra for each order.

The final average spectra appear in Fig. 1. All the spectra of each target were transformed to a common wavelength grid and then summed to form a global average spectrum. The global average was smoothed using a Gaussian transfer function (truncated at 3σ) with a FWHM $=0.35$ Å. These merged spectra are plotted in Fig. 1 (separated in intensity by 50% of the continuum for clarity) in a format similar to the illustrations in the spectral atlas of Walborn and Fitzpatrick (1990) [see their Fig. 4 and Fig. 12(a) of Massey and Johnson 1993 for HD 93129 A]. The redward portion of the diagram corresponds to data obtained on the first night (some wavelength gaps) while the blueward portion represents the sum of the final four nights. Some discontinuites appear at the junction of individual orders due to continuum placement errors at the edges. These spectra are available to other investigators upon request.

3. RADIAL VELOCITY MEASUREMENTS

We measured the radial velocities of the program stars by fitting parabolas to the lower (upper) half of the absorption (emission) lines. Only features with a line depth significantly greater than the noise level were measured. All profiles and fits were inspected interactively to discard problem lines or to adjust the portion of the line included in the fit in the case of partially blended lines. Our sample of lines and adopted wavelengths are listed in Table 2; an "*X*" indicates which lines were measured for each star (noted by HD or FMM designation in the top line). Lines identifications marked with an "*e*" refer to emission lines measured in the spectra of three hot stars. These emission lines appear to have the same radial velocities as the absorption lines for these stars. We attempted to measure the same set of lines for a given star in each spectrum since it is well established that different lines may yield different velocities because of outward acceleration in the photosphere (Hutchings 1976; Bohannan and Garmany 1978).

Tables 3 and 4 summarize our measurements for the program stars and constant radial-velocity stars, respectively. These tables list the heliocentric Julian date, mean radial velocity for the observation, number of lines measured, and mean error associated with the mean radial velocity. We also measured radial velocities for the Ca II $\lambda\lambda$3933, 3968 interstellar lines as an additional check on any night-to-night errors in the data. These lines appear as two partially blended absorption components in the spectra of both the program and standard stars, and the average velocity is given in the tables for both blue and red components. Interstellar velocities are absent from the first

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

© Astronomical Society of the Pacific • Provided by the NASA Astrophysics Data System

