“SLOW” AND FAST ROTATORS AMONG HYPERVELOCITY STARS

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Received 2008 February 19; accepted 2008 August 6; published 2008 August 22

ABSTRACT

We measure the projected rotational velocities of the late B-type hypervelocity stars HVS 7 and HVS 8 from high-resolution spectroscopy to be 60 ± 17 km s\(^{-1}\) and 260 ± 70 km s\(^{-1}\). The “slow” rotation of HVS 7 is in principle consistent with having originated in a binary system, assuming a high inclination angle of the stellar rotation axis. However, the fast rotation of HVS 8 is more typical of single B-type stars. HVS 8 could have therefore been ejected by a mechanism other than that proposed by Hills. We also estimate the effective temperatures and surface gravities for HVS 7 and HVS 8 and obtain an additional measurement of their radial velocities. We find evidence in support of a blue horizontal branch nature for HVS 7 and a main-sequence nature for HVS 8.

Subject headings: Galaxy: center — Galaxy: halo — Galaxy: stellar content — stars: early-type — stars: fundamental parameters — stars: rotation

Online material: color figures

1. INTRODUCTION

The recent discovery of 10 hypervelocity stars (HVSs; Brown et al. 2005; Edelmann et al. 2005; Hirsch et al. 2005; Brown et al. 2006a, 2006b, 2007) has raised many questions about their nature and origin. The most widely accepted ejection mechanism, proposed by Hills (1988), involves the encounter of a close binary with a supermassive black hole (SMBH). Other possible mechanisms for ejecting stars from the Galactic center involve intermediate-mass black holes (IMBHs; e.g., Yu & Tremaine 2003; Lückmann & Baumgardt 2008), a binary massive black hole (BMBH; e.g., Yu & Tremaine 2003; Merritt 2006; Sesana et al. 2006, 2007), or a cluster of stellar-mass black holes around the SMBH (O’Leary & Loeb 2008). Hansen (2007) claimed that the rotational velocities of HVSs should be lower than those measured for single stars of the same spectral type if they originated in binaries, because of tidal effects. He predicted that the rotational velocities of the known B-type HVSs should be ~70–90 km s\(^{-1}\), based on values compiled by Abt & Boynar (2004) for B stars in binaries. Lückmann & Baumgardt (2008) predicted high rotational velocities for HVSs that were ejected by a very close encounter with an IMBH in the Galactic center; however, such encounters are very unlikely.

These predictions cannot be tested with existing observations, as the low resolution of the discovery spectra of most HVSs is not sufficient to determine projected rotational velocities (v sin i). The only HVS with high-resolution spectroscopy and a v sin i measurement is HE 0437–5439, found by Edelmann et al. (2005). It has v sin i = 55 ± 1 km s\(^{-1}\) (Bonanos et al. 2008), in agreement with the prediction of Hansen (2007). However, Bonanos et al. (2008) and Przybilla et al. (2008) measured half-solar metallicity for this early B star, establishing its origin in the Large Magellanic Cloud (LMC). The possible ejection mechanisms for this star include an interaction with an IMBH or a SMBH and a dynamical interaction of a single star in a dense cluster. This example demonstrates the importance of high-resolution spectroscopy for understanding this newly discovered class of objects.

Of the remaining HVSs, HVS 2 (or US 708; Hirsch et al. 2005) is classified as an evolved sdO star and reasonably well understood. However, there is some ambiguity in the nature of the late B-type HVSs, since at their temperatures and gravities, the blue horizontal branch (BHB) crosses the main sequence. Hot BHB stars generally have low rotational velocities and peculiar chemical abundances (Behr 2003a); thus, high-resolution spectroscopy of these faint HVSs can determine their nature by measuring their atmospheric parameters, chemical abundances, and v sin i. In addition, time series photometry can reveal pulsations and confirm their main-sequence nature, as was done for HVS 1 by Fuentes et al. (2006).

Motivated by the lack of v sin i and stellar parameter measurements for most of the known HVSs and the possibility of testing the nature of the SMBH in the center of our Galaxy, we performed high-resolution spectroscopy of two HVSs. In this Letter we present our results.

