Draft version July 21, 2005
Preprint typeset using LaTeX style emulateapj v. 5/14/03

THE HYPERVELOCITY STAR SDSS J090745.0+024507 IS A SHORT-PERIOD VARIABLE[1]

Cesar I. Fuentes[2], K. Z. Stanek[2,3], B. Scott Gaudi[2], Brian A. McLeod[2], Slavko Bogdanov[2], Joel D. Hartman[2], Ryan C. Hickox[2], Matthew J. Holman[2]

Draft version July 21, 2005

ABSTRACT

We present high-precision photometry of the hypervelocity star SDSS J090745.0+024507 (HVS), which has a Galactic rest-frame radial velocity of $v = 709$ km s^{-1}, and so has likely been ejected from the supermassive black hole in the Galactic center. Our data were obtained on two nights using the MMT 6.5m telescope, and is supplemented by lower precision photometry obtained on four nights using the FLWO 1.2m telescope. The high-precision photometry indicates that the HVS is a short-period, low-amplitude variable, with period $P = 0.2 - 2$ days and amplitude $A = 2 - 10\%$. Together with the known effective temperature of $T_{\rm eff} \simeq 10,500$ K (spectral type B9), this variability implies that the HVS is a member of the class of slowly pulsating B-type main sequence stars, thus resolving the previously-reported two-fold degeneracy in the luminosity and distance of the star. The HVS has a heliocentric distance of 71 kpc, and an age of $\lesssim 0.35$ Gyr. The time of ejection from the center of the Galaxy is ≤ 100 Myr, and thus the existence of the OS constitutes observational evidence of a population of young stars in the proximity of the central supermassive black hole ~ 0.1 Gyr ago. It is possible that the HVS was a member of a binary that was tidally disrupted by the central black hole; we discuss constraints on the properties of the companion's orbit.

Subject headings: Galaxy Center – Stellar Dynamics

1. INTRODUCTION

In their survey of blue horizontal branch (BHB) stars, Brown et al. (2005) discovered that the Galactic halo star SDSS J090745.0+024507 (hereafter HVS) has a radial velocity of 853 ± 12 km s^{-1}. This corresponds to a Galactic rest-frame radial velocity of ~ 700 km s^{-1}, well above the local escape speed from the Galaxy. As reviewed by Brown et al. (2005), the only plausible mechanism for achieving this extreme velocity is ejection from the vicinity of the central supermassive black hole (CBH), as predicted by Hills (1988), and studied in detail by Yu & Tremaine (2003). The detection of the HVS and other hypervelocity stars is important because it allows one to probe the population of stars near the CBH in the Milky Way's recent past. In addition, it may be possible to use these stars to constrain the various scenarios for the origin of the young stars detected near the Galactic center (Genzel et al. 2003; Ghez et al. 2005; Gould & Quillen 2003; Hansen & Milosavljević 2003). Finally, precise proper motion measurements of hypervelocity stars ejected from the Galactic center can be used to probe the shape of the Galactic halo (Gnedin et al. 2005).

The intrinsic luminosity and distance to the HVS suffers from a two-fold degeneracy which hampers the interpretation of its origin. This degeneracy arises from the coincidence that the main sequence and horizontal branch overlap at the measured effective temperature $T_{\rm eff} = 10,500$ K and surface gravity of the HVS. Thus the HVS could be either a BHB giant or a B9 main-sequence star. The intrinsic luminosities of these two types of stars differ by a factor of ~ 4, and thus the inferred distances to the HVS differ by a factor of ~ 2. The distance is 39 kpc or 71 kpc if the HVS is a BHB star or main-sequence star, respectively.

In order to search for photometric variability and so pin down its properties, we performed precise photometry of the HVS using the MMT 6.5m telescope. We describe our observations and data reduction in §2. As we discuss in §3, we find that the star is indeed variable, and we constrain the variability to be short-period ($0.2 - 2$ days) and low-amplitude ($2 - 10\%$). Together with the measured effective temperature, we argue in §4 that this puts the HVS in the class of B9 main-sequence stars that pulsate with periods of the order of one day, so-called slowly pulsating B (SPB) stars (Waelkens 1991). Therefore, our observations resolve the two-fold ambiguity and indicate that the HVS is a main-sequence star with heliocentric distance of 71 kpc. We discuss the implications of this result in §5.

