WEIGHING THE GALACTIC DARK MATTER HALO: A LOWER MASS LIMIT FROM THE FASTEST HALO STAR KNOWN

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ABSTRACT

The mass of the Galactic dark matter halo is under vivid discussion. A recent study by Xue et al. revised the Galactic halo mass downward by a factor of $\sim 2$ relative to previous work, based on the line-of-sight velocity distribution of $\sim 2400$ blue horizontal-branch (BHB) halo stars. The observations were interpreted with a statistical approach using cosmological galaxy formation simulations, as only four of the six-dimensional phase-space coordinates were determined. Here we concentrate on a close investigation of the stars with the highest negative radial velocity from that sample. For one star, SDSSJ153935.67+023909.8 (J1539+0239 for short), we succeed in measuring a significant proper motion, i.e., full phase-space information is obtained. We confirm the star to be a Population II BHB star from an independent quantitative analysis of the Sloan Digital Sky Survey (SDSS) spectrum—providing the first non-LTE (NLTE) study of any halo BHB star—and reconstruct its three-dimensional trajectory in the Galactic potential. J1539+0239 turns out to be the fastest halo star known to date, with a Galactic rest-frame velocity of $694^{+300}_{−221}$ km s$^{-1}$ (full uncertainty range from Monte Carlo error propagation) at its current position. The extreme kinematics of the star allows a significant lower limit to be put on the halo mass in order to keep it bound, of $M_{\text{halo}} \geq 1.7^{+2.3}_{−1.5} \times 10^{12}$ $M_{\odot}$. We conclude that the Xue et al. results tend to underestimate the true halo mass as their most likely mass value is consistent with our analysis only at a level of 4%. However, our result confirms other studies that make use of the full phase-space information.

Key words: dark matter – Galaxy: halo – stars: atmospheres – stars: horizontal-branch – stars: kinematics and dynamics – stars: Population II

Online-only material: color figures

1. INTRODUCTION

Knowledge of the properties of dark matter halos is an important issue for our understanding of galaxy formation and evolution, and for unveiling the nature of dark matter. The halo of the Milky Way therefore is of highest interest, as it allows unique observational constraints to be obtained for testing theoretical models (e.g., Navarro et al. 1996). Several observational campaigns—e.g., the Sloan Digital Sky Survey (SDSS; York et al. 2000), the Radial Velocity Experiment (RAVE; Steinmetz et al. 2006), the Sloan Extension for Galactic Understanding and Exploration (SEGUE; Yanny et al. 2009)—provide the tracers for studying halo properties, like the total mass of the halo and its extent.

Several studies in the past decade determined the halo mass from ever increasing samples of halo stars, globular clusters, and/or satellite galaxies. However, it is in fact only a few objects at the highest velocity that are largely affecting the mass estimates (Sakamoto et al. 2003; Smith et al. 2007). While larger halo masses of about $2 \times 10^{12}$ $M_{\odot}$ were favored earlier (Wilkinson & Evans 1999; Sakamoto et al. 2003), lower masses of about half this value were derived more recently (Battaglia et al. 2005; Smith et al. 2007; Xue et al. 2008). The precise value determines, e.g., among others, whether satellite galaxies like the Magellanic Clouds (e.g., Kallivayalil et al. 2006; Costa et al. 2009) or hyper-velocity star\textsuperscript{3} candidates (Abadi et al. 2009) are on bound orbits, or not.

\textsuperscript{3} Hyper-velocity stars move at such high velocity that they may be gravitationally unbound to the Galaxy. Their supposed place of origin is the Galactic center, where they may have been accelerated by gravitational interactions with the supermassive black hole (Hills 1988).

Most of the previous studies had to rely substantially on the distributions of radial velocities in their samples to derive their conclusions as full space motions for halo objects are unavailable in many cases at present. In such cases, only four coordinates (i.e., two position values, distance, and radial velocity (RV)) of the six-dimensional phase space are determined and the missing data (the proper motion components) are handled with a statistical approach. For example, radial velocities for more than 10,000 blue halo stars from the SDSS were measured in the most extensive study yet by Xue et al. (2008). The sample was composed of blue horizontal-branch (BHB), blue straggler, and main-sequence stars with effective temperatures roughly between 7000 and 10,000 K according to their colors. Here, we focus on the fastest stars of the Xue et al. sample in terms of negative line-of-sight velocity, indicating a bound orbit.

