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Rotational velocities of B-type stars from the Edinburgh-Cape survey

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Abstract. The projected rotational velocity distribution for a sample of 34 high Galactic latitude B-type stars from the Edinburgh-Cape Faint Blue Object Survey is presented to investigate the evolutionary status of the group as a whole. Statistical analyses of the distribution show it to be similar to that expected if the sample contained mainly normal Population I early B-type stars, although a contamination of up to 20 % by evolved stars cannot be ruled out. This implies that a large fraction of the sample consists of normal Population I B-type stars similar to those found in the Galactic disk. Possible mechanisms explaining the presence of these stars in the halo are briefly discussed.

Key words: stars: early-type – stars: rotation – stars: formation Galaxy: halo – Galaxy: stellar content

1. Introduction

The discovery of blue stars at high Galactic latitudes (often called halo stars) was made in the photographic survey of Humason & Zwicky (1947). Subsequent surveys (for example the Palomar-Haro-Luyten Survey, Haro & Luyten 1962) confirmed the existence of many such stars and the first attempt at a quantitative analysis was made by Greenstein & Sargent (1974). Recently model atmosphere analyses have revealed that some of these stars have chemical compositions very similar to the Population I OB-type objects in the plane of the Galaxy, leading to two possible explanations. Either these are normal, distant objects (Keenan 1992), or they are in fact low mass, evolved, nearby objects whose spectra mimic those of young Population I stars even at high dispersion (Carrasco et al. 1982).

If these stars are indeed normal Population I stars then a large number of them may be runaways which have been ejected from the disk. However, there remain several whose kinematics and location imply that they could have formed in the halo (Conlon et al. 1992), which is difficult to understand in view of the low halo gas density. Additionally, halo stars have been used extensively in interstellar medium studies (see, for example, Ryans et al. 1997 and references therein) and it is therefore important to establish whether they are in fact young, distant Population I objects.

One possible method for discriminating between Population I and II objects is to examine their projected rotational velocity, v sin i (Peterson 1993). Hot stars possess substantial angular momentum when they are formed and tend to retain this throughout their relatively short main-sequence lifetime. Evolved Population II stars, however, are old enough to have undergone surface spindown and therefore should have smaller rotational velocities. Blue Horizontal Branch (BHB) stars, which may have formed from these Population II main-sequence stars, do show detectable rotation. This is probably due to their passing through a giant branch evolution where they have shed the outer layers of their atmosphere, exposing the inner layers which have retained their angular momentum. However even then their v sin i, are normally less than 30 km s $^{-1}$ (Peterson 1983).

Hence Population I OB-type stars are usually rapid rotators, with mean v sin $i > 100$ km s^{-1}, while Population II objects (which include BHB stars) have values less than 50 km s^{-1} (Peterson 1993; Peterson et al. 1995; Cohen & McCarthy 1997). The evolutionary status of a sample of high latitude stars can therefore be inferred from an investigation of their projected rotational velocity distribution. Here we present measurements of v sin i for a group of stars, which are believed to be normal B-type stars with V $<$ 14, taken from the Edinburgh-Cape Survey of Stobie et al. (1997).

2. Observations and data reduction

2.1. Target selection

The Edinburgh-Cape Survey aims to detect all blue objects ($U-B \lesssim$ –0.04) brighter than B $\approx$ 16.5 at Galactic latitudes $|b| > 30$ ° and with declinations south of $\delta \sim$ –13°. Table 1 lists the programme stars along with their UBV photometry, taken from the source references cited in the table. As the Survey is still ongoing, there are some stars, indicated in Table 1, which have been taken from fields not yet completed in the Survey. However, there is no reason to believe that the stars presented here are not representative of the sample as a whole. In addition, high resolution spectroscopy has confirmed that three of the programme stars are subdwarf B-type stars and these have been

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Table 1. Observational details of the programme stars

