THE GALACTIC POTENTIAL AND THE ASYMMETRIC DISTRIBUTION OF HYPERVELOCITY STARS

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ABSTRACT

In recent years several hypervelocity stars (HVSs) have been observed in the halo of our Galaxy. Such HVSs have possibly been ejected from the Galactic center and then propagated in the Galactic potential up to their current position. The recent survey for candidate HVSs show an asymmetry in the kinematics of candidate HVSs (position and velocity vectors), where more outgoing stars than ingoing stars (i.e., positive Galactocentric velocities versus negative ones) are observed. We show that such kinematic asymmetry, which is likely due to the finite lifetime of the stars and Galactic potential structure, could be used in a novel method to probe and constrain the Galactic potential, identify the stellar type of the stars in the survey and estimate the number of HVSs. Kinematics-independent identification of the stellar types of the stars in such surveys (e.g., spectroscopic identification) could further improve these results. We find that the observed asymmetry between ingoing and outgoing stars favors specific Galactic potential models. It also implies a lower limit of $\sim 54 \pm 8$ main-sequence HVSs in the survey sample ($\geq 648 \pm 96$ in the Galaxy), assuming that all of the MS stars in the survey originate from the GC. The other stars in the survey are likely to be hot blue horizontal branch stars born in the halo rather than stars ejected from the GC.

Key words: black hole physics – galaxies: nuclei – stars: kinematics

Online-only material: color figures

1. INTRODUCTION

Hypervelocity stars (HVSs) are stars with extremely high peculiar velocities relative to the velocity distribution of their parent population. In recent years several HVSs have been observed in the Galactic halo, some of them unbound to the Galaxy (with velocities beyond the escape velocity; Brown et al. 2007b). From these a Galactic population of $96 \pm 10$ such HVSs was inferred (Brown et al. 2007b), up to the 100 kpc distance limit of the survey. Many similar bound HVSs (with velocities lower than the escape velocity) have been observed at larger numbers. Most of the observed HVSs are B-type stars (Brown et al. 2005, 2006a, 2006b, 2007a, 2007b; Edelmann et al. 2005; future observations of HVSs of other stellar types are discussed in Kollmeier & Gould 2007; Brown et al. 2009; Kenyon et al. 2008). Given the color selection of the targeted survey for these stars (Brown et al. 2006a), such stars could be either main-sequence (MS; or blue straggler) B stars or hot blue horizontal branch (BHB) stars. Currently, only three of the stars in the survey have specific unambiguous identification and were found to be MS stars (Fuentes et al. 2006; Lopez-Morales & Bonanos 2008; Przybilla et al. 2008a).

Extreme velocities as found for these stars most likely suggest a dynamical origin from an interaction with or close to the massive black hole (MBH) in the Galactic center (GC; Hills 1988; Yu & Tremaine 2003; Levin 2006; O’Leary & Loeb 2007; Perets et al. 2007). In the following we discuss only HVSs ejected from the GC and observed in the Galactic halo, > 10 kpc from the GC, which would require ejection velocities from the GC of $\geq 800$ km s$^{-1}$. Such HVSs could serve as probes of the GC environment, stellar population and dynamics (see, e.g., Sesana et al. 2007; Kenyon et al. 2008; Perets 2009b) and serve as an independent evidence for the existence of an MBH in the GC (Hills 1988). Most of the B-type stars observed through the HVSs survey have lower velocities and are either bound HVSs (Brown et al. 2007a) or are just halo stars. The survey shows an asymmetry in the kinematics of the stars, where more stars have positive radial velocities in Galactocentric coordinates (i.e., outgoing stars) than negative ones (ingoing or returning stars). As we show this asymmetry is dependent on both the absolute velocity and the distance of the stars from the GC, and could be used in a novel method to probe and constrain the Galactic potential, identify the stellar type of the stars in the survey and estimate the number of HVSs.

This paper is organized as follows. We first briefly describe the HVSs survey (Section 2), and then suggest a novel method to probe the Galactic potential using such surveys (Section 3). In Section 4, we use a similar analysis to infer the statistics of the stellar type of stars in the HVSs survey and estimate a lower limit to the number of HVSs in the Galaxy.