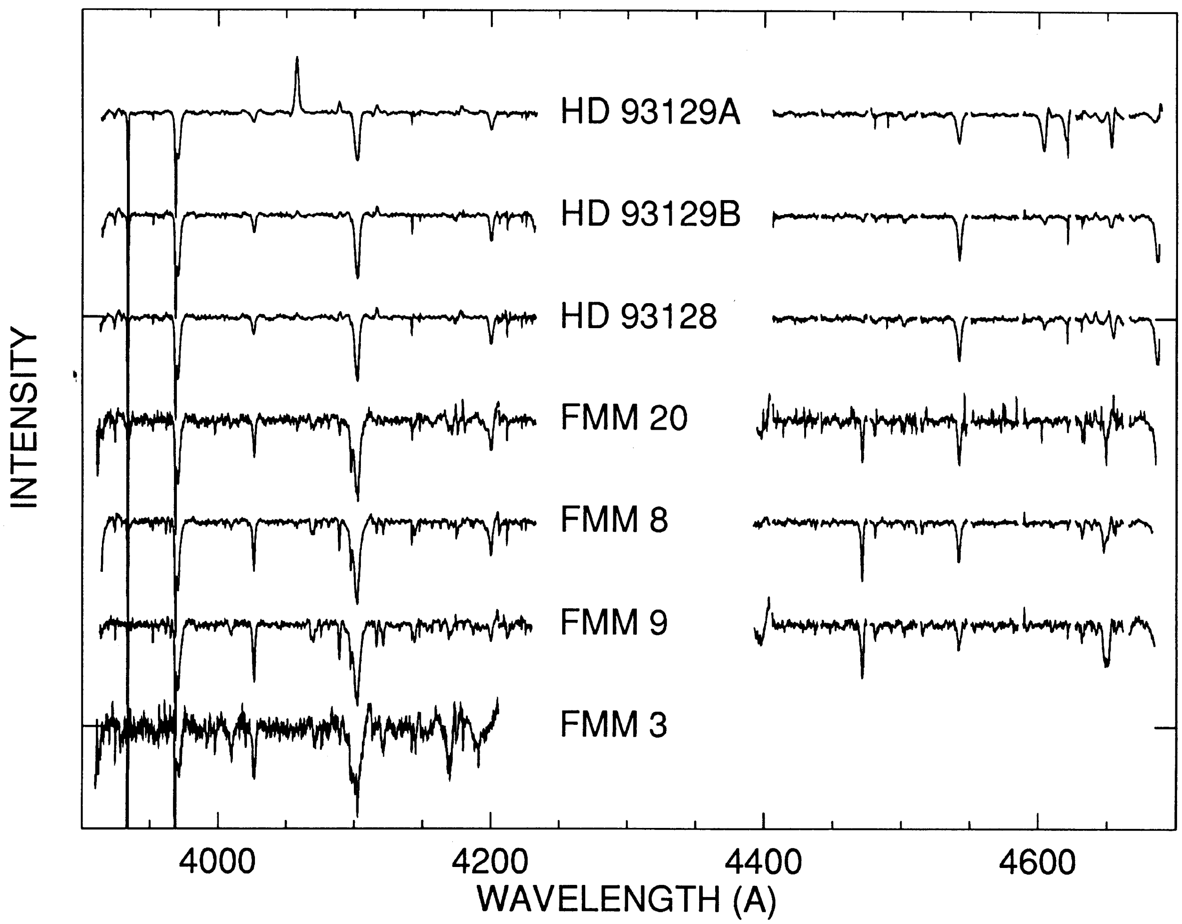

FIG. 1—Merged spectra of our program stars plotted vs. heliocentric wavelength. Each spectrum has been rectified to a unit continuum, and the spectra are offset in intensity by 50% of the continuum to avoid overlap. Line identifications are given in Table 2.

night observations because these lines were outside the spectral region recorded. All stars were measured on all five nights, except for program star FMM 9 (four nights); a fainter cluster member, FMM 3, was observed on two nights. Our results for the constant radial-velocity stars are consistent with published values. Garmany et al. (1980) give radial velocities of 28.0 ± 4.8 and 109.8 ± 2.8 km s^{-1} for HD 57682 and HD 38666, respectively, in good agreement with our mean values of 25.9 ± 0.4 and 106.6 ± 2.2 km s^{-1}, for the same two stars.

Since we expect that the radial velocities of spectral lines formed in the upper photosphere of the star will be systematically more blue-shifted than lines formed in the lower photosphere due to acceleration into the stellar wind, we have used the two-way analysis of variance method (Conti et al. 1977a; Bohannan and Garmany 1978; Garmany et al. 1980; Gies and Bolton 1986) to study both night-to-night and line-to-line variability. The results of this analysis are presented in Table 5. The successive columns list the star identification, overall mean radial velocity computed from the mean of each night, external error, internal error, number of observations included in the mean (different usage of n from Tables 3 and 4), and range

TABLE 2
Lines Measured

Line		93129 A	93129 B	93128	20	8	9	3	57682	38666
O III	3961.590	...	...	...	...	X	...	...	X	...
He I	3964.727	...	...	...	...	X	...	...	X	...
Hϵ	3970.074	X	X	X	X	X	X	X	X	X
He I	4009.270	...	...	...	...	X	X	...	X	X
He II	4025.60	X	X	X	...	...	...	...	...	...
He I	4026.140	...	...	...	X	X	X	X	X	X
N II	4041.321	...	...	...	...	...	...	...	X	...
N IV e	4057.80	X	X	X	...	...	...	...	...	...
O II	4069.794	...	...	...	...	...	...	...	...	X
O II	4072.164	...	...	...	...	...	X	...	X	...
O II	4075.868	...	...	...	...	...	X	...	X	X
Si IV e	4088.863	X	X	X	...	...	...	...	...	...
Si IV	4088.863	...	...	...	X	X	X	...	X	X
N III	4097.310	...	...	...	X	X	X	...	X	...
Hδ	4101.737	X	X	X	X	X	X	...	X	X
Si IV	4116.104	...	...	...	...	X	X	...	X	X
He I	4120.812	...	...	...	...	X	X	...	X	X
He I	4143.759	...	...	...	...	...	X	...	X	X
He II	4199.830	X	X	X	X	X	X	...	X	X
He I	4471.477	...	...	...	X	X	X	...	X	X
Mg II	4481.228	...	...	...	X	X	X	...	X	X
N III	4514.890	...	...	...	X	X	X	...	X	...
He II	4541.590	X	X	X	X	X	X	...	X	X
Si III	4552.622	...	...	...	...	...	...	...	X	X
Si III	4567.872	...	...	...	...	...	...	...	X	X
N V	4603.730	X	X	X	...	...	...	...	...	...
N II	4607.153	X	...	...	...	...	...	...	...	...
N V	4619.980	X	...	...	...	...	...	...	X	...
N II	4630.537	...	...	...	...	...	...	...	...	X
N III	4634.160	...	...	...	X	...	...	...	X	...
N III	4640.640	...	...	...	...	X	...	...	...	X
O II	4641.811	...	...	...	...	...	X	...	X	...
O II	4649.139	...	...	...	...	X	X	...	...	...
He II	4685.682	...	X	X	...	...	...	...	...	...

