HD 69686: A MYSTERIOUS HIGH VELOCITY B STAR

WENJIN HUANG1, D. R. GIES2, AND M. V. MCSWAIN3
1 Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195-1580, USA; hwenjin@astro.washington.edu
2 Center for High Angular Resolution Astronomy, Department of Physics and Astronomy, Georgia State University, P.O. Box 4106, Atlanta, GA 30302-4106, USA; gies@chara.gsu.edu
3 Department of Physics, Lehigh University, 16 Memorial Drive East, Bethlehem, PA 18015, USA; mcswain@lehigh.edu
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ABSTRACT
We report on the discovery of a high velocity B star, HD 69686. We estimate its space velocity, distance, surface temperature, gravity, and age. With these data, we are able to reconstruct the trajectory of the star and to trace it back to its birthplace. We use evolutionary tracks for single stars to estimate that HD 69686 was born 73 Myr ago in the outer part of our Galaxy (r ∼ 12 kpc) at a position well below the Galactic plane (z ∼ −1.8 kpc), a very unusual birthplace for a B star. Along the star’s projected path in the sky, we also find about 12 other stars having similar proper motions, and their photometry data suggest that they are located at the same distance as HD 69686 and probably have the same age. We speculate on the origin of this group by star formation in a high velocity cloud or as a Galactic merger fragment.

Key words: line: profiles – stars: early-type – stars: fundamental parameters – stars: individual (HD 69686) – stars: rotation

1. INTRODUCTION

The objects in the solar neighborhood with high peculiar velocities can always be placed into one of two categories: the disk-origin or non-disk origin. The normal, young, disk stars in the solar neighborhood share the same circular motion with the Sun, and have small velocity residuals in a Gaussian distribution with a standard deviation of 10−16 km s−1 (Gies & Bolton 1986, and references therein). The disk-origin high velocity stars are the objects whose peculiar velocities are far beyond the velocity dispersion of normal disk stars. They are often called runaway stars because the high peculiar velocities of these stars are thought to be caused by two possible mechanisms: (1) supernova (SN) explosion in a binary system (Zwicky 1957; Blaauw 1961) or (2) strong gravitational interaction in a multiple star system that often occurs in a dynamically chaotic, young, dense stellar cluster environment (Poveda et al. 1967; Leonard & Duncan 1988; Gaburov et al. 2008). Previous studies of runaway stars show that both mechanisms generate runaway objects, but an early systematic survey by Gies & Bolton (1986) suggests that the second mechanism is dominant. On the other hand, most of the non-disk-origin, high velocity objects in the solar neighborhood are thought to belong to the old halo population. The halo stars have high peculiar velocities because they do not follow the circular motion of the normal disk stars but move in their own very diverse orbits. Because of the significant difference in the ages of high velocity stars associated with these two origins, the runaway, disk origin is generally assumed for young objects such as high velocity B stars. However, in this paper, we discuss the unusual case of a nearby, high velocity B-star, HD 69686, and we argue that it may have been born far from the Galactic disk.

We currently make a spectroscopic survey of field B stars to study the evolution of stellar rotation. One of our targets, HD 69686, was selected because it is fairly bright (V ∼ 7.1) and is classified as a B8 star in the Smithsonian Astrophysical Observatory (SAO) star catalog. In this paper, we present what we have learned about HD 69686. At the time of writing, the target’s listing in the SIMBAD database includes only very basic astrometry and photometry data and no published references. After measuring radial velocities of our program stars, HD 69686 was immediately singled out by having the largest radial velocity, 148 km s−1, among our sample B stars. It was only after this that we noted that this star also has quite a large proper motion (μa cos δ = −86.17 ± 0.67 mas yr−1, μδ = 7.21 ± 0.42 mas yr−1, from the newly released Hipparcos remeasurements by van Leeuwen 2007). Thus, HD 69686 is a previously unknown high velocity B star. How old is this star now? Is it a runaway star? Where did it come from? Is it a binary system? These are the kind of questions that we want to answer.

In the following section, we briefly describe the instrumental setup and how we obtained the final spectra of HD 69686. In Section 3, we present the details of the procedure we used to determine the key parameters, such as the space velocity, the effective temperature, gravity, and age of the star. In Section 4, we use a modern Galactic potential model to reconstruct the full trajectory of HD 69686 that helps us to locate its birthplace and leads us to suggest that HD 69686 might not be a runaway star as we thought previously. In the final section, we provide additional evidence implying that HD 69686 may have been born in the Galactic halo.