2. THE VELOCITY–DISTANCE DISTRIBUTION OF HVSs

HVSs of almost any stellar type could theoretically be observed, since the currently suggested scenarios for the origin of HVSs give rise to only limited number of constraints on their stellar characteristics (e.g., Hansen 2007; Perets 2009b). However, given their relatively small numbers in the Galaxy, it is practically impossible to find HVSs close by. For this reason, following the discovery of the first HVSs in the Galactic halo (Brown et al. 2005; Hirsch et al. 2005; Edelmann et al. 2005; Brown et al. 2006b) have issued a survey of HVSs extending to large distances. They have searched for HVSs among color
hot BHB stars, and therefore less distant. The velocity–distance distribution survey also searches for A type stars; Brown et al. 2009; not selected B-type halo stars of limited magnitude (a more recent ∼ such stars (see legend), for propagation up to the maximal lifetime of MS stars. The lines represent the critical asymmetry lines (see the text) for (2007b) observations (blue circles). (a) The observed stars are assumed to be Figure 1. Distance–velocity distribution of Halo B-type stars from Brown et al. (2007b) observations (blue circles). (a) The observed stars are assumed to be MS stars. The lines represent the critical asymmetry lines (see the text) for various potentials (see legend), for propagation up to the maximal lifetime of such stars (∼ 4 × 10^8 yr). (b) The same, but now assuming all the stars are hot BHB stars, and therefore less distant. The velocity–distance distribution of regular halo BHB stars (× marks; taken from Xue et al. 2008), is shown for comparison. Dashed middle line in both panels separates between outgoing and ingoing stars. The escape velocity (in the KZS model) is also shown for comparison in both panels. (A color version of this figure is available in the online journal.) Figure 2 in Brown et al. (2007b) shows a definite asymmetry in the distribution of ingoing and outgoing HVSs, where the velocities of ingoing stars do not extend beyond 300 km s^−1. Given that the escape velocity at these distances is much higher, one would expect to see bound HVSs returning at velocities up to the escape velocity, in striking contrast with observations. In order to study this behavior, we turn to the velocity–distance distribution of these stars. In Figure 1, we show the radial velocity–distance distribution (relative to the GC) for all of the observed B-type stars in the Brown et al. (2007b) survey, assuming they are either MS stars (and are therefore more luminous and more distant; Figure 1(a)), or hot BHB stars (and therefore closer; Figure 1(b)).

3. PROBING THE GALACTIC POTENTIAL USING HYPERVELOCITY STARS

Many studies have been done to constrain the Galactic potential at large distances through observations (see, e.g., Fich & Tremaine 1991; Battaglia et al. 2005; Smith et al. 2007; Xue et al. 2008, and references therein). Some of these studies use the velocity dispersion of observed objects to constrain the Galactic potential (e.g., Battaglia et al. 2005; Xue et al. 2008), however these suffer from uncertainties regarding the velocity anisotropy and the behavior of the stellar halo density at very large distances, and require some a priori assumptions regarding these parameters, which may lead to large uncertainties (see, for example, discussion in Dehnen et al. 2006). In addition, many objects are needed in order to obtain the velocity dispersion at a given distance from the GC. Other studies explore the local escape velocity from the Galaxy through observations of high-velocity stars (Smith et al. 2007). However, such analysis contains degeneracies and depends on the unknown structure of the tail of the velocity distribution of the high-velocity stars. Consequently, specific assumptions must be taken for the velocity distribution, which could be strongly affected by the small number statistics of the observed highest velocity stars in the distribution tail. Moreover, the assumptions used for the stellar velocities depend on their being extended up to the escape velocity from the Galaxy. Although large surveys may help solve this problem, very high velocity stars are quite rare in the Galaxy,
and would be difficult to find especially in surveys limited to relatively close environment of the solar neighborhood.