2. OBSERVATIONS

We collected spectra of HVS 7 and HVS 8 (SDSS J113312.12+010824.9 and J094214.04+200322.1) with the blue chip of the MIKE spectrograph (Bernstein et al. 2003) installed at the 6.5 m Magellan Clay Telescope at Las Campanas Observatory (Chile), on two half-nights on UT 2008 January 18–19. Each star was observed twice, with individual exposure times between 900 and 1200 s, using a 1" × 5" slit and 3 × 3 binning. The total exposure times were 2100 s for HVS 7 and 2400 s for HVS 8. The resolution of the spectra is R = 32,000 at 4500 Å.

The spectra were extracted using the MIKE reduction pipeline (Kelson et al. 2000; Kelson 2003). The extracted spectra for each star were then averaged, normalized, and merged. The wavelength coverage of the merged spectra is 3900–5050 Å, with an average S/N ratio per pixel of 15 for HVS 7 and 14 for HVS 8, based on the extracted continuum around 4500 Å. These S/N ratios and our spectral resolution are sufficient to distinguish between high (>130–140 km s\(^{-1}\); Abt et al. 2002)
and low (70–90 km s$^{-1}$; Hansen 2007) $v\sin i$ values for B stars. Next, we corrected the wavelength scale for Doppler shift, to allow comparison of the spectra with models (see § 3). We measured the heliocentric radial velocity of each star using the IRAF$^5$ cross-correlation package RVSAO (Kurtz & Mink 1998) and the grid of models described in § 3. Table 1 lists our results and the values previously reported by Brown et al. (2007). Section 4 discusses the implications of our new radial velocity measurements.

### 3. SPECTRAL ANALYSIS

Our high-resolution spectra allow direct determination of the effective temperature $T_{\text{eff}}$, surface gravity $g$, and $v\sin i$ of the stars by comparing synthetic model spectra to the observations. The S/N ratio of the data is however too low to reliably measure abundances.

We generated a grid of synthetic spectra using the LTE ATLAS9 models and opacities developed by Kurucz (1993). The grid covers $T_{\text{eff}}$ between 8000 and 15,000 K in steps of 1000 K and $log g$ between 3.0 and 5.0 in steps of 0.25 dex. The metallicity was set to solar, assuming that the HVSs are ejected from the Galactic center, where abundances are solar or supersolar (Carr et al. 2000; Ramírez et al. 2000; Najarro et al. 2004; Wang et al. 2006; Cunha et al. 2007). For the macro- and microturbulence velocities we adopted 0 and 2 km s$^{-1}$, which are typical for late B stars (Fitzpatrick & Massa 1999). The models were broadened by 0.15 Å to match MIKE’s instrumental profile and resampled to a dispersion of 0.03 Å.

The agreement between each model and the observed spectra is quantified by the spectroscopic quality-of-fit parameter, $z$ (normalized $\chi^2$), defined by Behr (2003a) and given by the equation

$$z = \sqrt{\frac{N_{\text{points}}}{2}} \left( \frac{\text{rms}^2}{\text{rms}_\text{min}^2} - 1 \right),$$

where $N_{\text{points}}$ is the number of points in the spectrum, and rms and rms$_\text{min}$ are the root mean squared deviation between each model and the stellar spectrum, and the smallest value of the rms found; $z = 0$ gives the best model fit, and $z = 1$ defines the statistical 1 σ confidence interval of the result. The following subsections describe the derivation of $T_{\text{eff}}$, $log g$, and $v\sin i$ for each target.

$^5$ IRAF is distributed by the NOAO, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the NSF.
of the models to the observed spectrum shows that they are too large. Instead we adopted the errors resulting from the fits to individual metal lines. The left panel in Figure 2 compares the best-fit model to the Balmer lines of HVS 7.