2. OBSERVATION

The spectra of HD 69686 were obtained on the 2.1 m telescope at Kitt Peak National Observatory (KPNO) using the Goldcam spectrograph (with a 3072 × 1024 CCD detector, T3KC) on 2008 November 17 and 18. The spectrograph grating (G47, 831 lines mm−1) was used in second order with a CuSO4 blocking filter, and this arrangement provided a spectrum coverage of about 900 Å around the central wavelength of 4400 Å. The slit width was set at 1′′, leading to a resolving power R ∼ 2400 (FWHM ∼ 1.83 Å, measured in the comparison spectra). The integration time for HD 69686 was 55 s yielding spectra with S/N ∼ 280 in the continuum regions. During the entire observing run, we took comparison (HeNeAr lamp) exposures for each of our program stars, including HD 69686, to ensure accurate wavelength calibration of the spectra. The accuracy of wavelength calibration is estimated to be around...
6 km s\(^{-1}\) in velocity space by checking the wavelength fitting residuals of the comparison spectra and by comparing multi-night spectra of all our program stars that are not spectroscopic binaries. We obtained the final reduced spectra by going through the standard IRAF\(^4\) CCD image reduction (subtracted the bias level, divided the flat images, removed cosmic rays, and fixed the bad pixels/columns) and the long-slit stellar spectrum extraction procedures (traced and binned the spectrum, calibrated wavelength).

3. STELLAR PARAMETERS

The procedure to determine the physical parameters of HD 69686 is similar to that used in our previous studies of cluster B stars (Huang & Gies 2006a, 2006b). The \(V\) \(\sin i\) value was derived by fitting synthetic model profiles of \(\text{He}\ \lambda\,4471\) and \(\text{Mg}\ \text{II} \lambda\,4481\), using realistic physical models of rotating stars (considering Roche geometry and gravity darkening). The details of this step are described in Huang & Gies (2006a). The best fit of \(\text{He}\ \lambda\,4471\) is illustrated in Figure 1. With \(V\ \sin i\) at hand, we then determined both the effective temperature \((T_{\text{eff}})\) and gravity \((\log g)\) of the star by fitting the \(\text{H}\gamma\) profile (see details in Huang & Gies 2006b). The best fit of the \(\text{H}\gamma\) profile is shown in Figure 2. By shifting the best-fit profiles in wavelength to match the observations, we also obtained an accurate radial velocity of each night’s spectrum. The radial velocities were transformed into the heliocentric frame by removing the orbital motion of the Earth (using the RVCORRECT function in IRAF), and these velocities are given in Table 1. We do not see any significant change in the radial velocity between the two nights that is larger than the errors (6 km s\(^{-1}\)). Even if HD 69686 were a long period, spectroscopic binary system, any orbital velocity variations will be small compared to its radial velocity. Thus, we adopted the mean of the radial velocities in Table 1 as the systemic radial velocity of HD 69686 for later analysis (Table 2).

For a rotating star such as HD 69686, the derived gravity \((\log g)\) represents an average of gravity over its visible hemisphere. It may not be a good indicator of the evolutionary status of the star because the effective gravity on the equatorial region is lowered by centrifugal force induced by stellar rotation. Instead, we use the gravity at the poles of the star \((\log g_{\text{polar}})\) to estimate the age of the star since the \(\log g_{\text{polar}}\) value is not significantly influenced by rotation. The method to estimate \(\log g_{\text{polar}}\) is described in Huang & Gies (2006b) and has been applied to many of our studies on the evolution of B stars (Huang & Gies 2008; McSwain et al. 2008). Based on our model simulation results (Huang & Gies 2006b), except for those extreme cases where the stars spin at or very close to the breakup velocity, the estimations of \(\log g_{\text{polar}}\) are quite accurate (the statistical errors are 0.03 dex or less).

We need one additional step to correct \(T_{\text{eff}}\) and \(\log g\) derived from the \(\text{H}\gamma\) fit. We noted that we had to use a model with

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\(^4\) http://iraf.noao.edu/
much higher temperature (16,200 K) to fit the He\textsc{i} 4471 line while our H\textsc{i}\textsc{r} line fit suggests that the effective temperature of HD 69686 should be around 14,500 K. This discrepancy implies that HD 69686 is a helium strong star. When we use models with solar abundances (H:He = 0.9:0.1) to synthesize the H\textsc{i} profile and to fit the observed spectrum of a He-peculiar star, we get systematic errors in the derived parameters (\(T_{\text{eff}}\) and log \(g\)).

The systematic errors can be corrected using the results given by Huang & Gies (2008) who used the same technique to determine the photospheric parameters. The correction procedure was done in an iterative manner. We first determine the He abundance using the derived \(T_{\text{eff}}\) and log \(g\) values, and then correct \(T_{\text{eff}}\) and log \(g\) based on the He abundance according to Table 3 of Huang & Gies (2008). We then determine the He abundance again with the updated \(T_{\text{eff}}\) and log \(g\) values, and repeat the steps until convergence is reached. At the end, we obtained the final corrected \(T_{\text{eff}}\) and log \(g\) (listed in Table 2) for HD 69686, with abundances typical of a He-strong star, with a number ratio of H:He = (0.82 ± 0.04):(0.18 ± 0.04).