Gnedin et al. (2005) and Yu & Madau (2007) suggested to use the kinematics of HVSs in order to probe the Galactic potential using the position and velocity vectors of HVSs at large Galactocentric distances. Under the assumption that HVSs were ejected from the GC they suggest to measure the slight departure from purely radial orbits of these HVSs, due to the (possible) triaxiality of the Galactic potential. These methods require the accurate distance and three-dimensional velocity of HVSs, and focus on the triaxiality of the Galactic potential, which is important in the context of hierarchical, cold dark matter (CDM) models of structure formation (e.g., Hayashi et al. 2007), although we note this should be interesting also in respect to modified Newtonian dynamics (MOND) theories (Milgrom 1983). Recently, Kenyon et al. (2008) have studied the propagation of HVSs in the Galactic potential and showed that it could depend strongly on the Galactic potential at the central regions of the Galaxy (200 pc). They also showed the dependence of the HVSs radial distributions on the stellar type, and their observational implications.

In the following, we suggest a method which is more general in nature and more useful in constraining and distinguishing between different Galactic mass distributions which are required by the different Galactic potential models at large distances (although it could also be relevant to probing the triaxiality of the Galactic potential). This can also be used in order to discriminate between different CDM Galactic potential models and/or between Galactic potentials in MOND theories. This method makes use of the asymmetry in velocity distributions of ingoing and outgoing HVSs (see also related discussion in Kenyon et al. 2008). We begin with a naive description of the method, assuming one could observe even the oldest bound HVSs (i.e., those that could not leave the Galaxy, and could have gone through the Galaxy a few times). We then continue with a more realistic treatment which takes into account the finite lifetime of stars observable in the halo, given the limited observational capabilities.

3.1. Long-Lived, Observable Hypervelocity Stars

Let us assume that HVSs have been continuously ejected from the GC with some distribution of velocities, which would produce both bound and unbound HVSs. Unbound stars eventually leave the galaxy. Bound stars reach the apo-apse point of their orbit and then return back to the GC with negative radial velocity (in Galactocentric coordinates). The Galactocentric distance–velocity distribution of ingoing stars would then have a cutoff, which would correspond to the escape velocity of these stars at a given distance from the GC. Such a cutoff is distance dependent and thus more distant HVSs would have lower absolute velocities. At the same time, we should see that the distribution of outgoing HVSs extends to much higher absolute velocities, since this population includes the unbound stars, on their way out of the galaxy. Consequently, a clear asymmetry should be observed between the distribution of ingoing and outgoing stars. This asymmetry or cutoff in the distance–velocity distribution would map the escape velocity of stars from the galaxy at any given distance where HVSs are observed, and serve as a direct probe of the galactic potential. Note, however, that very different galactic potential may have escape velocities which are quite similar at a wide range of distances from the GC (Wu et al. 2008). In such cases, observations of more distant HVSs (i.e., wider distance range) may be required to distinguish between such potentials. Since such stars would be fainter, this would be more difficult observationally.

The use of ingoing and outgoing halo HVSs has three advantages over methods used to probe the local escape velocity from the Galaxy. First, there is a clear natural separation between bound and unbound stars, and the latter cannot contaminate the sample of ingoing high-velocity bound stars which are used to calculate the escape velocity. Second, there is no required assumption regarding the structure of the velocity distribution and its tail. Third, the HVSs are observed over a large distance range, and could thus map the Galactic potential in this full range, and not only at the local scale as have been done with high-velocity stars in surveys such as the Rave survey (Smith et al. 2007).

3.2. Realistic Short-Lived Hypervelocity Stars

In reality, observable stars in the HVSs targeted survey may not have an unlimited propagation time, as was our naive assumption. This may result either because of their short lifetimes (after which they evolve to a different stellar type, which cannot be observed at such distances with current instruments) or due to their possible origin from a burstlike event, which ejected HVSs only over a limited short time, and not as a continuous process occurring over the lifetime of the Galaxy (see Perets 2009b). Nevertheless, the general method prescribed above could still be applicable, with some modifications. In fact, as we the limited propagation time of HVSs may prove to be more advantageous in some respects).