2. OBSERVATIONS AND DATA REDUCTION

We obtained photometric data on the HVS during two nights (UT 2005 January 15, April 13) with the Megacam CCD camera (McLeod et al. 2000) on the MMT 6.5m telescope, and during four nights (UT 2005 January 13,15-17) with the 1.2-meter telescope at FLWO. Using MegaCam we obtained 9 g-band images on the first night, and 16 g-band and 9 r-band images on the second night. These high signal-to-noise ratio data were used to detect the variability of the star. The FLWO data were obtained in the V-band over 7 epochs, in order to constrain the amplitude of the variability.

The raw images were reduced in the usual manner. Photometry was carried out using PSF-fitting photometry with the package DAOPHOT II (Stetson 1987, 1992). We used 15-30 reference stars to obtain the relative photometry between different epochs. We roughly calibrated our relative photometry using Sloan Digital Sky Survey

---

[1] Based on data from the MMTO 6.5m telescope and the FLWO 1.2m telescope

[2] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; cfuentes@cfa.harvard.edu

[3] Department of Astronomy, The Ohio State University, Columbus, OH 43210

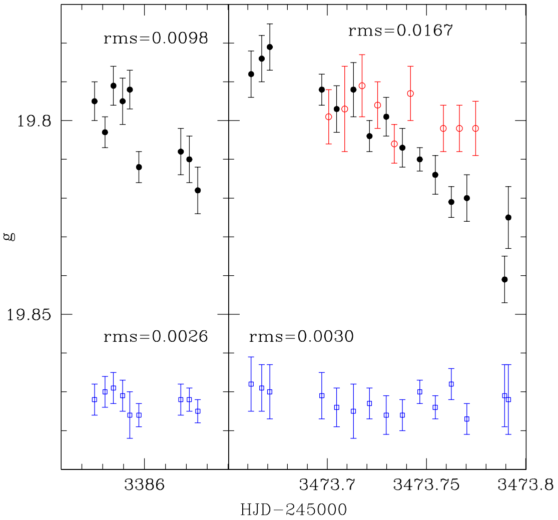

FIG. 1.— Relative photometry of the hypervelocity star SDSS J090745.0+024507 (HVS). The black solid circles show the g-band magnitude of the HVS versus HJD-2450000. In the second panel the red open circles show the r-band data. The blue open squares show the photometry for the slightly fainter and nearby star SDSS J090751.07+024534.9. Note that the scales in both panels are the same.

(SDSS) absolute photometry (Abazajian et al. 2005) of the nearby comparison star SDSS J090751.07+024534.9.

Figure 1 shows the g-band and r-band light curves for the HVS constructed from the MegaCam data. The g-band data from the two nights are shown in separate panels. The HVS is variable in the g-band, but shows no evidence for variability within the errors in the r-band. The g-band variability is certainly real, as evidenced by the photometry of the slightly fainter and nearby comparison star SDSS J090751.07+024534.9, which is constant to within the errors (see Fig. 1).

The FLWO data are of considerably lower precision than the MMT data, with photometric errors of $\sim 5-10\%$, as compared to $\sim 0.5-1\%$ for the MMT data. The FLWO data therefore do not provide strong constraints on the periodicity of the HVS's variability. As we explain in §3, these data are nevertheless very useful because they constrain the amplitude of the variability to be $\lesssim 10\%$.

3. ANALYSIS AND RESULTS

Figure 1 shows that the HVS star is variable in the g-band. The RMS deviation over the ~ 3.5 hours of data on the second night is nearly 6 times larger than that of the comparison star. A constant flux fit to the g-band data has $\chi^2 = 155.9$ for 24 degrees-of-freedom (dof), and so is a poor representation of the data. On the other hand, the r-band data are consistent with a constant flux, with $\chi^2 = 4.5$ for 8 dof.