For one of them, we were able to measure a significant proper motion, which allowed a detailed three-dimensional kinematic investigation when combined with quantitative spectroscopic analysis that facilitated the determination of the star’s distance. SDSSJ153935.67+023909.8 (J1539+0239 for short) is an inbound\textsuperscript{4} Population II horizontal branch star with a Galactic rest-frame (GRF) velocity of $\sim 700$ km s$^{-1}$ at its current position, making it the fastest known halo object. This allows a significant lower limit for the total halo mass of the Galaxy to be

\textsuperscript{4} An extragalactic origin of the star as an unbound low-mass hyper-velocity star from another galaxy is imaginable but unlikely. The local volume is devoid of galaxies in a wide range (several 10 deg) around the infall direction of J1539+0239 at present (for the Local Group, see van den Bergh 1999, and later discoveries). If ejected early after its formation, the star could have traveled $\sim 8$ Mpc during its lifetime, such that a final answer on this may be only obtained when full space motions of the nearby galaxies are known.
set. The present work provides a glimpse into the detailed kinematic investigations feasible once the European Space Agency’s Gaia satellite mission (e.g., Turon et al. 2005) becomes operational, at much higher precision.

2. TARGET SELECTION AND PROPER MOTION

In a previous paper (Tillich et al. 2009), we already investigated the high-velocity tail of the Xue et al. (2008) sample and found a hyper-velocity candidate of spectral type A among the stars with the highest positive radial velocities in the GRF. Here we study the most extreme stars approaching us, applying the same techniques. We selected all stars with GRF velocities $v_{\text{GRF}} < -350 \text{ km s}^{-1}$ from the RV-based sample of Xue et al. (2008) and obtained five targets for which we attempted to measure proper motions. All available independent position measurements on Schmidt plates (APM—McMahon et al. 2000; SSS—Hambley et al. 2001) were collected and combined with the SDSS and other available positions (CMC14 Carlsberg-Meridian-Catalog 2006; 2MASS—Cutri et al. 2003; UKIDSS—Lawrence et al. 2007) for a first linear proper motion fit. However, there were even more measurements of Schmidt plates, from up to 14 different epochs in case of overlapping plates of the Digitised Sky Surveys.5 FITS images of 15 by 15 arcmin size were extracted from all available plates and ESO

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### Table 1

| Quantity | Value | Quantity | Value |
|----------|-------|----------|-------|
| $V$ (mag)$^a$ | 15.72 ± 0.02 | $E(B - V)$ (mag)$^b$ | 0.04 ± 0.03 |
| $\mu_{\alpha} \cos \delta$ (mas yr$^{-1}$) | $-10.6$ ± 1.6 | $\mu_{\delta}$ (mas yr$^{-1}$) | $-10.0$ ± 2.3 |
| $l$ (deg) | 8.9836 | $b$ (deg) | 42.9515 |
| $\mu_{\alpha} \cos b$ (mas yr$^{-1}$) | $-14.3$ ± 2.1 | $\mu_{b}$ (mas yr$^{-1}$) | $+2.8$ ± 1.9 |
| $T_{\text{eff}}$ (K) | 7700 ± 250 | $\log g$ (cgs) | 3.00 ± 0.15 |
| $[M/\text{H}]$ | 2.0 | $[\alpha/\text{Fe}]$ | 4.0 |
| $M/(M_{\odot})$ | 0.68 ± 0.05 | $d$ (kpc) | 12.0 ± 2.3 |
| $v_{\text{rad}}$ (km s$^{-1}$) | $-372.6$ ± 5.8 | $v_{\text{GRF}}$ (km s$^{-1}$) | 519 |

**Notes.**

1 The interstellar color excess $E(B - V)$ has been determined by comparing the observed colors to synthetic ones from the model spectral energy distribution.