1993PASP..105..588P

© Astronomical Society of the Pacific • Provided by the NASA Astrophysics Data System

1993PASP..105..588P

TABLE 3
Program Star Radial-Velocity Measurements

HJD (2440000+)	V_r (km s^{-1})	n	m.e. (km s^{-1})	Ca II blue (km s^{-1})	Ca II red (km s^{-1})
			HD 93129 A		
6840.594	-13.9	4	2.0	...	...
6841.607	-6.2	5	4.2	-30.8	3.8
6842.630	-7.8	6	6.1	-26.2	4.8
6843.548	-3.0	6	4.4	-29.5	3.2
6844.549	8.7	6	6.8	-27.7	3.1
			HD 93129 B		
6840.650	10.7	3	5.7	...	...
6841.769	4.6	5	5.9	-29.1	4.4
6842.695	7.5	6	4.9	-29.6	3.6
6843.681	6.4	6	4.2	-28.5	4.3
6844.670	6.9	5	5.0	-28.9	3.9
			HD 93128		
6840.611	13.1	3	3.5	...	...
6841.633	2.5	4	15.3	-19.0	4.8
6842.657	11.1	5	5.3	-26.4	3.3
6843.577	2.3	6	4.6	-25.4	4.8
6844.577	7.5	6	4.0	-24.5	5.7
			FMM 20		
6840.884	-2.6	5	3.9	...	...
6841.721	4.0	5	4.6	-34.4	3.9
6842.796	0.8	5	5.7	-35.6	3.2
6843.728	2.0	6	4.3	-34.8	3.2
6844.716	3.3	6	2.5	-36.6	1.6
			FMM 8		
6840.788	-6.0	7	2.0	...	...
6841.672	-0.7	9	3.0	-24.0	5.3
6842.743	-8.9	11	2.7	-25.9	2.8
6843.619	-6.6	11	2.6	-18.2	6.5
6844.623	-0.9	11	2.2	-23.0	6.6
			FMM 9		
6840.837	4.4	6	5.3	...	...
6841.814	4.7	10	4.5	-30.2	3.7
6843.789	-1.0	12	4.2	-30.2	4.2
6844.762	1.9	11	2.5	-25.7	2.5
			FMM 3		
6843.852	15.0	2	3.4	-28.4	7.0
6844.809	18.1	2	2.5	-29.2	4.9

of the nightly mean velocities. The final columns give the results of the statistical analysis derived from velocities for the last four nights (uniform line sample). P(n–n) is the probability that a variance as large or larger than the observed night-to-night variance could be derived from a random set of data. We adopt the 1% probability level as our detection threshold (as has been done in all the 2AOV studies cited above), and thus none of our program stars have significant night-to-night variability. If, for the sake of argument, the detection threshold is set at the 5% probability level, then two of the program stars, HD 93129 A and FMM 8, are possible radial-velocity variables. However we doubt these are binary candidates for several reasons. Neither star shows any obvious orbital trend in velocity from night to night, and FMM 8 has a small velocity range (8.3 km s^{-1}). The O3 If* star, HD 93129 A, was observed on 69 occasions by Conti et al. (1979), and a histogram of their data has a Gaussian distribution with a width consistent with their observational errors. Conti et al. consider this star to be a constant velocity object, and they place an upper limit of 20 km s^{-1} on the semiamplitude of any binary motion. Our data would appear to place an even tighter limit ($\approx$10 km s^{-1}) on the semiamplitude of any short-period binary. Another possible source of radial-velocity variability is photospheric line variations (Fullerton 1990). Baade (1991) found significant photospheric profile variations in Zeta Puppis, an O4 I(n)f type star (Walborn 1972). If these line profile variations are present in HD 93129 A, an intrinsic velocity variability of $\sim$10 km s^{-1} would not be surprising. The final column in Table 5 gives P(l–l) which is the corresponding probability that the line-to-line variance is as large or larger than expected from a random set of data. Again, if the 1% probability criterion is adopted, then all program and standard stars show significant line-to-line velocity differences with the exception of FMM 20 and FMM 3 (the latter observed only twice).