Assuming some finite propagation time for HVSs, we would still expect an asymmetry in the ingoing and outgoing HVSs distance–velocity distributions. However, in this case the cutoff in the ingoing HVSs distribution would be at much lower velocities than the escape velocity. This cutoff corresponds to the maximal return velocity of HVSs which could still be observed coming back during their short propagation time. Assuming a maximal propagation time for the HVSs (its lifetime), this cutoff could thus be used as a probe of the Galactic potential in the same way as the naive method outlined above. Moreover, the short propagation time of stars can be advantageous for our purposes. Stars of different stellar types have different maximal lifetimes and would produce different distance–velocity cutoffs. Consequently, these different populations can supply us with several independent probes of the Galactic potential, that, combined together, would further assist in constraining the Galactic potential. A higher velocity at a given distance implies a longer travel time (as the travel time depends on the potential out to the apo-apse of the orbit), ingoing HVSs provide information not only on the escape velocity at the point where they are observed today, but even further away. Furthermore, up to the distance–velocity cutoff the distribution of outgoing and ingoing stars (with lower velocities than the cutoff velocity at their position) could be compared,7,8 in terms of the number of stars; the two-dimensional distance–(absolute) velocity distribution and the stellar types (if known) or color–color distributions of the samples of outgoing and ingoing stars. Any difference between these distributions is due to the further propagation in the Galactic potential of the ingoing HVSs to the apocenter of their

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7 In such a case, for example, the highest velocity bound HVSs may never be observed as ingoing HVSs, since a longer propagation time is required for them to reach the apo-apse point of their orbit and become ingoing HVSs.

8 This, however, is true only under the assumption of a continuous and constant ejection rate, which is not the case for burst ejection of HVSs by an inspiralling MBH (Levin 2006; Baumgardt et al. 2006; L"{o}ckmann & Baumgardt 2008; Sesana et al. 2008).
orbit and back. Different Galactic potential models give different return times that are also highly sensitive to the velocity of the HVSs. Consequently, the statistical correlation between the ingoing and outgoing distance–velocity distributions could serve as a quantitatively sensitive method for discriminating between models for the Galactic potential than just the population of the highest velocity ingoing HVSs.

3.3. Discriminating Between Galactic Potential Models

Currently, only three HVSs in the HVSs survey have an unambiguous stellar-type identification, and the analysis suggested here for probing the Galactic potential cannot be used directly. The clear cutoff in the ingoing stars distribution would not be observed, as it would be smeared by the existence of hot BHB stars contaminating the sample. Nevertheless, we still expect a statistical asymmetry between the number of ingoing versus outgoing stars in the sample, which should be observable beyond the theoretical cutoff. As an illustrative example we show the critical asymmetry lines for propagation of MS B stars HVSs up to a maximal lifetime of $4 \times 10^8$. In Figure 1(a), we show the critical asymmetry lines for such time-limited propagation in different models for the Galactic potential. The different models we use include five dark matter (CDM) potentials and one MOND potential. Beside the Paczynski (1990) model (hereafter PAC) all models are described in detail in Wu et al. (2008), where the same reference names are used (KZS, BSC, RAVE 1–3, and MOND). The PAC, KZS, BSC, and the MOND models are almost indistinguishable in this range of distances, whereas the RAVE 1–2 (indistinguishable in this range) and RAVE 3 models show very different behavior (see Appendix A for a short discussion on the differences between these Galactic potential models). We look for asymmetry by counting the numbers of outgoing versus ingoing stars in the sample, for the different potentials, i.e., counting the number of stars above and below the positive and negative velocity lines of the critical asymmetry curves shown in Figure 1(a). We look for the best fit model, which should show the largest asymmetry. We find a total of 166 outgoing stars versus 112 ingoing stars for the PAC, KZS, BSC and MOND models (the probability for getting such an asymmetric distribution from an a priori symmetric distribution is $p = 10^{-3}$) and 378 (452) outgoing stars versus 319 (388) ingoing stars for the RAVE 3 (RAVE 1–2) models ($p = 0.025 (0.027$)). Although all models show asymmetric distributions, the stars counted for the RAVE models contain the contribution from the PAC/KZS/BSC/MOND models. When subtracting this contribution, we find that the RAVE models do not show any additional asymmetry (212 (286) outgoing vs. 207 (276) ingoing stars; $p = 0.8 (0.67)$). Therefore, the HVSs sample favors the PAC, KZS, BSC and MOND models over the RAVE models.