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3. OBSERVATIONS AND QUANTITATIVE SPECTROSCOPY

In order to exclude RV variability, we re-observed J1539+0239 with the TWIN spectrograph at the 3.5 m telescope on Calar Alto in 2009 May. RVs were derived by $y^2$-fitting of adequate synthetic spectra over the full spectral range, yielding a heliocentric RV of $v_{\text{rad}} = -366.6$ ± 4.0 km s$^{-1}$ for the TWIN spectrum, which is consistent with the $v_{\text{rad}} = -372.6$ ± 5.8 km s$^{-1}$ measured from the SDSS data within the mutual uncertainties. We use the latter value for the kinematic study.

A quantitative analysis of J1539+0239 was carried out following the hybrid NLTE approach discussed by Przybilla et al. (2006). In brief, line-blanketed LTE model atmospheres were computed with ATLAS9 (Kurucz 1993) and NLTE (and LTE) line-formation calculations were performed using updated versions of DETAIL and SURFACE (Giddings 1981; Butler & Giddings 1985). Many astrophysically important chemical species were treated in NLTE, using state-of-the-art model atoms (H: Przybilla & Butler 2004a; C: Przybilla et al. 2001b; N: Przybilla & Butler 2001; O: Przybilla et al. 2000; Mg i/ii: Przybilla et al. 2001a; Ti ii and Fe ii: Becker 1998).

The effective temperature $T_{\text{eff}}$ and the surface gravity $\log g$ were determined by fits to the Stark-broadened Balmer and Paschen lines and an ionization equilibrium, here of Mg i/ii, analogous to previous work on hyper-velocity stars at similar temperatures (Przybilla et al. 2008; Tillich et al. 2009). The
stellar metallicity was derived by model fits to the observed metal line spectra. Results are listed in Table 1 and a comparison of the resulting final synthetic spectrum with observation is shown in Figure 2. Overall, excellent agreement is obtained for the strategic spectral lines throughout the entire wavelength range. Our stellar parameters ($T_{\text{eff}} = 7700 \pm 250$ K, $\log g = 3.00 \pm 0.15$) are consistent with those derived in the LTE analysis by Xue et al. (2008): $T_{\text{eff}} = 7807$ K, $\log g = 3.16$. We constrained the errors in the stellar parameters by the quality of the match of the spectral indicators within the given signal-to-noise ratio (S/N) limitations.

Its parameters place J1539+0239 on the horizontal branch at a mass of $0.68 \pm 0.05 M_\odot$ as derived by comparing the position of the star in the $T_{\text{eff}} - \log g$ diagram to predictions of the evolutionary models of Dorman et al. (1993). No rotational broadening was detected at the resolution of the SDSS spectrum. The metallicity is lower than solar by a factor of 100 and the abundances of the $\alpha$-elements are enhanced by about 0.4 dex with respect to iron, which is typical for the halo population. We conclude that the star is a horizontal branch star of Population II. All results are summarised in Table 1.

Before proceeding to further discussion it may be instructive to take a closer look on the spectrum synthesis in NLTE and LTE, as this has not been done for Population II BHB stars so far. A few comparisons of NLTE and LTE profiles are therefore shown in Figure 3. The combination of a higher $T_{\text{eff}}$ than typically found for Population II stars and the diminished line blocking because of the low metal content results in a hardened radiation field, which along with reduced thermalizing effects because of smaller collision rates in the low-density atmosphere, leads to pronounced NLTE effects on many diagnostic lines. NLTE strengthening is found for the Doppler core of Hα—in line with the behavior in cool stars (e.g., Przybilla & Butler 2004b)—while the inner line wings are weakened. The higher Balmer and Paschen lines show much lower deviations from LTE. Our calculations predict the majority of the weak lines to be described well by the assumption of LTE. On the other hand, many of the stronger metal lines, as of e.g., C1, O1, Mg II/II, or Fe II—the diagnostic lines at the spectroscopic resolution achieved within the SDSS—show pronounced NLTE strengthening. In order to reproduce the NLTE equivalent widths of these particular lines, abundance corrections need to be applied of about 0.1 dex (Mg II), 0.2 dex (Mg I, Fe II), 0.5 dex (O I), and 1.9 dex (C I) in LTE. Note, however, that these
lines are close to saturation. LTE computations with increased abundances can therefore not reproduce the NLTE line depths at all, instead stronger line wings develop. Abundance studies based on equivalent widths may therefore be misleading, as such differences remain unnoticed. An investigation at high spectral resolution would therefore be worthwhile in order to facilitate the NLTE effects to be studied in detail.