Star	l°	b°	V	$(B-V)$	$(U-B)$	Ref[a]
EC 00321-6320	306.22	-53.96	9.30	-0.15	-0.60	2
EC 00358-1516	108.16	-77.49	10.88	-0.20	-0.78	3
EC 00468-5622	303.63	-61.03	10.35	-0.17	-0.65	3
EC 01483-6804	294.73	-48.36	11.13	-0.16	-0.77	3
EC 03240-6229	278.05	-46.71	11.12	-0.09	-0.31	1
EC 03462-5813	270.68	-46.53	9.95	-0.12	-0.47	1
EC 04067-2957*	228.61	-46.88	12.27	-0.12	-0.48	3
EC 04420-1908	217.44	-36.30	13.14	-0.07	-0.49	3
EC 04460-3215	233.72	-39.00	11.67	+0.05	-0.44	1
EC 05229-6058†	269.97	-34.08	11.20	-0.19	-0.91	1
EC 05438-4741	254.39	-30.53	12.66	-0.08	-0.42	3
EC 05490-4510	251.72	-29.22	10.57	-0.12	-0.63	3
EC 05515-6107	270.08	-30.61	11.19	-0.19	-0.86	1
EC 05582-5816	266.84	-29.61	9.48	-0.16	-0.67	3
EC 06387-8045	292.58	-27.43	11.02	-0.02	-0.73	2
EC 12235-3202	296.76	30.25	9.35	-0.15	-0.81	3
EC 19071-7643	317.98	-27.65	10.23	-0.16	-0.79	2
EC 19476-4109	358.72	-28.17	10.23	-0.15	-0.67	3
EC 19489-5641	341.10	-30.71	13.72	-0.16	-0.83	3
EC 19490-7708	317.37	-29.99	12.86	-0.02	-0.48	1
EC 19563-7205*	323.11	-31.13	12.95	-0.14	-0.83	3
EC 19584-4727	351.99	-31.22	10.80	-0.11	-0.50	3
EC 19586-3823	2.33	-29.61	10.77	-0.14	-0.73	3
EC 20011-5005	348.97	-31.97	13.87	-0.11	-0.56	3
EC 20089-5659	340.84	-33.45	8.68	-0.10	-0.46	3
EC 20104-2944	12.68	-29.78	12.90	-0.05	-0.51	3
EC 20140-6935*	325.78	-32.93	8.85	-0.05	-0.82	3
EC 20153-6731*	328.19	-33.37	10.81	-0.12	-0.53	3
EC 20252-3137	11.54	-33.33	10.32	-0.14	-0.85	1
EC 20292-2414	20.27	-32.14	9.21	-0.18	-0.90	1
EC 20411-2703‡	17.95	-35.51	11.42	-0.05	-0.58	1
EC 20419-7535*	318.23	-33.38	11.40	-0.09	-0.57	3
EC 20485-2420	21.76	-36.35	11.78	-0.15	-0.73	1
EC 21313-7301*	319.23	-37.50	12.40	-0.22	-0.93	2
EC 21435-7634*	315.01	-36.15	12.07	-0.11	-0.92	2
EC 23029-7809*	309.66	-37.84	13.69	-0.08	-0.78	3
EC 23073-6905	315.67	-45.73	12.95	-0.23	-0.93	2
EC 23169-2235	40.89	-68.63	12.22	-0.13	-0.56	1

[a] References: 1) Kilkenny et al. 1991. 2) Kilkenny et al. 1995. 3) Previously unpublished SAAO results.
† possible post-AGB star ‡ possible extended horizontal branch object * taken from an incomplete field

excluded from the distribution of rotational velocities along with one additional star, EC 04460-3215, which has been reclassified as A3/HBA.

2.2. Observations

Spectroscopic observations were obtained with the 1.9m telescope at the South African Astronomical Observatory (SAAO) between 6-13 September 1994 and 24 October-1 November 1995. A Reticon photon counting system (RPCS) was used as a detector along with a 830 lines mm^{-1} grating, giving spectra with a dispersion of 30 Å mm^{-1} and a full-width-half-maximum resolution of approximately 1 Å, covering the wavelength region from 3800 Å to 4500 Å. Flat field exposures were taken at the beginning and end of each night, and Copper-Argon arc exposures were interleaved with the stellar frames to provide a wavelength calibration.