In order to constrain the period and amplitude of the variability, we fit the data to the model:

$$m(t_i) = A\sin\left[\frac{2\pi}{P}(t_i - t_0) + \phi_0\right] + m_{0,j}, \qquad (1)$$

where $m(t_i)$ is the magnitude of observation i taken at time t_i, P is the period, A is the amplitude, and $m_{0,j}$ and ϕ_0 correspond to the magnitude zero point and phase at the error-weighted mean observation time, $t_0 - 2450000. = 3441.95357$. We assume separate magnitude zero points $m_{0,j}$ for each data set j (MMT or FLWO). Fitting equation (1) is equivalent to a Lomb-Scargle periodogram with a floating mean (Cumming 2004; Lomb 1976; Scargle 1982). We search for fits at 10^6 equally-spaced steps in $\log P$ in the range $-2 \leq \log(P/\mathrm{days}) \leq 2$.

If we fit only the MMT g-band data, we can only place a lower limit on the period and amplitude of the variability, $A \geq 2\%$ and $P \geq 0.2$ days. This fact can be understood from inspection of the data in Figure 1. The g-band data for both nights are nearly consistent with a simple linear decline with slope $m \sim 0.4$ mag/day. Thus the data can be approximately described by any model satisfying $A \simeq (2\pi)^{-1}mP$, for P much larger than the duration of the observations on any given night, ~ 3.5 hr.

Fitting both the g-band MMT and V-band FLWO datasets simultaneously constrains the period and amplitude of the variability. We assume that the amplitude, period, and phase of the variability is the same in the g and V bands. Figure 2 shows the resulting periodogram, plotted as $\Delta\chi^2 \equiv \chi^2 - \chi^2_{\rm min}$ versus P. We find a best-fit for $P = 0.355188 \pm 0.000021$ days, $A = 0.0280 \pm 0.0033$ mag, and $\phi_0 = 2.98 \pm 0.17$, with $\chi^2_{\rm min} = 24.5$ for 32-5=27 dof. The best-fit model is shown in Figure 3, together with both the MMT and FLWO data folded about the best-fit period. This fit is not unique. There are flanking aliases with periods separated by 2.06 min, corresponding to an integer number of additional cycles between the ~ 88 days separating the two nights of the g-band data. There are also fits at periods of ~ 0.43 days and ~ 0.55 days that are equally good ($\Delta\chi^2 \leq 1$). Finally, essentially all periods with $P = 0.2 - 1.5$ days are allowed at the 3σ level.

Because the g-band data on any individual night show little curvature, only the slope is well constrained, and so the amplitude of the fit is correlated with the period. This is shown in Figure 4, where we show the 1, 2, and 3σ allowed regions in the $A-P$ plane. We see that longer periods require larger amplitudes. However, regardless of the best fit, we can rule out periods $P \lesssim 0.2$ days and $\gtrsim 1.5$ days and amplitudes $A \lesssim 2\%$ and $\gtrsim 10\%$.

The r-band data show no evidence for variability. Adopting the best-fit period and phase from the g and V-band data, the amplitude of the r-band variability is $A_r \leq 0.016$ mag at the 95% confidence level.

4. THE HYPERVELOCITY STAR IS A SLOWLY PULSATING B-TYPE MAIN-SEQUENCE STAR

The amplitude and period of the HVS's variability, as well as its effective temperature, are all consistent with the class of slowly pulsating B-type main-sequence stars first identified by Waelkens (1991). These stars are multi-periodic, non-radial pulsators with periods of $P = 0.4 - 4$ days, amplitudes of a few millimagnitudes to a few percent, and effective temperatures of $T_{\rm eff} = 10,000 - 20,000$ K. According to Waelkens et al. (1998) the HVS would fall in the low temperature boundary of the instability strip calculated by Pamyatnykh (1999) for SPBs. In fact, there is a striking similarity between the HVS and the known SPB star HD45953, reported by Waelkens et al. (1998), which is also at the low temperature edge of the class with $T_{\rm eff} = 11,500$