4. DISTANCE, KINEMATICS, AND ERRORS

Using the mass, effective temperature, gravity, and extinction-corrected apparent magnitude, we derive the distance following Ramspeck et al. (2001) using the fluxes from the final model spectrum analogous to previous work (Tillich et al. 2009). The distance error is dominated by the gravity error.

Applying the Galactic potential of Allen & Santillan (1991) we calculated orbits and reconstructed the path of the star through the Galactic halo with the program of Odenkirchen & Brosche (1992). The distance of the Galactic center from the Sun was adopted to be 8.0 kpc and the Sun’s motion with respect to the local standard of rest was taken from Dehnen & Binney (1998). As the RV is well known the error of the space motion is dominated by that of the distance, ruled by the gravity error, and those of the proper motion components. Varying these three quantities within their respective errors we applied a Monte Carlo procedure to derive the median GRF velocity $v_{\text{GRF}}$ at the present location and the velocity distribution (see Figure 4) and compare with the local escape velocity $v_{\text{esc}}$ as calculated from the Galactic potential of Allen & Santillan (1991).

A median GRF velocity of 694 km s$^{-1}$ (with the velocity distribution ranging from $-221$ to $+300$ km s$^{-1}$ around this value) makes J1539+0239 the fastest known halo star, superseding CS 22183–0014 (at $v_{\text{GRF}} = 635 \pm 127$ km s$^{-1}$; Sakamoto et al. 2003). This value is above the local escape velocity of $v_{\text{esc}} \approx 519$ km s$^{-1}$ in the potential of Allen & Santillan (1991). This three-component potential consists of a central bulge and a disk, which have a combined mass of $M_{\text{bulge+disk}} \approx 10^{11} M_\odot$. The halo out to 100 kpc is assumed to have a total mass of $M_{\text{halo}} \approx 8 \times 10^{11} M_\odot$. This total halo mass is insufficient to keep the star bound to the Galaxy.

J1539+0239 is located in the northern Galactic hemisphere ($l \approx 9.0$, $b \approx 42.95$), in the direction close to the Sagittarius stream (Belokurov et al. 2006; Fellhauer et al. 2006) and in particular close to the globular clusters NGC 5904 and Palomar 5, with its tidal tail (Odenkirchen et al. 2003). However, it is unlikely that J1539+0239 is related to either of those because of its distinct space motion and its position in the foreground. Its position and kinematics also rule out a scenario of a recent acceleration by an interaction with the supermassive black hole in the Galactic center, the principal mechanism for generating hypervelocity stars (Hills 1988). The star is currently approaching the Galactic disk and will pass the Galactic center at a minimum distance of about 8 kpc in the future. See Figure 5 for a visualization of the orbit of J1539+0239 in the Galactic halo (upper panel) and for a magnification of the Galactic disk region of the trajectory (lower panel).

Hence, in order to keep the trajectory of J1539+0239 bound to the Galaxy, the dark matter halo mass needs to be adjusted. We carried out numerical experiments increasing the halo density by a constant factor. Finally, we found a bound trajectory for a minimum mass of $M_{\text{halo}} \approx 1.7 \times 10^{12} M_\odot$. The last pericenter passage occurred at a distance of $\sim 7.7$ kpc and the apocenter distance of the star’s trajectory is located far out in the halo at $\sim 250$ kpc in this case. If we take into account the full velocity distribution (see Figure 4) of the star we can even derive solutions for the extrema, which correspond to the absolute errors, giving $M_{\text{halo}} \sim 1.7^{+2.3}_{-1.1} \times 10^{12} M_\odot$.