2.3. Data reduction

The spectra were reduced using the STARLINK packages FIGARO (Shortridge et al. 1997) and DIPSO (Howarth et al. 1996). The spectra were flatfielded, wavelength calibrated and sky backgrounds were removed. Due to a small shift between the two channels of the detector it was necessary to wavelength calibrate them independently. Low-order polynomials were fitted to features in the arc spectra which gave wavelength calibrations with RMS residuals of less than 0.06 Å. Spectra were shifted to the dynamical standard of rest (Mihalas & Binney 1981), cross correlated to ensure no wavelength shifts between exposures and

Table 2. Stellar parameters

Star	$T_{\rm eff}$ (K)	log g	$v_{\rm LSR}$(km s^{-1}) Previous	$v_{\rm LSR}$(km s^{-1}) Measured	Spectral Type		v sin i (km s^{-1})	No. of Lines Measured	Ref[a]
EC 00321-6320	16000	3.0	-23	-21	B5		100±40	3	2
EC 00358-1516				87	B2(He?)		60±30	3	4
EC 00468-5622				1	B3		180±50	2	4
EC 01483-6804				61	B2		0±30	4	4
EC 03240-6229‡	12000	3.8	37,-17	-45	B7/HBB	CPD-62 272	130±30	2	1,3
EC 03462-5813‡	13500	4.2	-29,24	-23	B6/HBB	HD 24101	220±50	2	1,3
EC 04067-2957				44	Mid B		0±30	2	4
EC 04420-1908				76	B6/HBB		250±50	2	4
EC 04460-3215			-31	-17	A3/HBA		—	–	1
EC 05229-6058	24500	3.7	12	17	B2	CPD-61 455	0±30	3	3
EC 05438-4741	13500	4.1	37	23	B6/HBB		60±30	2	3
EC 05490-4510	17000	4.2	16	12	B3		40±30	4	3
EC 05515-6107	22000	4.0	91,75	82	B2		250±50	2	1,3
EC 05582-5816	17000	4.0	66	51	B3	CPD-58 600	260±50	2	3
EC 06387-8045	22500	3.9	55,49	43	B3	CPD-80 190	220±50	2	2,3
EC 12235-3202				-64	B		150±50	1	4
EC 19071-7643	22000	3.8		-25	B2		0±30	3	2
EC 19476-4109				-16	B2		70±30	3	4
EC 19489-5641				9	B2(He?)		0±30	1	4
EC 19490-7708			-31	-31	HBB/B8		160±50	1	1
EC 19563-7205				-10	sdB		—	–	3
EC 19584-4727				38	Late B/HBB		140±40	2	4
EC 19586-3823				-164	B2		170±30	4	4
EC 20011-5005				-210	B7		70±30	2	4
EC 20089-5659				-70	B7		100±30	1	4
EC 20104-2944	15000	4.0	131	139	B5		0±30	2	1
EC 20140-6935‡	20500	3.7	0	-45	B2	HD 192273	30±30	4	3
EC 20153-6731	14500	3.8	-39	-45	B5		150±50	3	3
EC 20252-3137			26	29	B2		40±30	4	1
EC 20292-2414	25000	4.1	24,8	8	B2	HD 195455	200±50	4	1,3
EC 20411-2703	16500	4.8	39	18	B4		0±30	4	3
EC 20419-7535				-75	B5e		250±50	1	4
EC 20485-2420			-28	-40	B3		0±30	4	1
EC 21313-7301	25000	5.0	-12	18	sdB		—	–	2
EC 21435-7634	30000	5.0	-20	-13	B2He		120±50	2	2
EC 23029-7809				14	B3/sdB?		170±30	1	4
EC 23073-6905	27000	5.0		23	sdB		—	–	2
EC 23169-2235‡	15000	4.4	105,79	62	B4	PHL 460	190±40	4	1,3

[a] References: 1) Kilkenny et al. 1991. 2) Kilkenny et al. 1995. 3) Rolleston et al. 1997 (and references therein). 4) Previously unpublished SAAO results.

‡ possible binary systems

then co-added and normalised by selecting continuum regions that were believed to be free from absorption lines and fitting low order polynomials. The effect of instrumental broadening on the absorption lines was determined from a measure of the FWHM of the copper-argon arc lines in the calibration spectra.

3. Measurement of projected rotational velocity

Projected rotational velocities were determined from a comparison of the observed stellar absorption lines of neutral helium with unbroadened theoretical line profiles generated using model atmosphere codes based on the fully line blanketed Local Thermodynamic Equilibrium (LTE) model atmosphere calculations of Kurucz (1991). Effective temperatures and surface gravities had been previously only estimated for approximately 50% of the programme stars. The calibration of Napiwotzki et al. (1993) was applied to the reddening free Strömgren indices to obtain the effective temperatures. The surface gravities were obtained from the Hγ profiles as outlined in the references cited in Table 2. Numerical experiments showed that rotational broadening in the wings of the Hγ profiles is unlikely to result in significant errors. Also listed in this table are the estimated stellar spectral types and both the observed radial velocities, measured relative to the Local Standard of Rest, $v_{\rm LSR}$, and previously measured values taken from the references cited in the table.