TABLE 4
Standard Star Radial Velocity Measurements

HJD (2440000+)	V_r (km s^{-1})	n	m.e. (km s^{-1})	Ca II blue (km s^{-1})	Ca II red (km s^{-1})
			HD 57682		
6840.578	23.5	9	1.1	...	...
6841.535	26.9	17	1.5	21.6	30.5
6842.603	26.8	16	2.1	20.5	28.1
6843.533	26.0	17	1.4	20.4	26.1
6844.538	26.2	17	1.6	21.0	26.1
			HD 38666		
6840.550	108.4	8	5.3	...	...
6841.575	107.0	11	5.1	24.9	37.9
6842.591	102.9	10	3.0	21.2	38.3
6843.522	109.3	10	2.7	23.6	40.1
6844.523	105.2	11	2.4	22.5	39.8

TABLE 5
Statistical Analysis

Star	< V_r > (km s^{-1})	E (km s^{-1})	I (km s^{-1})	n	Range (km s^{-1})	P(n-n) (%)	P(l-l) (%)
HD 93129 A	-4.4	7.4	3.4	5	22.6	1.6	0.6
HD 93129 B	7.2	2.4	2.6	5	6.1	50.7	0.1
HD 93128	7.3	3.3	4.1	5	10.8	59.2	1.0
FMM 20	1.5	0.8	3.4	5	6.7	98.1	25.8
FMM 8	-4.6	4.0	2.1	5	8.3	2.5	6.1
FMM 9	2.5	3.9	2.9	4	5.7	18.5	1.6
FMM 3	16.6	2.2	2.9	2	3.1	59.3	90.4
HD 57682	25.9	0.4	0.4	5	3.3	54.1	<0.01
HD 38666	106.6	2.2	2.0	5	6.4	30.0	<0.01

Our velocity results are very different from those reported by Levato et al. (1991) in their radial-velocity study of Tr 14. First, Levato et al. claim that three of our constant velocity targets are spectroscopic binaries. They fit an orbit with a 2.8-day period and a semiamplitude of K=30 km s^{-1} to their velocities for HD 93128 but our observations show a range of only 11 km s^{-1} over five nights. They also present an orbit for FMM 20 having a period of 5.0 days and a semiamplitude of K=20 km s^{-1} which conflicts with our observed range of 7 km s^{-1}. Levato et al. observed HD 93129 B to be double-lined in one of five consecutive nights of observations. It is possible that this star is a binary with a large eccentricity, but we see no evidence of double lines or velocity variability in our data with similar temporal sampling. In addition, FMM 3 was also determined to be a double-lined spectroscopic binary by Levato et al.; there are no obvious double lines in our two spectra of this star, but the spectra have a very low S/N ratio so we can neither rule out nor confirm their claim. The other three stars in common, HD 93129 A, FMM 8, and FMM 9, are found to be constant radial-velocity objects by both us and Levato et al. The second major difference concerns the absolute values of velocity. Our mean radial velocity for the cluster is 2.8 km s^{-1}, after exclusion of HD 93129 A (whose negative velocity may reflect outflow at the base of its prodigious stellar wind)

© Astronomical Society of the Pacific • Provided by the NASA Astrophysics Data System

1993PASP..105..588P

and FMM 3 (which may be a binary). The Levato et al. mean velocity is -37 km s^{-1} for the same five stars. In fact, our radial velocities are generally 30–60 km s^{-1} more positive than given by Levato et al. for our targets. As stated above, we observed two radial-velocity constant stars, HD 38666 and HD 57682, and our velocities agree well with published values. Our mean velocity for HD 93129 A, -4.4 ± 7.4 km s^{-1}, is consistent with the many measurements by Conti et al. (1979), which average -12.9 ± 11.2 km s^{-1} for the same set of lines (error reflects scatter in line-to-line means); both of these values are much more positive than the value of -71 ± 6 km s^{-1} quoted by Levato et al. Furthermore, Conti et al. (1977b) report a radial velocity of 5.0 ± 2.2 km s^{-1} for HD 93128, which compares well with our value of 7.3 ± 3.3 km s^{-1} but poorly with the value of -36 ± 2 km s^{-1} given by Levato et al. (systemic velocity). We suspect that the velocities reported by Levato et al. have major systematic errors.