The best available parallax and proper motion data of HD 69686 come from the Hipparcos catalogue (van Leeuwen 2007). However, the parallax measurement, 2.35 ± 0.58 mas (1\(\sigma\) range: 341–565 pcs), is still too uncertain to provide us with an accurate tangential velocity for tracing the star’s trajectory in space. We have to find an alternative method to determine the rotational velocity in space. We have to find an alternative method to obtain a reliable distance of the star. Our method is described as follows:

1. By comparing the derived \(T_{\text{eff}}\) and log \(g_{\text{polar}}\) of HD 69686 with evolutionary tracks of stellar models (Schaller et al. 1992), we can estimate its stellar mass; (2) we then can calculate the stellar radius from the mass and log \(g_{\text{polar}}\); (3) from the radius and surface temperature, we can calculate the true luminosity of the star (we considered a distorted shape of a rotating star in this step, see details below); (4) with the true luminosity and the \(V\) magnitude of the star, we can derive the distance for assumed values of extinction and bolometric correction.

The \(B - V\) color index from the Hipparcos/Tycho catalogue\(^5\) (ESA 1997) is \(-0.15 ± 0.01\), which is basically no different from the zero-reddening color of a star with a temperature of 14,800 K. Thus, we can safely set \(A_V = 0\) in the last step. The bolometric correction data we used here are from Balona (1994). Finally, we estimated the age of the star from its mass and polar gravity by comparing with the non-rotating theoretical models by Schaller et al. (1992). The whole procedure was also repeated with other denser model grids by Lejeune & Schaerer (2001), Demarque et al. (2004), and Marigo et al. (2008), and we found no noticeable difference in the derived parameters between these model grids. All the derived parameters are listed in Table 2.

Heger & Langer (2000), Meynet & Maeder (2000), and, more recently, Ekström et al. (2008) (EKS models, hereafter) have predicted that, due to rotationally induced mixing, fast rotating stars may evolve on main sequence (MS) tracks quite differently from non-rotating stars. Fresh hydrogen can be brought down to the core due to rotationally induced mixing and make rotating stars have a longer MS lifetime. To investigate the difference in ages between rotating and non-rotating stars, we calculated the ages of the rotating models with various spin rates at a fixed evolutionary status (at log \(g_{\text{polar}}\) = 4.04). We choose the 3 \(M_\odot\) model (the rotating model with mass closest to HD 69686) from EKS models. The results is given in Table 3. As expected, fast rotating stars evolve more slowly than slow- or non-rotating stars with the same mass in term of surface gravity at poles. As shown in Table 3, a very fast rotating star with \(\Omega/\Omega_{\text{crit}} = 0.9\) probably takes 20% more time than a non-rotating star to reach log \(g_{\text{polar}}\) = 4.04.

It is worthwhile noting that HD 69686 is a rotating star with a moderate \(V\) sin \(i\) value (= 141 km s\(^{-1}\)). Because of the centrifugal force on its surface, the projected disk of HD 69686 on the sky is not perfectly round, and the projected angular area is expected to be slightly larger than \(\pi R_{\text{polar}}^2/D^2\) (\(D\) is the distance) by a factor \(f\), which depends on the inclination angle \(i\). Because we do not know the exact value of the inclination angle, we can only estimate it by averaging all possible values of \(i\). The range of \(i\) is between \(\arcsin(V \sin i/V_{\text{crit}})\) and \(\pi/2\), where \(V_{\text{crit}}\) is the breakup velocity of the star (\(V_{\text{crit}}\) = 411 km s\(^{-1}\) for HD 69686). We found that the statistical mean of the acceptable inclination range is \(i = 60^\circ\). If we assume that HD 69686 (with \(M = 4.42 \, M_\odot\), log \(g_{\text{polar}}\) = 4.04, and, therefore, \(R_{\text{polar}} = 3.32 \, R_\odot\)) has an inclination of \(i = 60^\circ\), then we obtain \(R_{\text{eq}} = 3.51 \, R_\odot\) and \(f = 1.07\) from calculations based on simple Roche geometry. With estimates in hand for the effective temperature and gravity, we can compare the observed and model spectral energy distributions (SEDs) of the star to determine its angular size, and then use our estimate of its physical size to derive a second determination of distance. In Figure 3, we plot the optical/IR flux points that are converted from the \(B, V, I_C,\) and \(JHK_s\) magnitudes of the star and from the

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\(^5\) http://archive.ast.cam.ac.uk/hipp/hipparcos.html

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**Table 3**

| \(\Omega/\Omega_{\text{crit}}\) | Evolving Time (Myr) |
|-----------------------------|---------------------|
| 0.1                         | 244                 |
| 0.3                         | 262                 |
| 0.5                         | 269                 |
| 0.7                         | 275                 |
| 0.8                         | 279                 |
| 0.9                         | 281                 |

Notes.

\(a\) This table is based on the data of the rotating models of 3 \(M_\odot\) from Ekström et al. (2008).

\(b\) The time that a rotating model takes to evolve from zero-age main sequence (ZAMS) to log \(g_{\text{polar}} = 4.04\).