There was insufficient Strömgren photometry available to determine temperatures and gravities for the remainder of the stars using methods such as those described in Kilkenny et al. (1991). For these stars model atmospheres with effective temperatures and logarithmic gravities comparable with the estimated spectral types were chosen. Where the spectral type was uncertain, a standard model atmosphere with an effective temperature of 22 000 K and logarithmic gravity of 4.0 was adopted. The validity of this approach was tested by generating theoretical line profiles for individual helium lines for a range of effective temperatures and surface gravities. A comparison of these profiles indicated that, for virtually all the helium lines considered, differing temperatures and gravities did not affect the general shape of the line significantly. One exception was the He I line at 4009 Å which has particularly gravity sensitive wings, and it was therefore considered unsuitable for this work.

For each programme star, suitably strong He I lines were selected and theoretical profiles with the observed equivalent widths generated. The projected rotational velocity was then estimated by convolving theoretical spectra (including instrumental broadening) with a rotational broadening function (Lennon et al. 1991) until a good match with the observed line profiles was achieved by eye. This broadening function is based on the formulae given by Gray (1976) and assumes a constant limb darkening coefficient of 1.5. A more rigorous approach would be to calculate the emergent intensity at many points on the stellar surface and integrate to obtain the flux, thus automatically taking account of center to limb variations. However the quality of the observational data does not warrant using such a sophisticated approach, or indeed the use of quantitative fitting procedures, as the errors involved would not be significantly reduced.

Fig. 1 shows a range of plots showing the match between the observed profiles and artificially broadened theoretical profiles. These plots have been chosen to illustrate the range in the quality of the observational data.

As many He I lines as possible were fitted to derive values of $v \sin i$ for each star and the simple averages are listed in Table 2, along with their standard errors and number of lines fitted. In addition for stars whose effective temperatures and gravities were known a further measurement of $v \sin i$ was made using the standard theoretical profile. These second sets of measurements did not differ significantly from the previously measured values, supporting the use of a standard profile where no atmospheric parameters were available.

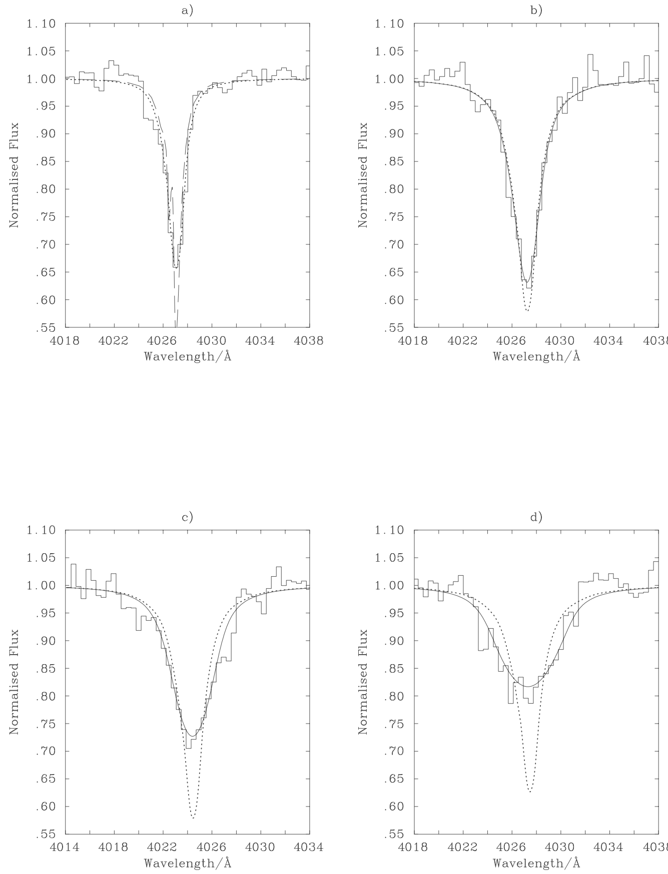

Fig. 1a–d. Examples of fits between artificially broadened theoretical profiles (solid line) and observed stellar spectra. A lso shown are the theoretical profiles with only instrumental broadening applied (dotted line). For plot **a** (EC 01483-6804) has $v \sin i$ = 0 km s^{-1} the dashed line represents the theoretical profile before instrumental broadening had been applied. The other plots are: **b** EC 00358-1516 has $v \sin i$ = 60 km s^{-1}. **c** EC 19586-3823 has $v \sin i$ = 180 km s^{-1}. **d** EC 05582-5816 has $v \sin i$ = 260 km s^{-1}.