The significance of our derived low fraction of velocity variables must be judged in comparison to similar surveys of large samples of O-type stars. The survey of Garmany et al. (1980) indicates a binary fraction of 36% for O stars as a whole based on two criteria, P(n–n) < 1% or an observed range greater than 45 km s^{-1}. However, Gies (1987) has shown that the binary frequency is larger among members of clusters and associations, and from a literature survey he finds a 55% frequency of velocity variables based on stars with orbits, displaying double lines, or having a velocity range greater than 35 km s^{-1}. Thus, taken at face value, Tr 14 has a low binary frequency, 0% for the six bright stars surveyed here. The Levato et al. (1991) results suggest a frequency of velocity variables of 27% (3/11 stars) after correction for the stars common to both our programs. However, since we find that three of the stars suspected to be binaries by Levato et al. are constant velocity objects, we believe the binary status of their remaining three binary candidates, FMM 3, 6, and 21, need independent confirmation.

A direct comparison of our results with prior binary surveys is problematical because of differences in experimental technique and sampling. Our mean internal error, $I=3.1$ km s^{-1}, represents a higher precision than has been obtained in most previous work (because of the higher resolution and S/N ratio of our spectra), and when future surveys are completed with similar precision the fraction of velocity variables will certainly increase. Thus we regard the 55% frequency for O stars in clusters and associations derived by Gies (1987) as a probable lower limit to the frequency that would be obtained using methods comparable to our own. On the other hand, the referee pointed out that our five night sampling of the velocities will result in nondetection of binaries with long periods and/or high eccentricities that are included in the Gies (1987) compilation (based on a literature search of velocities that generally span much longer than five nights). To judge the significance of this bias, we took the O-type binary list of Garmany et al. (1980; Table 3) as a typical sample of binaries found in recent surveys, and we determined how many of these binaries would be detected as velocity variables using the sampling and precision of our Tr 14 study. We define detection here as an observed night-to-night scatter (external error E) greater than 4.6 times the average scatter within a sample of lines from a single spectrum (internal error I). This ratio corresponds to the 1% probability threshold for a one-way analysis of variance for four degrees of freedom (5 nights minus 1 parameter for the mean). Our measurements have an average internal error of $I=3.1$ km s^{-1}, so the detection criterion is $E>14.1$ km s^{-1}. For each star in the Garmany et al. list, we calculated an orbital velocity curve using the program of Morbey and Brosterhus (1974) and the orbital elements listed in Batten et al. (1989), and we then sampled the curve at five times each separated by one day and calculated E for these five velocities. Since the sampled velocity range depends critically on which part of the orbit is observed in binaries with long periods and/or high eccentricities, we made 200 such samples starting at randomly selected orbital phases, and then determined the median value of E which we regard as the most appropriate choice for a stochastic analysis. We find that 35 of the 40 binaries (88%) would be detected as velocity variables in a study similar to ours (the five undetected systems all have periods greater than 20 days). Thus our low observed binary frequency is not the result of incomplete sampling.

4. PROJECTED ROTATIONAL VELOCITIES

We have measured the widths of several important lines to estimate the projected rotational velocities, $V \sin i$. The derivation of $V \sin i$ generally requires a comparison of observed profiles with computed models that account for all the important sources of line broadening including rotation (Gray 1976). Conti and Ebbets (1977) have measured projected rotational velocities for a large sample of O stars using model techniques, and we decided to relate our measured widths to their velocity system using a simplified transformation. We assume that the full width of the line represents the quadratic sum of the rotational broadening function with a constant term representing all other sources of broadening (by thermal, pressure, turbulence, and instrumental effects). Thus we relate the observed half-width at half maximum (HWHM) to $V \sin i$ by