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**Figure 3.** Theoretical unreddened SED based on a Kurucz model (Castelli & Kurucz 2003) with \(T_{\text{eff}} = 14760\), log \(g = 3.93\), and an angular diameter of 0.085 ± 0.004 mas (limb darkened). The optical/IR (transformed from the \(B, V, I_C,\) and \(JHK_s\) magnitudes) and UV flux measurements are plotted as plus signs.
Meanwhile, the model star rotates faster and faster (increasing $f$ as the inclination angle goes lower, the factor gets bigger). Using the projected area at one inclination angle, we have also checked the projected area of the models on sky. We arrive at a distance of 377 ± 16 pc, which is fully consistent with the spectroscopic distance derived earlier.

We also apply our Hγ fit method to a set of realistic models of HD 69686 to investigate more closely the difference between the statistically estimated log $g_{\text{polar}}$ and the true values of log $g_{\text{polar}}$ for models at various inclination angles. The model star has a mass of 4.42 $M_\odot$. At different inclination angles, we synthesize the Hγ profiles by considering Roche geometry (controlled by both rotational and gravitational potential on the surface) and the gravity darkening effect ($T_{\text{local}} \propto g^{0.25}_{\text{polar}}$). We adjust $T_{\text{polar}}$ and $R_{\text{polar}}$ of the model stars for each inclination angle so that the measured values ($T_{\text{meas}}$ and log $g_{\text{meas}}$ from the Hγ fit) always equal the values given in Table 2. All results are given in Table 4, where we can see that the range of log $g_{\text{polar}}$, 4.04 ± 0.04, covers all inclination angles from $i = 90^\circ$ down to $i = 30^\circ$. Below $i = 30^\circ$ (i.e., $V_{\text{eq}} > 282$ km s$^{-1}$), the model star spins close to the critical speed (around $i = 20^\circ$). Because of low probability that the star rotates with higher $V_{\text{eq}}$ than the model stars, its age would be older than what its polar gravity implies because it rotates much faster than at a high inclination angle (see Table 3). In this numerical simulation, we have also checked the projected area of the models on sky. We found that the projected area of the models at all investigated inclination angles is basically the same (different within ±1%).

As the inclination angle goes lower, the $f$ factor gets bigger. Meanwhile, the model star rotates faster and faster (increasing $V_{\text{eq}}$). In order to keep the measured log $g$ constant, we have to lower the polar radius, $R_{\text{polar}}$. Thus, the net effect is that the projected area on the sky, $\pi R_{\text{polar}}^2/D^2$ multiplied by $f$, stays almost unchanged. In other words, it is safe to derive the distance using the projected area at one inclination angle. It should be noted that, as we derived the surface log $g$ of HD 69686 from the Hγ profile fit, we did not consider possible systematic errors in the synthesized profiles. Our synthesis code took the specific intensity profile data generated by SYNSPEC43,6 which uses the Vidal–Cooper–Smith theory (Vidal et al. 1973). If the systematic error causes an underestimation of surface gravity, log $g$, by 0.1 dex or more, HD 69686 might be younger than we estimate above, and could be born on the Galactic plane (see Section 4).

Many previous studies (Tobin & Kilkenny 1981; Saffer et al. 1997; Magee et al. 2001; Ramspeck et al. 2001a; Lynn et al. 2004; Martin 2004) have pointed out that some old evolved objects in the halo, lying on a post-horizontal branch (PHB) or a post-asymptotic giant branch (PAGB), could have similar atmospheric parameters (temperature and gravity) as young massive OB stars of population I. Could HD 69686 be an old PHB or PAGB halo object with the same $T_{\text{eff}}$ and log $g$ values listed in Table 2? One key difference between the old blue halo objects and the young OB disk stars is that the former have much lower mass (<1 $M_\odot$). If HD 69686 had a mass lower than $M_\odot$, then for its observed gravity, it would have a small radius and a distance of less than 180 pc, which would yield a parallax more than 5" higher than the Hipparcos parallax (2.35 ± 0.58 mas). Thus, we are confident that HD 69686 is a young, massive, main-sequence B star instead of an old blue halo star with similar atmospheric parameters.

4. TRACING BACKWARD TO THE BIRTHPLACE

Now we have very accurate information that we list in Table 2 about the position and the space velocity of HD 69686 (resolved into three orthogonal components relative to the Sun: the radial velocity $V_r$, and the tangential velocity in the directions of increasing right ascension $V_{\text{RA}}$ and declination $V_{\text{decl}}$ for epoch J2000). With the help of a properly selected Galactic potential model, we should be able to follow the motion of HD 69686 backward to its birthplace. Among the many Galactic models available in the literature, we decided to choose the axisymmetric model proposed by Dehnen & Binney (1998b) (their model 2, DB2 hereafter). Their model mass distribution was constructed to meet the constraints imposed by the high quality kinematical data that were available at that time. The gravitational acceleration is related to the potential by $\vec{a}(R, z) = -\nabla \Phi(R, z)$. We obtained both the potential and the acceleration data of the model in a format of three-dimensional grids in space (0.1 kpc per step in $R$ and 0.01 kpc per step in $z$), and we made a bilinear interpolation in this grid to determine the acceleration at each time step.