As we have shown even the contaminated sample of HVSs could already constrain Galactic potential models. Future identification of the stellar types of the stars in the survey which could purify it could give even stronger constraints on these and other Galactic potential models. In Appendix B, we give a simple example for the use of such future data, using mock simulated data of ejected HVSs. We also note that stars with longer MS lifetimes could probe larger distance range during their propagation and still return during their MS lifetimes to be observed as ingoing HVS. Such stars could therefore serve as observable probes of the Galactic potential at even larger distances not accessible in any other ways (and could possibly discriminate between CDM and MOND models that differ only at these distance ranges). This would require the identification of later-type HVSs among halo stars (e.g., Brown et al. 2009, not analyzed here).

4. PROPAGATION IN THE GALACTIC POTENTIAL AND THE LIFETIMES OF OBSERVED HYPERVELOCITY STARS

The method described above uses the finite lifetimes of stars and their kinematics to constrain the Galactic potential. A very similar approach could also be used to constrain the number of the HVSs and their lifetimes, given a specific Galactic potential. Making use of this approach we show that most of the stars in the HVSs survey, especially with ingoing velocities, are likely to be halo hot BHB stars and have not been ejected from the GC (see also Kollmeier & Gould 2007; Yu & Madau 2007; Brown et al. 2007b; Kenyon et al. 2008, for related discussions), but nevertheless the number of HVSs ejected from the GC could be much higher than previously thought.

In the previous section, we described the critical distance–velocity asymmetry lines. For a given Galactic potential and a given propagation time of an HVS, one could find the critical line outside which no such ingoing stars should be observed. In other words any ingoing star beyond this line cannot be an HVS from the GC with such (or shorter) lifetime. We can therefore identify at least some of the HVSs sample stars as stars that are not MS stars ejected from the GC using this criteria (see Svensson et al. 2007 for a related discussion). Moreover, since the distribution of such stars should be symmetric (as observed for other samples of halo objects, such as regular halo BHB stars) any asymmetry beyond the critical lines is due to the outgoing MS HVSs from the GC (or from the Galactic disk, a possibility which we do not discuss here).

Assuming the PAC model (or the KZS and BSC model that give similar results) and a maximal propagation time of $4 \times 10^8$ yr (lifetime of a $3 M_\odot$ MS B star) we find an overabundance of $116 = 112 = 54$ outgoing stars, where an asymmetry of eight stars correspond to the 1σ probability level. We therefore give a lower limit estimate for the number of HVSs beyond the critical line of $\gtrsim 54 \pm 8$ HVSs, from which we infer, following the calculations by Brown et al. (2007b), that a total number of $\gtrsim 648 \pm 96$ such stars (MS B stars of $3-4 M_\odot$ at distances of $10 kpc \lesssim r \lesssim 100 kpc$ ejected from the GC) exist in the Galaxy. We expect that most if not all of the ingoing stars beyond the critical line are hot BHB stars, where outgoing stars beyond the line could be both hot BHB stars or MS stars, with a ratio of 2 to 1 ($166 - 54 = 112$ versus 54). These large estimated number of HVSs may suggest a different contamination from high-velocity stars ejected from the Galactic disk that could also produce an asymmetric distribution due to finite MS lifetimes of the stars. Here we do not address this possibility, which requires a more detailed study and would be addressed in another paper.