$$V \sin i = a\sqrt{\mathrm{HWHM}^2 - b^2}, \qquad (1)$$

where a and b are fitting constants. Fortunately, four of our targets (HD 38666, HD 57682, HD 93128, and HD 93129 A) were measured by Conti and Ebbets, so we used our measured HWHM and their derived $V \sin i$ values to determine the fitting constants a and b. We formed an average HWHM (in units of km s^{-1}) for each program star by measuring the FWHM of He II λ4541, He I λ4471, Si IV λλ4088, 4116, and N V λ4604, or a subsample of these lines that were clearly visible. For FMM 3, we measured the lines of He I λλ4009, 4026, 4120. A calibration of Eq. (1) using these measured widths and the Conti and Ebbets $V \sin i$ values yields constants $a=1.23$ and $b=35.8$ km s^{-1} with a standard deviation to the fit of 12 km s^{-1}.

© Astronomical Society of the Pacific • Provided by the NASA Astrophysics Data System

1993PASP..105..588P

We then used Eq. (1) with the HWHM data for the entire sample to derive a uniform set of projected rotational velocities (see Table 1). The mean $V \sin i$ for the cluster members we observed is 90 km s^{-1}. Abt (1983) suggests that clusters with large mean rotational velocities ($\langle V \sin i \rangle > 200$ km s^{-1}) have a low binary frequency which presumably reflects the absence of tidal braking in close binary stars. The mean projected rotational velocity of Tr 14 clearly places this cluster among those with a low mean $V \sin i$ which generally show a normal binary frequency. Thus the low binary frequency of our sample is unusual for O stars and also for members of clusters with comparable mean rotational velocities.

5. SPECKLE OBSERVATIONS

In order to search for possible long period binaries, a speckle interferometric survey of the six main targets within the cluster was conducted with the CTIO 4-m telescope on 1992 June 15. A description of the observing techniques and reduction methods is given in Bagnuolo et al. (1992). The observations were made with a Strömgren y filter for HD 93129 A and a "speckle y" filter (five times broader spectral range) for the rest. The cluster stars were observed at a zenith angle of 29°, and frames of 1/30 second duration were obtained over 1 or 2 min. A description of our new speckle camera is given by Mason et al. (1993), who also discuss the effects of seeing conditions on stellar brightness contrast and the detection of close binaries. None of these stars exhibited definitive multiplicity. For stars in this magnitude range ($7.3 < V < 10.8$) and for the seeing conditions (≈ 2 arcsec) at the time of the observations, these negative results can belong to one or more of the following cases: (1) the angular separation exceeds 1 arcsec (the effective field of view of the CCD detector is about 1.33×1.04 arcsec centered on the primary star), (2) the angular separation is less than the 0.035 arcsec diffraction limit of the 4-m telescope, (3) the magnitude difference is greater than about 1.5 mag, or (4) they are single stars.

6. DISCUSSION

Our spectroscopic and speckle observations indicate that there are few if any binaries with periods of the order of days or longer than a century among the six brightest members of Tr 14. Although our methods do not detect binaries with intermediate periods, the same is also true for most surveys of binary frequency, so we conclude that Tr 14 probably has a low binary frequency compared to O stars in clusters and associations (Gies 1987). In this section we argue that the lack of binaries may help explain why the cluster appears in a compact state.

We begin by comparing the cluster crossing time with its age. The standard deviation of the mean velocities is 4.9 km s^{-1} (after omission of the values for HD 93129 A and FMM 3; see Sec. 3). Thus we estimate that typical random motions in the cluster are $\sqrt{3}\,\sigma = 8.5$ km s^{-1}. The projected size in the sky is approximately 140 arcsec in diameter. Morrell et al. (1988) discuss two possible distances for Tr 14, 2.8 and 3.45 kpc (Massey and Johnson 1993 find an intermediate distance of 3.2 kpc), and thus the cluster radius is in the range 1.0 to 1.2 pc. The crossing time for the cluster is then $t_{\rm cross} = R/v = 1.1 \times 10^5 - 1.4 \times 10^5$ yr. The cluster relaxation time is