The star’s true space velocity in the Galactic potential field is its velocity relative to the local standard of rest (LSR, hereafter), $(U, V, W)$, plus the Galactic circular velocity of LSR, $(0, V_{\text{circ}}(R_0), 0)$. Here $R_0$ (= 8 kpc) is the Sun’s distance to the Galactic center (Reid 1993) and $V_{\text{circ}}(R_0) = 217$ km s$^{-1}$ is the circular velocity of DB2 at $R_0$ (very close to the IAU recommended value, 220 km s$^{-1}$).

In order to trace the star’s motion back in time, we use the reversed space velocity of HD 69686, $-(U, V + V_{\text{circ}}(R_0), W)$, as the initial velocity. The initial location of HD 69686 in the Galaxy is determined from its location relative to the Sun and the Galactic location of the Sun, 8 kpc away from the Galactic center (Reid 1993) and 8 pc above the Galactic plane (Holmberg et al. 1997). We calculated $\vec{a}(R, z)$ first, and then moved the star a very small step assuming that $\vec{a}(R, z)$ stays constant during this small move. We updated the star’s velocity and acceleration at the end of each step. Repeating this calculation until reaching the estimated age of the star (actually reaching

Table 4
Realistic Stellar Models at Different Inclination Angles

| Inclination (deg) | $T_{\text{polar}}$ (K) | $R_{\text{polar}}$ ($R_\odot$) | log $g_{\text{polar}}$ (dex) |
|------------------|------------------------|-------------------------------|---------------------|
| 90               | 15260                  | 3.52                          | 3.99                |
| 80               | 15270                  | 3.52                          | 3.99                |
| 70               | 15310                  | 3.50                          | 4.00                |
| 60               | 15370                  | 3.48                          | 4.00                |
| 50               | 15440                  | 3.43                          | 4.01                |
| 40               | 15525                  | 3.32                          | 4.04                |
| 30               | 16260                  | 3.13                          | 4.09                |
| 25               | 16960                  | 2.95                          | 4.14                |

Note. All models have the same stellar mass (= 4.42 $M_\odot$) and same $V \sin i$ (= 141 km s$^{-1}$). The parameters of the models in this table are prepared in such a way that when we apply our Hγ profile fit method to the synthesized Hγ profiles of these models, we obtain the same $T_{\text{meas}}$ (= 14.760 K) and log $g_{\text{meas}}$ (= 3.93).
to the zero age of the star because we move back in time), the integration follows the star back to its birthplace. The numerical errors of this integration depend on the size of each small step. We found that a step of 2 kyr is a good choice which results in only a very small difference (< 1 pc) from the integrated positions using a smaller step (1 kyr) over 80 Myr.

The reconstructed trajectory of HD 69686 is plotted in Figure 4 as a thick solid line. The dotted lines are those tracks that result by changing by 1 σ the space velocity component $V_{\odot}$ (with the dominant velocity error, 1σ = 8 km s$^{-1}$). Because of the very large peculiar velocity of HD 69686, it has a non-circular-orbital motion (the circular orbit of the Sun in the X–Y plane is plotted as a dashed line in Figure 4 for comparison). Currently, HD 69686 quickly passes through the solar neighborhood and moves away from the Galactic center ($U = -191$ km s$^{-1}$). When we first derived $U$, we suspected that this star might come from the very inner part of the Galaxy. After the full trajectory was reconstructed, we realized that HD 69686 has traveled a very long distance across the Galaxy before reaching its current location (see the top panel of Figure 4).

The birthplace of HD 69686 is located in the outer part of the Galaxy (about 12 kpc from the Galactic center and 4 kpc further out than the Sun). At its birth (73 Myr ago), HD 69686 was more than 10 kpc away from the Sun (compared to its current distance of 380 pc). About 26.6 Myr ago, HD 69686 reached its minimum distance from the Galactic center ($\approx 4.4$ kpc).

Martin (2006) studied more than 60 high Galactic latitude B stars and he suggested that all the young population I B stars in his sample are likely ejected from the Galactic plane. Magee et al. (2001) and Ramspeck et al. (2001b) found very similar results in their investigations of high-latitude blue objects. If the cause of the high peculiar velocity of HD 69686 is similar to other runaway OB stars, then its birthplace is expected to be in or very close to the Galactic plane because star formation activities are very rare at places far from the plane. However, our calculated trajectory suggests that HD 69686 is an exception. In the lower panel of Figure 4, HD 69686’s projected trajectory on the X–Z plane clearly shows that it was located well below the Galactic plane ($z \sim -1.8$ kpc) 73 Myr ago. Today, HD 69686 (only 150 pc above the Galactic plane) is on its way plunging into the Galactic plane ($W = -57$ km s$^{-1}$). Moving backward in time, it reached the highest position of its trajectory (860 pc above the Galactic plane) 19.5 Myr ago, and crossed the plane around 37 Myr ago, thanks to the stronger gravitational force in the z-direction in the inner part of the Galaxy. However, further back in time, HD 69686 was below the Galactic plane and further away from the Galactic center, and, therefore, it experienced a weaker $z$-force. The $z$-force was so weak that the star’s trajectory began 73 Myr ago at a position well below the plane ($z = -1.8$ kpc) and with a velocity approaching the plane ($W = +22$ km s$^{-1}$). The errors in the velocity components and the age estimation of HD 69686 are not large enough to make the range of its possible birthplace extend to the Galactic plane.