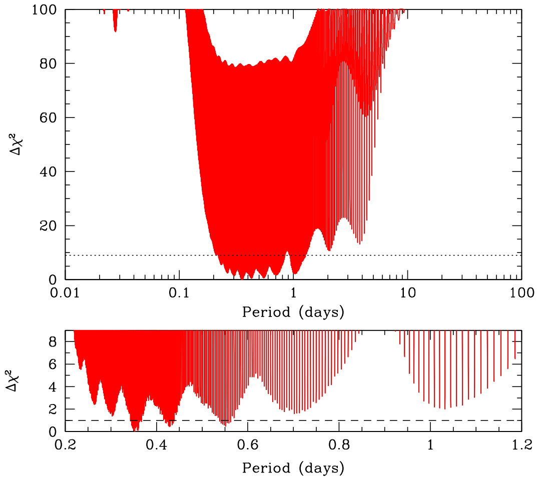

FIG. 2.— The difference in χ^2 of a sinusoidal model fit to the HVS light curve from the minimum χ^2 of the best-fit model with $P = 0.355188$ days, as a function of the period of the model. The upper panel shows the full range of periods searched and the lower is a zoom in the regime of most interest.

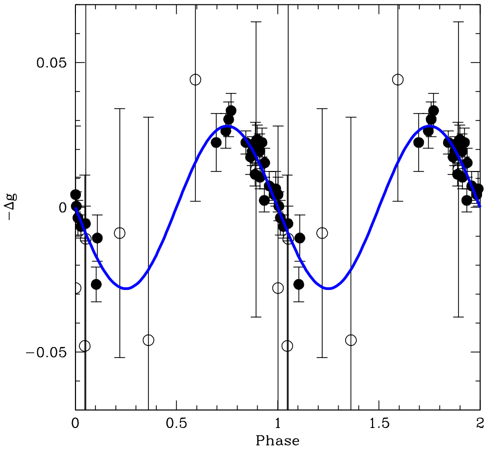

FIG. 3.— The photometry of the HVS is displayed as a function of phase angle, folded according to the best fit period $P = 0.355188$ days and with the zero point subtracted. The black points are the MMT g-band photometry for the HVS. The open circles are the 1.2-meter V-band photometry. Points are plotted twice for clarity.

K, $P = 0.43$ days, and $M = 2.89 \pm 0.07 M_\odot$ (de Cat 2002). SPB stars are also known to have lower amplitudes in redder bandpasses, with relative amplitudes that are consistent with the upper limit on the HVS's r-band variability of 0.016 mag.

On the other hand, there is evidence that BHB stars do not vary at this level. Studying a predominantly BHB cluster with high precision photometry, Contreras et al. (2005) found more than 200 RR Lyrae variables (with similar periods to the HVS), but no BHB stars that showed significant variation. See Catelan (2005) for more discussion on the variability of HB stars.

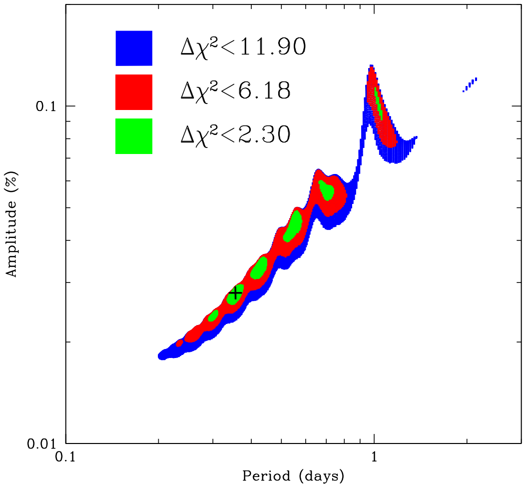

FIG. 4.— The 1, 2, and 3σ allowed regions ($\Delta\chi^2 \leq 2.30, 6.18, 11.90$) in the amplitude-period (A, P) plane for a sinusoidal fit to the HVS light curve. The best fit is attained with $P = 0.355188 \pm 0.000021$ days and $A = 0.0280 \pm 0.0033$ mag, and is indicated by the cross.