4. Results and analysis

Since the early work of Kreiken (1935), it has been known that the components of binary systems have significantly smaller rotational velocities than single stars of the same spectral type. Furthermore, Swings (1936) found that this rotation tends to be synchronised with the orbital motion. In addition, Guthrie (1982) has found evidence of a bimodal distribution of $v \sin i$ for late B-type stars in open clusters and associations, although he has not found a similar trend for early B-type stars (Guthrie 1984).

The radial velocities listed in Table 2 have been used to identify possible binary systems. These measurements were made at various times using different data sets and as a result even single stars may show some small differences in their radial velocities. However, there are 4 stars whose $v_{\rm LSR}$ differs by more than 30 km s^{-1}, indicating these stars may be in binary systems.

Fig. 2. presents the distribution of projected rotational velocities for the programme stars, excluding those classified as sdB and the A-type star EC 04460-3215. As can be seen the possible binary stars are uniformly distributed over the range of $v \sin i$ values and therefore their removal does not significantly affect the shape of the distribution. It should be noted, however, that there are a number of programme stars for which no previous measurements of radial velocity have been made and we are therefore unable to estimate how many additional binary stars the sample may contain.

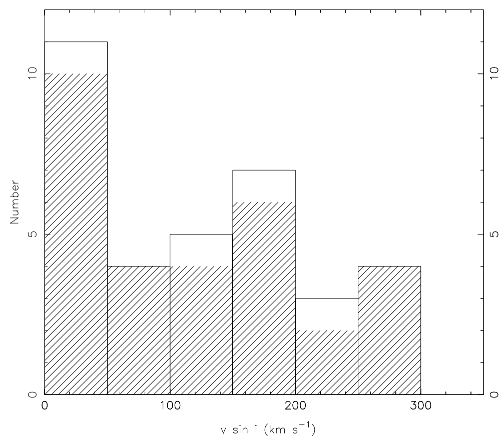

Fig. 2. Distribution of projected rotational velocities for the sample of high latitude programme stars - the hatched region represents the distribution with possible binary stars removed

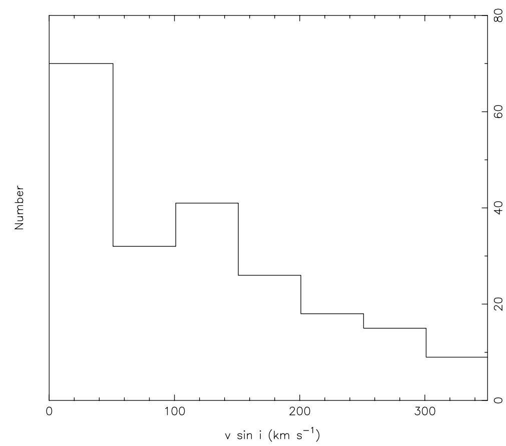

Fig. 3. Distribution of projected rotational velocities for the comparison sample of normal early B-type stars (Wolff et al 1982)

In order to determine the evolutionary status of the programme stars, and estimate the fraction of evolved stars the sample may contain, a standard distribution for normal B-type stars is required. The sample of stars compiled by Wolff et al. (1982) seems suitable for this purpose as it consists of 70 % of all stars of spectral type B0 to B5 and luminosity classes III to V in the Catalogue of Bright Stars (Hoffleit 1964). This sample was revised to include only field stars that were believed not to be in binary systems and the resulting distribution of 211 stars is presented in Fig. 3.

Both of the distributions show a maximum for v sin $i \leq 50$ km s^{-1}, which then decreases for higher rotational velocities. A comparison of these distributions with distributions of v sin i for evolved stars, such as those presented by De Medeiros et al. (1996), show significant differences. The distributions for evolved stars show the majority of stars rotating with v sin $i \leq$ 50 km s^{-1} and very few rotating faster than this.