In this calculation, we assumed a specific maximal propagation time for the GC HVSs. Instead, we can look at the asymmetric distributions for stars that propagated in the Galactic potential for shorter propagation times. Such stars could be either more massive MS B stars with shorter MS lifetimes, or MS stars ejected from the GC only after evolving for some time in the GC (or ejected more recently from the GC). Since the frequency of more massive stars is small, the latter possibilities are

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9 In fact, rejuvenated blue straggler stars could therefore contaminate the sample of the HVSs, however this population is not expected to be large (Perets 2009a).
more likely to apply. One would therefore expect to see an asymmetric distribution even at times shorter than the MS lifetime of 3 $M_\odot$ B MS star ($4 \times 10^8$ yr), likely of the order of half this time ($\sim 2 \times 10^8$ yr), assuming a continuous ejection rate of HVSs. In Figure 2, we show the number of outgoing versus ingoing stars for a range of propagation times. For the PAC potential model we used, the distribution begins to become asymmetric at propagation times of $2.5 \times 10^8$ yr, in good agreement with our expectations.

For completeness, we discuss the possibility that the HVSs are not MS stars but hot BHB stars ejected from the GC. In this case their absolute magnitude is different from that of MS stars, and the inferred distances change accordingly (see Figure 1(b)). Again we can look for the typical propagation time at which we see an asymmetric distribution of these stars assuming they were ejected from the GC. We find this to be at a few $10^8$ yr. This time is comparable, but longer, than the lifetime of hot BHB stars at this phase. It is also much shorter than the lifetime of hot BHB progenitors, which could extend up to a few Gyr. Both of these inconsistencies, together with the dynamical constraints against the ejection of hot BHB HVs (Perets 2009b), suggest a different identification of these stars. Furthermore, comparing their velocity–distance distribution to that of regular BHB stars, which could have correlated velocities, and not an isotropic distribution as we assumed. To check this, we repeated the asymmetry calculations described above, but this time for several different and distinct regions in the Galactic halo (different Galactic longitudes). Although some differences in the strength of the asymmetry are observed, all regions showed a clear asymmetry bias toward outgoing stars.

5. SUMMARY

In this paper, we studied the characteristics, the origins, and the use of stars observed in the survey for HVSs in the Galactic halo. The kinematics of currently observed HVSs ejected from the GC depend strongly on their lifetimes and their propagation in the Galactic potential. We suggest a novel method to probe the Galactic potential up to large distances using the kinematics and the spectral identification of HVSs. We also use a reverse method, where a specific Galactic potential model is assumed, to give lower limit estimates on the number of HVSs ejected from the GC. Future observations of HVSs in M31 (Sherwin et al. 2008) and in other galaxies could have a similar use for studies of galactic structures and potentials.

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stars which would end their lifespan on the MS before current
day, i.e., they would not have been observable today. Each of
the potentially observable HVSs is then propagated in a given
Galactic potential until the current day. For simplicity, we show
the results for the propagation of HVSs in two Galactic potential
models, which differ in only one parameter. We use the PAC
model which is parameterized by eight parameters (see details
in Paczynski 1990), to produce two potentials. The first (PAC)
is the Galactic potential as originally parameterized in
Paczynski (1990), and the second (PAC-2) differs only in the halo core
radius, \( r_c \), which is taken to be \( r_c = 2 \) kpc instead of \( r_c = 6 \) kpc
in the original PAC model. The number of simulated stars was
chosen such that the total number of HVSs with velocity greater
than 450 km s\(^{-1}\) observable in the Galactic halo would be
\( \sim 100 \), i.e., the total number of such HVSs estimated to exist in the
Galaxy based on current surveys.

The distance–velocity distribution of ingoing simulated HVSs
is shown in Figure 3, together with the critical asymmetry
lines for the two models. As can be seen in the figure, HVSs propagating in the PAC-2 model obtain distance–velocity
position beyond the critical asymmetry line of the PAC model,
i.e., the PAC model would be directly excluded, independently
of the detailed distribution of the HVSs. HVSs propagating in
the PAC model could never get beyond the critical asymmetry
line of the PAC-2 model and therefore can never totally exclude
this model. Nevertheless, the probability for not observing even
a single HVS beyond the PAC critical asymmetry line, assuming
that the HVSs did propagate in the PAC-2 model is \( \sim 0.007 \) (one
would expect to see five such stars in the sample of 25 ingoing
HVSs, given the PAC-2 model data, but none is observed), i.e.,
rejecting the PAC-2 model at high confidence.

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