The fact that the HVS is variable with $A = 2 - 10\%$, and that BHB stars do not vary at this level, implies that it is a main sequence star. Hence its temperature $T_{\rm eff} \sim 10,500K$ indicates a luminosity of $L \sim 160 L_\odot$, giving a distance of 71 kpc (Brown et al. 2005). Using the reported velocity for the HVS (709 $\rm km\,s^{-1}$) and assuming its movement is only radial we obtain a travel time from the center of the galaxy of ≤ 0.1 Gyr. For a $3M_\odot$ B9 star, the evolutionary tracks of Schaller et al. (1992) give a main-sequence lifetime of 0.35 Gyr.

5. SUMMARY AND DISCUSSION

We have performed high-precision, time-series photometry of the hypervelocity star SDSS J090745.0+024507, which shows that it is a low-amplitude, short-period variable. A sinusoidal fit to the light curve yields a best-fit period of $P \simeq 0.36$ days and amplitude of $A \simeq 2.5\%$, however this fit is not unique and the exact values of the amplitude and period of the variation are poorly constrained. Nevertheless, the period and amplitude are constrained to be in the range $A = 2 - 10\%$ and $P = 0.2 - 1.5$ days.

Together with the known effective temperature of $T_{\rm eff} \simeq 10,500$ K (spectral type B9), this variability implies that the HVS is a member of the class of slowly pulsating B-type main sequence stars identified by Waelkens (1991). This identification resolves the previously-reported two-fold degeneracy in the luminosity and hence distance to the HVS. The HVS has a mass of $\sim 3M_\odot$, an age of $\lesssim 0.35$ Gyr, a heliocentric distance of ~ 71 kpc and a travel time from the Galactic center ~ 0.1 Gyr.

The HVS can be used to probe the population of stars near the CBH in the Milky Way's recent past. The most plausible mechanism for creating hyper-velocity stars such as the HVS is a strong gravitational interaction with the Milky Way's CBH, perhaps as a member of a short-period binary that was disrupted by the tidal field of the CBH (Hills 1988; Yu & Tremaine 2003) As such, the existence of the HVS implies that young stars must have been present within ~ 0.1 pc of the CBH ~ 0.1 Gyr ago. There is observational evidence for even younger stars with ages of $\sim 1-10$ Myr currently orbiting the CBH (Genzel et al. 2003; Ghez et al. 2003) at distances of $\lesssim 0.1$ pc. The existence of such stars is puzzling, as strong tidal interaction with the black hole should prevent local star formation (but see Levin & Beloborodov 2003 and Milosavljević & Loeb 2004), and yet these stars are unlikely to live long enough to be scattered into such close orbits. Thus the existence of young stars near the CBH today (Genzel et al. 2003; Ghez et al. 2003), along with the inference from the HVS that they were also present ~ 0.1 Gyr ago, may suggest that the mechanism for delivering young stars to the CBH must be efficient and continuous, which may in turn constrain the various models for such delivery (Genzel et al. 2003; Ghez et al. 2005; Gould & Quillen 2003; Hansen & Milosavljević 2003). If the HVS migrated to near the CBH from outside, its expected MS lifetime (~ 0.35 Gyr), implies the migration time must be $\lesssim 0.2$ Gyr.

Assuming that the HVS is the ejected component of a binary that was tidally disrupted by the CBH, we can use its known mass and ejection velocity to place constraints on the properties of original binary, and on companion's current orbit about the CBH (see also Gualandris, Portegies Zwart & Sipior 2005). Assuming a mass for the companion m_1, we can determine that initial separation of the binary a_{bin}, and the peribothron q and eccentricity e of the companion's orbit around the CBH (Gould & Quillen 2003; Yu & Tremaine 2003). We find that the eccentricity of the bound star's orbit is always high, ranging from $e = 0.97$ to $e \sim 1$ as an increasing function of m_1. The binary separation a_{bin} and q increase with m_1. For a companion with $m_1 = 3\ M_\odot$ (i.e. an equal-mass binary), we find $a_{bin} = 0.69$ AU, q=72.8 AU and e=0.98. The semimajor axis of the bound star's orbit about the CBH is ~ 3830 AU.