The reconstructed trajectory of HD 69686 implies that HD 69686 might be born in a location with a particularly low density (1.8 kpc below the Galactic plane and 12 kpc away from the Galactic center), where star formation activity is expected to be very rare. Of course, we assume here that HD 69686 is a single-star system. Though our two consecutive night observations do not display any variation in radial velocity above the noise level, we cannot completely rule out the possibility that HD 69686 is a binary system with a longer period (>10 days). The mass-transfer events that often occur in close binary systems could totally invalidate our age estimation based on single-star evolutionary tracks. If HD 69686 is in a binary system and was ejected from the Galactic plane due to the SN explosion of its companion, the explosion occurred most likely about 37 Myr ago when HD 69686 was crossing the Galactic plane. The coordinates of the crossing position are $(x, y, z) = (2919, -4477, 0)$ pc, and the space velocity of HD 69686 at that moment is $(V_x, V_y, V_z) = (-326.2, -24.4, 84)$ km s$^{-1}$ while the Galactic circular velocity at that location is $V_c = (181.8, -118.5, 0)$ km s$^{-1}$ (using DB2). Then we can calculate HD 69686’s peculiar velocity (i.e., ejection velocity) at that location, which is 192 km s$^{-1}$. Nelemans et al. (1999) investigated the relation between the ejection velocity, the mass loss during the SN explosion, and the current binary period. For HD 69686 with a long period (>10 days) and a very high ejection velocity (192 km s$^{-1}$), Equation (7) in Nelemans et al. (1999) suggests a very large SN mass loss (>10 $M_\odot$), which is large for a binary containing a late B-type star. Although the over-solar abundance of helium on HD 69686’s surface could be a result of past mass transfer in a close binary, it is not the only explanation because helium-poor (both rich and poor) stars are quite common among young late B (single) stars (Huang & Gies 2006b). Also, as described in the following paragraphs, we found evidence indicating that HD 69686 seems to belong to a co-moving cluster that naturally explains its high peculiar velocity. All of these arguments suggest that HD 69686 does not belong to a binary system, and we can estimate its age using single-star evolutionary tracks.

Much effort has been invested in searching for young massive stars forming in situ in the halo (Ivezić & Christodoulou 1997; Lynn et al. 2002, 2004; Martin 2004, 2006). Most of the blue halo objects examined in these studies are either ejected disk stars or old evolved stars (PHB or PAGB). Only a few stars are possible candidates of massive star formation in the halo. de la Fuente Marcos & de la Fuente Marcos (2008, and references therein) summarized the observational evidence of star formation far from the Galactic plane. One possible mechanism that can trigger star formation at such an unusual place...
is a collision between high velocity clouds (HVCs) and/or Galactic accretion fragments (or tidal streams). Dyson & Hartquist (1983) proposed that early type star formation can be triggered by “cloudlet–cloudlet collisions occurring every 10^8 yr” in any particular high Galactic latitude cloud, and the formation rate could be 10^3 early type stars every 10^8 yr in the halo. Later, Christodoulou et al. (1997) suggested that the collisions between cloudlets within HVCs may occur less frequently than previously thought, and they derive a much lower star formation rate from the observational data. More recently, another mechanism of star formation in the halo was proposed by de la Fuente Marcos & de la Fuente Marcos (2008), that is, the tidal force of a passing massive cluster (such as a globular cluster) can trigger star formation in high Galactic latitude clouds. Though the proposed mechanisms are different, they all suggest a common scenario that a group of stars should be formed together in situ in the halo. If this indeed is the case for HD 69686, we expect to see a group of stars that share the same space velocity with and have the same age of HD 69686. Finding such co-moving stars would provide strong evidence to support their formation in situ in the halo.

Because HD 69686 has traveled a very long distance in 73 Myr, it is expected that the co-forming stars, if they exist, would spread into a much larger space around the current position of HD 69686 due to the velocity dispersion in the original cluster. A dispersion of 10 km s^{-1} in original space velocity would cause the co-forming group spread into a volume of 750^3 pc^3, that is, spread all over the sky as seen from the Sun. To make the search viable, we limit our search range to the vicinity of the trajectory of HD 69686. Thus, our search will detect only a very small fraction of any co-moving stars whose space velocities are similar to that of HD 69686.

To carry out this kind of search, we first need the projected trajectory of HD 69686 on the sky. Any co-moving objects are expected to be on or around this baseline and to have similar proper motions and radial velocities to the values of the nearest point on the trajectory. We calculated the projected positions of HD 69686’s trajectory on the sky every 0.05 Myr between 0.5 Myr in the past and 0.5 Myr in the future. The results are given in Table 5 and plotted in Figure 5. We used the Catalogue of Stars with High-Proper Motions (V2) by Ivanov (2008) to search for similar high proper motion stars. The search region (about 2° around the trajectory) is indicated as a shadowed area in Figure 5. We found a total of 26 stars (including HD 69686) from roughly 2000 high proper motion stars (>40 mas yr^{-1}) in the search region. Their proper motions (in both R.A. and decl. directions) have differences of 15 mas yr^{-1} or less from the reference points on the trajectory of HD 69686. All 25 stars other than HD 69686 are plotted in Figure 5 as open or filled circles with their proper motions indicated by line segments.