A significant number of slowly rotating stars are to be expected in both the Wolff et al. sample and the programme stars, due to the assumption that the spin axes of stars in both samples are orientated randomly and hence some fast rotators will be observed pole-on. However, Wolff et al. (1982) and Guthrie (1984) have both detected an excess of slow rotators within the distribution for early B-type field stars. One possible explanation for this is that some early B-type stars are a result of the dispersal of associations (Guthrie 1984) with intrinsically low rotational velocities.

Kolmogorov-Smirnov (Kennedy & Neville 1986) and Mann-Whitney (Conover 1971) two-tailed tests were applied to test the similarity of our modified distribution from the Wolff et al. (1982) sample to the observed distribution for the high latitude stars. Both tests indicated that there was no difference between the two distributions to a level of significance of greater than 20 %. An estimate of the number of evolved stars that may be present in our sample was obtained by progressively increasing the number of slow rotators in the Wolff et al. sample and comparing it with the observed halo star distribution. A Kolmogorov-Smirnov test was applied and the distributions were found to be significantly different when an additional 20 % of slow rotators had been added. Hence it is possible that our sample may contain up to 20 % of evolved stars.

5. Discussion

The distribution of projected rotational velocities for the high latitude stars has been found not to be significantly different from that of normal Population I B-type stars in the disk of the Galaxy. Within the statistical uncertainties, however, the sample may contain up to 20 % evolved stars which would appear as very slow rotators. It appears evident, therefore, that the sample on the whole is comparable with young Population I objects found in the Galactic disk.

There are two possible explanations for the presence of Population I stars in the halo; they either i) formed in the disk and were ejected up into the halo or ii) they were actually formed in the halo itself. For the former, several ejection mechanisms have been suggested, including:

a). *Supernova Ejection Scenario*; this involves the supernova explosion of the primary star in a massive close binary system (Blaauw 1961). For spherically symmetrical supernova explosions the system is not expected to be disrupted and the complete binary system is ejected from its original position.

b). *Dynamical Ejection Scenario*; this involves ejection of stars from young stellar clusters via strong dynamical interactions involving close binaries (Poveda et al. 1967). Here two high velocity single runaways may be ejected along with an intact binary (Leonard 1990). Extensive numerical solutions by Leonard (1990) and Leonard & Duncan (1990) have shown that binary-binary interactions in even young, low density clusters can eject stars with velocities of the order of 200 km s^{-1} and occasionally much higher.

Blaauw (1993) found that while the majority of non-runaway OB-type stars had v sin i between 0 and 150 km s^{-1} and helium abundances between 0.04 and 0.13 dex, their runaway counterparts had values lying outside these ranges i.e. v sin i up to 350 km s^{-1} and helium abundances of up to 0.20 dex. He attributed these properties to the mass transfer to the secondary star which occurs in the supernova scenario. However, Leonard (1995) suggests that higher than average rotational velocities and enhanced helium abundances are not solely a characteristic of runaways produced by the supernova ejection method. A number of dynamically ejected merged runaway stars may also exhibit these properties, although in general their ejection velocities are lower than for unmerged stars. Merged stars may be formed during the physical stellar collisions which can occur during the binary-binary collisions that produce dynamically ejected runaway stars. The interiors of these merged stars are well mixed and material from the core is diluted with hydrogen rich material in the outer layers, effectively resetting their nuclear clocks (Benz & Hills 1987).

It would therefore appear that a simple measure of the projected rotational velocity of a runaway star is insufficient to determine the ejection method responsible for the star's presence far from the Galactic plane. However, we note that the radial velocity measurements would appear to indicate that few of the stars are in binary systems. For example, of the 34 stars in Table 1 for which previous radial velocity measurements are available only 4 stars show significant differences (≥ 30 km s^{-1}) between these velocities and those determined by us, indicating possible binarity. As the Blaauw (1961) supernova ejection scenario predicts that the binary system is not disrupted, the presence of few possible binaries in our sample may provide some evidence against this ejection mechanism. It would be advantageous however, if radial velocities were obtained for the remainder of the stars in Table 1 to determine the number of binaries in the sample as a whole.

6. Conclusions

The distribution of projected rotational velocities for the sample of high latitude stars implies that the sample as a whole is comparable with young Population I stars. A measure of the projected rotational velocity does not in itself conclusively discriminate between ejection mechanisms which may be responsible for removing a star from its place of formation in the disk. However, the radial velocities of the stars indicate that few are in binary systems, which may argue against the supernova ejection hypothesis.

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