Figure 3 shows metal lines detected in HVS 7 with \( \nu \sin i = 40, 60, \) and 80 km s\(^{-1}\) models overplotted. The purpose of this plot is twofold: the left-hand-side panels show how the Ca II K and Fe II \( \lambda 4233 \) lines (\( \nu \sin i \) is derived from these two and the Fe II \( \lambda 4549, 4583 \) lines) give \( \nu \sin i = 60 \) km s\(^{-1}\) as the best model fit, and their depths agree with the solar abundance adopted in the models. The \( \nu \sin i \) from these lines also agrees with the fits to the full spectrum and the Balmer lines. The right-hand-side panels show the behavior of the Si II doublet and the Mg II and He I lines. None of the models in the grid can reproduce the depths of those lines. While He I and Mg II seem depleted in the atmosphere of HVS 7, the Si II \( \lambda 4128/4130 \) lines seem strongly enhanced. The models cannot reproduce either the depth or the line strength ratio of the He I and Mg II lines. The enhancement of the Si II \( \lambda 4128/4130 \) doublet is even more significant when taking into account that the Kurucz LTE ATLAS9 models overpredict the strengths of these lines. This problem persists even after including non-LTE corrections (Smartt et al. 2001). Abundance peculiarities have been noticed before in BHB stars by several authors (Glaspey et al. 1989; Moehler et al. 1999; Behr et al. 1999); however, most of these are very slow rotators (<8 km s\(^{-1}\); Behr 2003a).

3.2. HVS 8

The spectrum of HVS 8 (\( V = 18.09 \) mag, S/N = 14) has a S/N similar to the HVS 7 spectrum; however, inspection of the spectrum of HVS 8 for metal lines gives null results. This can be explained by very low metal abundances, strong depletion, or highly broadened metal lines. The \( \nu \sin i \) obtained below points toward the latter case.

To derive \( T_{\text{eff}}, \log g, \) and \( \nu \sin i \) we used only the spectrum above 4000 Å because of problems with the continuum normalization at shorter wavelengths. As with HVS 7, we simultaneously fit for \( T_{\text{eff}}, \log g, \) and \( \nu \sin i \) by iteratively comparing the spectrum of HVS 8 to our model grid. We ran fits to the entire spectrum and 160 Å windows centered on the Balmer lines, which gave consistent parameters: \( T_{\text{eff}} = 11,000 \pm 1000 \) K, \( \log g = 3.57 \pm 0.25 \) dex, and \( \nu \sin i = 260 \pm 70 \) km s\(^{-1}\). The lack of metal lines in the spectrum of HVS 8 is consistent with a high \( \nu \sin i \) that results in strong line broadening. The error in \( \nu \sin i \) in this case comes directly from the \( z = 1 \) statistical 1 \( \sigma \) result, as visual comparison of the spectrum to the models does not allow us to place a finer constraint. The right-hand-side panel in Figure 2 compares the best-fit model to the Hb, H7, and H8 lines of HVS 8. The flat-bottomed cores of the Balmer lines, which are the most sensitive regions to \( \nu \sin i \), clearly illustrate that HVS 8 rotates faster than HVS 7.

4. RADIAL VELOCITIES

The new radial velocity observations in Table 1 provide a third epoch for each star and allow us to check for variations. Our radial velocity measurement for HVS 7 is identical to the values reported by Brown et al. (2006b, 2007) within errors. Such measurements provide clues to the nature of HVSSs. As pointed out by Brown et al., determining the nature of late B-type HVSSs is not straightforward because late-type main-sequence B stars and hot BHB stars have identical atmospheric parameters. BHB stars are less luminous and therefore closer in distance to us. Establishing the evolutionary stage of HVS 7 is critical because its radial velocity is marginally consistent with it being a BHB runaway star bound to our Galaxy (Brown et al. 2006b). The lack of significant radial velocity variations for HVS 7 suggests that it is not a binary, nor a pulsator. Slowly
pulsating main-sequence B-type stars typically show radial velocity variations of ≳20 km s\(^{-1}\) in amplitude (Aerts et al. 1999; Mathias et al. 2001), while BHB stars appear to be stable, as they fall outside the RR Lyrae instability strip (Contreras et al. 2005; Catelan 2005). The long-term radial velocity stability of HVS 7, combined with the metal abundance anomalies (see § 3.1), hint toward HVS 7 being a BHB star. Its \(v \sin i\) (60 ± 17 km s\(^{-1}\)) is higher than that typically found for BHB stars (<8 km s\(^{-1}\)), although rotators with \(v \sin i\) up to ~40 km s\(^{-1}\) have been observed (e.g., Behr 2003a, 2003b). The true nature of HVS 7 as a bound BHB star will have to be disentangled by astrometry.