Note that the proper motions illustrated in Figure 5 are not aligned with the projected trajectory (HD 69686 seems to move away from its own trajectory). The trajectory of HD 69686 in space (Figure 4) is a curve in the Galactic potential field that differs from circular motion. In order to find the co-moving stars that move on a similar trajectory, we need to project the whole trajectory on the current sky. This means that both the past and future parts of the trajectory of HD 69686 have to be projected on the present sky. However, HD 69686’s proper motion is related to projected positions on the sky at different moments, that is, the past-time positions on the past-time sky and the future positions on the future sky. This is different from their position in the present sky (the solid line in Figure 5) because of the Sun’s orbital motion in the Galaxy. As the Sun (and Earth) moves at ∼220 km s^{-1} around the Galactic center, the projected trajectory of HD 69686 (the solid line) will move downward (and slightly to the left) in Figure 5 (in the reverse direction of the solar circular motion, which is approximately parallel to Galactic latitude). Thus, although HD 69686 seems to carry out this kind of search, we first need the projected trajectory of HD 69686 on the sky as a baseline. Any co-moving objects are expected to be on or around this baseline and to have similar proper motions and radial velocities to the values of the nearest point on the trajectory.

Table 5: Projected Trajectory of HD 69686 on the Sky

| Time (Myr) | R.A. (J2000) | Decl. (J2000) | μ_x cos δ (mas yr^{-1}) | μ_y (mas yr^{-1}) | V_r (km s^{-1}) | Dist. (pc) |
|------------|-------------|-------------|-------------------------|------------------|----------------|-------------|
| -0.50      | 09 12 58.4  | -06 18 28   | -101.0                  | 26.7             | 100            | 389         |
| -0.45      | 09 07 41.2  | -04 49 00   | -100.3                  | 25.6             | 100            | 386         |
| -0.40      | 09 02 21.0  | -03 18 07   | -99.5                   | 24.3             | 111            | 384         |
| -0.35      | 08 56 57.9  | -01 46 02   | -98.5                   | 22.7             | 116            | 381         |
| -0.30      | 08 51 32.2  | 00 13 00    | -97.3                   | 21.0             | 121            | 380         |
| -0.25      | 08 46 04.3  | +01 20 41   | -95.9                   | 19.1             | 126            | 378         |
| -0.20      | 08 40 34.5  | +02 54 47   | -94.3                   | 17.0             | 131            | 378         |
| -0.15      | 08 35 03.2  | +04 28 57   | -92.5                   | 14.7             | 135            | 377         |
| -0.10      | 08 29 30.5  | +06 02 56   | -90.6                   | 12.3             | 140            | 378         |
| -0.05      | 08 23 57.0  | +07 36 24   | -88.5                   | 9.8              | 144            | 378         |
| 0.00       | 08 18 23.0  | +09 09 05   | -86.2                   | 7.2              | 148            | 380         |
| 0.05       | 08 12 48.8  | +10 40 41   | -83.8                   | 4.6              | 152            | 381         |
| 0.10       | 08 07 14.9  | +12 10 59   | -81.3                   | 1.8              | 155            | 383         |
| 0.15       | 08 01 41.5  | +13 39 41   | -78.7                   | -0.9             | 158            | 386         |
| 0.20       | 07 56 09.0  | +15 06 37   | -75.9                   | -3.6             | 161            | 389         |
| 0.25       | 07 50 37.8  | +16 31 33   | -73.2                   | -6.2             | 164            | 392         |
| 0.30       | 07 45 08.3  | +17 54 19   | -70.3                   | -8.8             | 166            | 396         |
| 0.35       | 07 39 40.7  | +19 14 46   | -67.4                   | -11.4            | 169            | 401         |
| 0.40       | 07 34 15.4  | +20 32 48   | -64.5                   | -13.8            | 171            | 405         |
| 0.45       | 07 28 52.7  | +21 48 19   | -61.6                   | -16.1            | 172            | 411         |
| 0.50       | 07 23 32.9  | +23 01 14   | -58.8                   | -18.4            | 174            | 416         |

Figure 5. Sky map of high proper motion stars around HD 69686. HD 69686 is plotted as a diamond. The candidate members of the HD 69686 co-moving group are plotted as filled circles. The foreground/background stars with similar proper motions are plotted as open circles. All other high proper motion stars from the Catalogue of Stars with high-proper motions (V2; Ivanov 2008) are plotted as small dots. The solid line is the projected trajectory of HD 69686 on the sky. The plus signs mark the positions at 0.05 Myr intervals. The proper motion lines associated with individual objects indicate the size of their motions on the sky over a time period of 0.04 Myr.