$$t_{\rm relax} = \frac{N}{8 \ln N}\, t_{\rm cross}\,, \qquad (2)$$

(Binney and Tremaine 1987), and for $N \approx 40$ (Feinstein 1983), $t_{\rm relax} = 1.4\, t_{\rm cross} = 1.5 \times 10^5$ to 1.8×10^5 yr. Morrell et al. (1988) suggest that the cluster age is less than 10^6 yr based on the fact that the hot star HD 93128 is still on the main sequence. Kudritzki et al. (1992) have derived $T_{\rm eff}$ and $\log L/L_\odot$ from atmospheric analysis for HD 93129 A and HD 93128, and we have plotted these properties against theoretical evolutionary paths by Maeder (1990) to estimate their ages. The supergiant HD 93129 A has definitely moved off the main sequence, and its age is estimated to be $(9 \pm ^{2}_{4}) \times 10^5$ yr. On the other hand, HD 93128 appears to be a ZAMS object, and we estimate its age as $(0 \pm ^{6}_{0}) \times 10^5$ yr. We assume for simplicity that both stars were born at the same time, and thus the cluster age is approximately 5.5×10^5 yr. Therefore, the cluster has lived through approximately four to five crossing times, and it should have attained dynamical relaxation. The average spatial number density is in the range 11–6 pc^{-3} which is approaching densities in globular clusters.

It is clear from its compact appearance that Tr 14 is still a bound cluster, and that the forces that cause expansion of subgroups in OB associations have not yet played a significant role. Three processes are known that can cause clusters to expand: (1) dispersal of the remaining natal gas cloud by the photoionizing flux of the massive stars, (2) mass loss from the cluster by stellar winds and supernovae, and (3) dynamical exchanges involving binaries. Loss of the remaining gas will decrease the gravitational well binding the cluster and it will expand (Lada et al. 1984). Presumably much of the gas surrounding Tr 14 has already been dispersed by the hot stars in the cluster (see CO maps of de Graauw et al. 1981), and we currently have a reasonably clear view to the cluster (mean extinction $A_V = 1.74$ mag; Tapia et al. 1988). Thus the cluster has remained intact despite the change in gravitational potential with the loss of the cloud. Mass loss from the stars themselves (through winds or supernovae) cannot account for a substantial change in gravitational binding energy because of the extreme youth of the cluster. Thus there remains only dynamical interactions with binaries as a source of expansion. In small N systems, the binding energy of the cluster can be transformed into the dynamical formation of binaries or hardening of primordial binaries (Clarke and Pringle 1992). The former process may be responsible for the formation of the HD 93129 AB pair. These stars have a separation of 2.8 arcsec, and if the projected separation corresponds to the orbital separation in a true binary, then their relative orbital velocity would be 4 km s^{-1}, less than the random motions in the cluster. Thus this binary is only loosely bound and could be disrupted by gravitational encounters with cluster members. The same holds true for

© Astronomical Society of the Pacific • Provided by the NASA Astrophysics Data System

1993PASP..105..588P

the other visual binaries in the cluster, HD 93128+FMM 3 (6.6 arcsec separation) and FMM 8 (3.7 arcsec separation). If primordial binaries did exist in the cluster, the conditions are right for binary–binary encounters of the kind described by Leonard and Duncan (1988, 1990). Gravitational interactions between such binaries and other cluster members would lead to heating (expansion) of the cluster and hardening of the binaries, and, eventually, collisions between binaries would produce high-speed escapees. We suspect that it is the anomalous lack of such binaries in Tr 14 that has negated the importance of this expansion process, so that Tr 14 has remained a compact system even after several crossing times. The apparent similarity of the runaway stars' times of flight (kinematical ages) with the ages of their parent cluster or association (Gies and Bolton 1986) suggests that binary–binary collisions can occur early in the life of a compact cluster. Only those clusters lacking primordial binaries would avoid expansion by this process, and therefore we predict that other dense clusters of somewhat evolved OB stars will also have a low binary frequency.

We thank the Director and staff of Cerro Tololo Inter-American Observatory for the telescope allocation and observational support. We are grateful for the financial support of the Chancellor's Initiative Fund from the Board of Regents of the University System of Georgia administered through the GSU office of the Vice President for Research and Technology. D.R.G. gratefully acknowledges the financial support of a Natural Sciences and Engineering Research Council of Canada Postdoctoral Fellowship at the time of the observations. D. R. G. also expresses his thanks to the American Astronomical Society for a Chrétien International Research Grant that provided partial funding for the purchase of a workstation used in this analysis. This work was supported by the National Science Foundation Grant Nos. AST-9115121 and AST-9141927.