For HVS 8 we detect a radial velocity variation of 23 km s\(^{-1}\), consistent with a pulsating main-sequence B-type star. We cannot discard the possibility of HVS 8 being a binary, although the system would have a very low mass ratio, since there is no evidence of lines from a companion in the spectrum. The star is most likely a main-sequence slow pulsator, like HVS 1 (Fuentes et al. 2006). The low S/N of our spectrum does not allow to test for metal abundance anomalies in HVS 8; however, the high rotational velocity of this star will make its abundance analysis difficult, even with higher S/N spectra.

5. DISCUSSION

We have derived \(v \sin i\), \(T_{\text{eff}}\), and \(\log g\) for HVS 7 and HVS 8, two of the 10 currently known HVSs. Their\(T_{\text{eff}}\) and \(\log g\) are consistent with the stars being late B type, as initially classified by Brown et al. (2006b, 2007) using photometric color indexes. HVS 7 has a projected rotational velocity \(v \sin i\) = 60 ± 17 km s\(^{-1}\), while for HVS 8 \(v \sin i\) = 260 ± 70 km s\(^{-1}\). These measurements provide the first direct observational test of the prediction by Hansen (2007), who suggests that HVSs ejected via Hills’s mechanism should rotate systematically slower (70–90 km s\(^{-1}\)) than single stars of the same spectral type (134 ± 7 km s\(^{-1}\); Abt et al. 2002). If the HVSs have fast rotational velocities typical of single B-type stars in the field, other ejection mechanisms, such as three-body encounters of single stars with ~10\(^{-1}\)–10\(^{2}\) M\(_\odot\) MBHs, with a binary MBH, or with ~10 M\(_\odot\) stellar-mass black holes orbiting the Galactic SMBH, have to be invoked.

The \(v \sin i\) values of HVS 7 and HVS 8 are lower limits to their true rotational velocities, imposed by the inclination angle of the rotation axis of the stars. If the inclination of the rotation axis of HVS 7 is low, its rotational velocity could in principle be much higher. In that case both targets are inconsistent with Hansen’s prediction for Hills’s scenario. However, a sample of only two \(v \sin i\) measurements is not enough to conclusively discern between the different scenarios proposed, and more \(v \sin i\) measurements are necessary. Statistical tests performed by Perets (2007) conclude that a sample of 25 or more HVSs will be needed to distinguish between scenarios at a ≥95% confidence level.

We also detect abnormal enhancement and depletion effects in the strength of some of the metal lines of HVS 7. These anomalies, together with the apparent lack of pulsations, are consistent with HVS 7 being a BHB star. Its \(v \sin i\) is also marginally consistent with it being a fast-rotation BHB star, if the inclination angle of the star’s rotation axis is close to 90°. However, confirmation that HVS 7 is a BHB star will not be possible until its proper motion is accurately measured. Finally, we find evidence of radial velocity variations in HVS 8 consistent with a pulsating main-sequence B-type star nature. Additional radial velocity measurements and time-series precision photometry will confirm this detection.

We thank N. Morrell for doing the observations, I. Ribas for his script to merge echelle orders, and W. Brown for suggestions. M. L. M. acknowledges support provided by NASA through Hubble Fellowship grant HF-01210.01-A awarded by the STScI, which is operated by the AURA, Inc., for NASA, under contract NAS5-26555. A. Z. B. acknowledges support from the Carnegie Institution of Washington through a Vera Rubin Fellowship.

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