7 http://cdsarc.u-strasbg.fr/viz-bin/Cat?I/306A
to move away from its projected trajectory on the sky, it actually stays on the trajectory because the projected trajectory moves downward at the same time.

Having similar proper motions does not necessarily imply that these stars belong to a co-moving group. Some foreground and background high proper motion stars can be mixed in. We argue that these stars belong to a co-moving group. Some foreground stars stay on the trajectory because the projected trajectory moves away from its projected trajectory on the sky, it actually moves to the trajectory.

Table 6: Candidates of the HD 69686 Co-Moving Group*

| R.A. (J2000) | Decl. (J2000) | $\mu_\alpha \cos \delta$ (mas yr$^{-1}$) | $\Delta \mu_\alpha \cos \delta$ (mas yr$^{-1}$) | $\mu_\delta$ (mas yr$^{-1}$) | $\Delta \mu_\delta$ (mas yr$^{-1}$) | Ref.$^b$ | $J$ (mag) | $K_s$ (mag) |
|-------------|--------------|-------------------------------------|-----------------------------------|----------------|----------------|--------|----------|----------|
| 08 18 22.98  | +09 09 05.1  | −86.2                              | 0.67                             | 7.2            | 0.42           | 1      | 7.38     | 7.51     |
| 08 20 29.24  | +09 39 52.6  | −88.7                              | 5.9                             | 8.1            | 5.6            | 2      | 13.60    | 13.15    |
| 08 19 28.74  | +08 26 23.8  | −79.4                              | 3.0                             | 3.0            | 11.28          | 3      | 11.86    | 11.37    |
| 08 14 18.90  | +10 56 48.2  | −70.0                              | 36.0                             | −6.6           | 37.5           | 4      | 12.82    | 12.41    |
| 08 16 02.71  | +10 47 35.2  | −81.4                              | 28.9                             | 18.1           | 30.5           | 4      | 12.68    | 12.12    |
| 08 05 53.09  | +13 58 28.0  | −93.2                              | ...                             | 5.1            | ...            | 3      | 10.90    | 10.83    |
| 08 03 02.59  | +13 21 47.1  | −62.4                              | 5.5                             | −13.2          | 5.4            | 2      | 12.94    | 12.58    |
| 07 54 38.84  | +15 17 09.0  | −60.9                              | 2.1                             | −14.9          | 2.0            | 2      | 11.76    | 11.44    |
| 07 58 03.59  | +14 30 24.8  | −58.8                              | 5.2                             | −8.9           | 5.2            | 4      | 12.45    | 11.78    |
| 07 55 50.86  | +17 30 35.4  | −67.8                              | 5.8                             | −19.7          | 5.8            | 4      | 13.31    | 12.47    |
| 07 47 04.61  | +15 06 15.7  | −61.3                              | 6.0                             | −11.2          | 5.9            | 4      | 12.71    | 11.91    |
| 07 42 50.37  | +16 19 00.7  | −69.1                              | 6.1                             | 3.8            | 6.0            | 2      | 13.01    | 12.20    |
| 07 58 14.04  | +17 18 01.8  | −61.5                              | 29.5                            | −14.8          | 31.0           | 4      | 11.78    | 11.71    |

Notes.

* The first row is for HD 69686.

1 The Catalogue of Stars with High Proper Motions (Ivanov 2008) does not provide the errors in the proper motions. This column indicates sources for the errors: (1) van Leeuwen 2007; (2) Zacharias et al. 2004; (3) Kislyuk et al. 2000; (4) Ducourant et al. 2006.

Figure 6. CMD of the HD 69686 co-moving group. HD 69686 is plotted as a diamond. The candidate members of the HD 69686 co-moving group are plotted as filled circles. The foreground/background stars with similar proper motions are plotted as open circles. The solid line is the isochrone of log Age = 7.84 and metallicity Z = 0.020 from Lejeune & Schaerer (2001) for a distance of 380 pc. The dotted lines are the same isochrone at distances 380 ± 60 pc.

(least likely in an HVC or Galactic merger fragment) with other stars 73 Myr ago.

The trajectory of HD 69686 covers a large range in all dimensions of the Galactic potential field (4–12 kpc in R, −1.8 to +0.9 kpc in z, and almost 180° of Galactic azimuth). Its shape may depend on the selection of different Galactic models. We did calculate the trajectory using different models (Parkinson 1990; Allen & Santillán 1991) and found similar results with trivial differences that are too small to change our analysis results. All the models used in our calculations assume a similar circular velocity at a distance to the Galactic center of 8 kpc (~ 220 km s$^{-1}$). We note that some observations (Miyamoto & Zhu 1998; Méndez et al. 2000; Uemura et al. 2000; Shattow & Loeb 2009; Reid et al. 2009) suggest that the circular motion of the solar neighborhood is faster than 220 km s$^{-1}$ by 30–40 km s$^{-1}$. Although it will be very interesting to see how much the trajectory of HD 69686 would change in a Galactic model characterized by a larger rotation speed at the solar circle, it is beyond the scope of the present paper.
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