The period of the companion of the HVS about the CBH will be of the order of ~ 100 yr. Furthermore, a $\sim 3\ M_\odot$ main-sequence star at the Galactic center would have $K \simeq 18.5$, over a magnitude fainter than the faintest stars for which accurate orbits are being measured in near-IR imaging studies of the Galactic center using 10m-class telescopes (Ghez et al. 2005; Schödel et al. 2003). As a result, unless it happens to be near peribothron and massive, the companion to the HVS will probably be difficult to find. Assuming tidal disruption of binaries is the mechanism by which most HVS are formed, it may be difficult to link an observed HVS with its orbiting stellar companion.

The fact that the HVS is an SPB star implies that it should be possible to study its properties in more detail with follow-up observations using asteroseismology. SPB stars show multi-periodic variability, with secondary period amplitudes that are of the same order as that of the primary period. This variability is thought to be due to non-radial g-mode pulsations (Waelkens 1991). Hence, the HVS should be targeted for more photometric data in order to unravel the possible different pulsation modes. Matching these g-modes would give additional and precise information about the properties of the star. We are specially interested in HVS's age, since an independent measurement from asteroseismology would provide further evidence of its origin and history across the Galaxy.

We would like to thank Andy Gould for helpful discussions, Warren Brown, Margaret Geller, and Scott Kenyon for useful comments on the manuscript, and Barbara Mochejska for help with the SM plotting package. BSG was supported by a Menzel Fellowship from the Harvard College Observatory.

REFERENCES

Abazajian, K., et al. 2005, AJ, 129, 1755

Brown, W. R., Geller, M. J., Kenyon, S. J., & Kurtz, M. J. 2005, ApJ, 622, L33

Catelan, M. 2005, ASP Conf. Ser.: Resolved Stellar Populations, in press (astro-ph/0507464)

Contreras, R., Catelan, M., Smith, H. A., Pritzl, B. J., & Borissova, J. 2005, ApJ, 623, L117

Cumming, A. 2004, MNRAS, 354, 1165

de Cat, P. 2002, ASP Conf. Ser. 259: IAU Colloq. 185: Radial and Nonradial Pulsations as Probes of Stellar Physics, 259, 196

Genzel, R., et al. 2003, ApJ, 594, 812

Ghez, A. M., et al. 2003, ApJ, 586, L127

Ghez, A. M., Salim, S., Hornstein, S. D., Tanner, A., Lu, J. R., Morris, M., Becklin, E. E., & Duchêne, G. 2005, ApJ, 620, 744

Gnedin, O. Y., Gould, A., Miralda-Escude, J. & Zentner, A. R. 2005, ApJ, submitted (astro-ph/0506739)

Gould, A., & Quillen, A. C. 2003, ApJ, 592, 935

Gualandris, A., Portegies Zwart, S., J. & Sipior, M. S. 2005, MNRAS, submitted (astro-ph/0507365)

Hansen, B. M. S., & Milosavljević, M. 2003, ApJ, 593, L77

Hills, J. G. 1988, Nature, 331, 687

Levin, Y., & Beloborodov, A. M. 2003, ApJ, 590, L33

Lomb, N. R. 1976, Ap&SS, 39, 447

McLeod, B. A., Conroy, M., Gauron, T. M., Geary, J. C., & Ordway, M. P. 2000, Further Developments in Scientific Optical Imaging, 11

Milosavljević, M., & Loeb, A. 2004, ApJ, 604, L45

Pamyatnykh, A. A. 1999, Acta Astronomica, 49, 119

Scargle, J. D. 1982, ApJ, 263, 835

Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269

Schödel, R., Ott, T., Genzel, R., Eckart, A., Mouawad, N., & Alexander, T. 2003, ApJ, 596, 1015

Stetson, P. B. 1987, PASP, 99 191

Stetson, P. B. 1992, in ASP Conf. Ser. 25, Astrophysical Data Analysis Software and Systems I, ed. D. M. Worrall, C. Bimesderfer, & J. Barnes (San Francisco: ASP), 297

Waelkens, C. 1991, A&A, 246, 453

Waelkens, C., Aerts, C., Kestens, E., Grenon, M., & Eyer, L. 1998, A&A, 330, 215

Yu, Q., & Tremaine, S. 2003, ApJ, 599, 1129