Whether the star is bound to the Galaxy, highly depends on the Galactic potential adopted, in particular on the mass of the dark matter halo, as pointed out by Abadi et al. (2009). Our $M_{\text{halo}}$ is similar to values found in several recent studies. Wilkinson & Evans (1999) used 27 satellite galaxies and globular clusters, and by assuming that they are bound, derived a total Galactic halo mass of $M_{\text{halo}} \sim 1.9^{+3.6}_{-1.6} \times 10^{12} M_\odot$. This value matches our derivation but has a larger uncertainty. Sakamoto et al. (2003) used 11 satellite galaxies, 137 globular clusters, and 413 field horizontal branch stars to derive a total Galactic mass. The exclusion of Leo I from their sample would lower the total Galactic mass from $M_{\text{total}} \sim 2.5^{+0.5}_{-1.0} \times 10^{12} M_\odot$ to a value of...
Figure 5. Upper panel: trajectories for the metal-poor horizontal branch star J1539+0239, relative to the Galactic disk (light blue). Applying a standard potential (Allen & Santillan 1991) the trajectory is unbound (black; $t \approx \pm 0.5$ Gyr), while increasing the halo density we found a bound trajectory (red; $-3$ Gyr $\leq t \leq +2$ Gyr). For reference, the Magellanic Clouds (blue dots) and the current position of J1539+0239 (black triangle) are marked. Lower panel: schematic two-dimensional visualization of the central region. Details of the trajectory in the immediate past and around the previous pericenter passage of J1539+0239 (brown solution) are shown in the X–Y, Y–Z, and X–Z planes. The positions of the Galactic center (black dot) and of the Sun are indicated.

(A color version of this figure is available in the online journal.)

$M_{\text{total}} \sim 1.8^{+0.4}_{-0.7} \times 10^{12} M_\odot$, both again in excellent agreement with our finding.

On the other hand, less than 4% of the trajectories resulting from our MC simulations would be bound for the most likely mass of Xue et al., $M_{\text{halo}} = 1.0 \times 10^{12} M_\odot$ (gray shaded area in Figure 4). Their RV study of ~2400 BHB stars—which includes J1539+0239 but lacks any proper motion measurements—therefore, likely underestimates the Galactic halo mass.

5. SUMMARY AND CONCLUSIONS

We reported the quantitative spectral analysis of a high-velocity star from the sample of faint blue halo stars of Xue et al. (2008). J1539+0239 was confirmed to be a Population II BHB star with a low metallicity of $[\text{Fe/H}] = -2.0$ and the characteristic enhancement of $\alpha$-elements. Hereby, we performed an NLTE analysis of a halo BHB star for the first time. While the majority of the weak lines were confirmed to be formed close to LTE conditions, many of the stronger metal lines—which are important diagnostics at the spectral resolution achieved within the SDSS—show pronounced NLTE strengthening, with the differences between the derived LTE and NLTE abundances typically amounting to 0.1 dex to 0.5 dex. In addition to information on the chemical composition, the RV, proper motion, and spectroscopic distance were derived and a detailed kinematical analysis was performed.

Carrying out kinematical numerical experiments using the Galactic potential of Allen & Santillan (1991) in order to obtain an orbit of J1539+0239 gravitationally bound to the Milky Way, we found that the mass of the dark halo has to be at least $M_{\text{halo}} \sim 1.7^{+2.3}_{-1.1} \times 10^{12} M_\odot$ (absolute uncertainties from extrema in MC error propagation). This mass limit is in good agreement with several previous studies (Wilkinson & Evans 1999; Sakamoto et al. 2003; Abadi et al. 2009). However, the significantly lower, most likely mass value of Xue et al. (2008) is consistent with our analysis only at a level of 4%, i.e., it likely underestimates the Galactic dark halo mass.

We conclude, that if the kinematics of a halo star is extraordinary enough, and the errors within the analysis are small, even one star alone can provide a significant lower limit to the dark matter halo mass, and to the total mass of the Milky Way (halo + bulge + disk), here $M_{\text{total}} \geq 1.8^{+2.3}_{-1.1} \times 10^{12} M_\odot$. The determining factor is that full kinematic information is available, as it will become routine in the era of the Gaia space mission, at much higher precision.

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