REFERENCES

Abt, H. A. 1983, ARAA, 21, 343
Baade, D. 1991, in ESO Workshop on Rapid Variability of OB-Stars: Nature and Diagnostic Value, ed. D. Baade (Garching bei München, ESO), ESO Proc. 36, p. 21
Baier, G., Ladebeck, R., and Weigelt, G. 1985, A&A, 151, 61
Bagnuolo, W. G., Jr., Mason, B. D., Barry, D. J., Hartkopf, W. I., and McAlister, H. A. 1992, AJ, 103, 1399
Batten, A. H., Fletcher, J. M., and MacCarthy, D. G. 1989, Publ. Dom. Astrophys. Obs. Victoria, 17
Binney, J., and Tremaine, S. 1987, Galactic Dynamics (Princeton, Princeton University Press)
Bohannan, B., and Garmany, C. D. 1978, ApJ, 223, 908
Campbell, B., et al. 1992, AJ, 104, 1721
Clarke, C. J., and Pringle, J. E. 1992, MNRAS, 255, 423
Conti, P. S., and Ebbets, D. 1977, ApJ, 213, 438
Conti, P. S., Garmany, C. D., and Hutchings, J. B. 1977a, ApJ, 215, 561
Conti, P. S., Leep, E. M., and Lorre, J. J. 1977b, ApJ, 214, 759
Conti, P. S., Niemela, V. S., and Walborn, N. R. 1979, ApJ, 228, 206
de Graauw, T., Lidholm, S., Fitton, B., Beckman, J., Israel, F. P., Nieuwenhuijzen, H., and Vermue, J. 1981, A&A, 102, 257
Elson, R. A. W., Schade, D. J., Thomson, R. C., and Mackay, C. D. 1992, MNRAS, 258, 103
Feinstein, A. 1983, Ap&SS, 96, 293
Feinstein, A., Marraco, H. G., and Muzzio, J. C. 1973, A&AS, 12, 331
Fullerton, A. W. 1990, Ph.D. thesis, University of Toronto
Garmany, C. D., Conti, P. S., and Massey, P. 1980, ApJ, 242, 1063
Gies, D. R. 1987, ApJS, 64, 545
Gies, D. R., and Bolton, C. T. 1986, ApJS, 61, 419
Gray, D. F. 1976, The Observation and Analysis of Stellar Photospheres (New York, Wiley)
Heggie, D. C., and Aarseth, S. J. 1992, MNRAS, 257, 513
Herbig, G. H., and Terndrup, D. M. 1986, ApJ, 307, 609
Hutchings, J. B. 1976, ApJ, 203, 438
Kudritzki, R. P., Hummer, D. G., Pauldrach, A. W. A., Puls, J., Najarro, F., and Imhoff, J. 1992, A&A, 257, 655
Lada, C. J., Margulis, M., and Dearborn, D. 1984, ApJ, 285, 141
Leonard, P. J. T. 1991, AJ, 101, 562
Leonard, P. J. T., and Duncan, M. J. 1988, AJ, 96, 222
Leonard, P. J. T., and Duncan, M. J. 1990, AJ, 99, 608
Levato, H., Malaroda, S., Garcia, B., Morrell, N., Solivella, G., and Grosso, M. 1991, Ap&SS, 183, 147
Maeder, A. 1990, A&AS, 84, 139
Massey, P., and Johnson, J. 1993, AJ, 105, 980
Mason, B. D., McAlister, H. A., Hartkopf, W. I., and Bagnuolo, W. G., Jr. 1993, AJ, 105, 220
Moffat, A. F. J. 1983, A&A, 124, 273
Morbey, C. L., and Brosterhus, E. B. 1974, PASP, 86, 455
Morrell, N., Garcia, B., and Levato, H. 1988, PASP, 100, 1431
Tapia, M., Roth, M., Marraco, H., and Ruiz, M. T. 1988, MNRAS, 232, 661
Walborn, N. R. 1972, AJ, 77, 312
Walborn, N. R. 1973, ApJ, 179, 517
Walborn, N. R. 1982, AJ, 87, 1300
Walborn, N. R., and Fitzpatrick, E. L. 1990, PASP, 102, 379
Walborn, N. R., Ebbets, D. C., Parker, J. W., Nichols-Bohlin, J., and White, R. L. 1992, ApJ, 393, L13

© Astronomical Society of the Pacific • Provided by the NASA Astrophysics Data System