The Astrophysical Journal, 664:343–348, 2007 July 20

WHERE ARE THE OLD-POPULATION HYPERVELOCITY STARS?

Juna A. Kollmeier[1,2] and Andrew Gould[3]
Received 2007 January 11; accepted 2007 March 22

ABSTRACT

To date, all of the reported hypervelocity stars (HVSs), which are believed to be ejected from the Galactic center, are blue and therefore almost certainly young. Old-population HVSs could be much more numerous than the young ones that have been discovered, but still have escaped detection because they are hidden in a much denser background of Galactic halo stars. Discovery of these stars would shed light on star formation at the Galactic center, would constrain the mechanism by which they are ejected from it, and, if they prove numerous, would enable detailed studies of the structure of the dark halo. We analyze the problem of finding these stars and show that the search should be concentrated around the main-sequence turnoff ($0.3 < g - i < 1.1$) at relatively faint magnitudes ($19.5 < g < 21.5$). If the ratio of turnoff stars to B stars is the same for HVSs as it is in the local disk, such a search would yield about 1 old-population HVS per 45 deg^2. A telescope similar to the Sloan 2.5 m could search about 20 deg^2 per night, implying that such a population, should it exist, would show up in interesting numbers in short order.

Subject headings: Galaxy: center — Galaxy: halo — Galaxy: kinematics and dynamics — Galaxy: stellar content — stars: late-type

1. INTRODUCTION

Hypervelocity stars (HVSs; stars with velocities in excess of the Galactic escape speed) have come a long way since Hills (1988) predicted their existence. It is now appreciated that, beyond being a dynamical curiosity, these stars are useful probes of multiscale Galactic phenomena. Their frequency, spectral properties, and distribution provide important constraints on the character of star formation in the Galactic center (GC), as well as the stellar ejection mechanism itself. Furthermore, in sufficient numbers these objects are unique dynamical tracers of the shape of the Milky Way's dark matter halo, a critical quantity in understanding how the Galaxy fits into the overall picture of hierarchical structure formation (Gnedin et al. 2005).

Due to their rapid Galactic exit times and low predicted ejection rates for plausible dynamical mechanisms (e.g., Yu & Tremaine 2003; Perets et al. 2007), these stars are relatively rare. The first HVS discovery was a serendipitous by-product of a kinematic survey of blue horizontal branch (BHB) stars (Brown et al. 2005). Through spectroscopic follow-up of 36 faint ($19.75 < g < 20.5$), color-selected [$(0.8 < u - g < 1.5) \cap (-0.3 < g - r < 0.0)$] BHB stars from the Sloan Digital Sky Survey (SDSS) First Data Release, these authors discovered a 6 σ radial velocity outlier at 709 km s^{-1} with $g = 19.81 \pm 0.02$ and dereddened colors of $(u - g)_0 = 1.04 \pm 0.09$ and $(g - r)_0 = -0.30 \pm 0.03$. This star was subsequently determined to be a pulsating B-type main-sequence star at a distance of 110 kpc (Brown et al. 2006a; Fuentes et al. 2006). Shortly after this discovery, two additional HVSs were found, also within surveys designed for the selection of early-type stars. During their survey for subluminous B stars (sdB), Edelmann et al. (2005) discovered an 8 $M_\odot$ B star with a radial velocity of 563 km s^{-1} located at $\sim$60 kpc from the Galactic center, potentially ejected from the LMC. Hirsch et al. (2005) followed up star US 708 as part of a survey of $\sim$100 subluminous O stars selected from SDSS that had colors of $u - g < 0.2$ and $g - r < 0.1$ and found it to be a helium-rich subluminous O star (HesdO) traveling at $\sim$720 km s^{-1} at 25 kpc from the GC. After these initial discoveries, in which HVSs were contaminants in surveys for other blue stars, Brown et al. (2006a) undertook the first *targeted* survey for HVSs, in which candidates were selected to be relatively faint, $17 < g < 19.5$, with B star colors. This search strategy has two key components: maximizing both the volume covered and the contrast with normal halo stars. The faint magnitudes achieve the first aim, while both the color and magnitude selection contribute to the second. Contrast is improved at faint magnitudes (large distances) because the HVS density should drop off as R^{-2}, where R is the Galactocentric distance, while the normal halo stars drop off faster than R^{-3}. It is improved at blue colors because the only blue halo stars are BHB stars, which have short lifetimes and therefore low density, and white dwarfs, which are even rarer. Brown et al. (2006a, 2006b, 2007) found 4 probable HVSs out of 894 candidates culled from 5000 deg^2; i.e., a density of 1/1250 deg^{-2}.

All reported HVSs are blue, which simply reflects the fact that, after the first three serendipitous discoveries, the searches were conducted among blue stars. One can imagine extending previous work in several possible directions in parameter space, for example, by searching for the A stars emerging from the same underlying population as the already discovered B stars. If the HVSs are typical of bulge stars, however, there should be many *old* ones. Due to the high background of unevolved halo stars, no one has yet undertaken the daunting (and seemingly hopeless) task of a comprehensive survey for this *late-type* population of HVSs.

However, determining whether this population exists and in what proportion would be of great interest. In particular, the ratio of old to young HVSs would place important constraints on the stellar ejection mechanism itself. It is possible that the distribution of HVS ages reflects the distribution in the stellar cusp near the GC. Models that suggest that HVS ejections are due to a short burst of scatterings from an intermediate-mass black hole (IMBH) that falls to the GC by dynamical friction

[1] Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, CA 91101.
[2] Hubble Fellow, Carnegie-Princeton Fellow.
[3] Department of Astronomy, The Ohio State University, 140 W. 18th Avenue, Columbus, OH 43210.

and disrupts the stellar cusp there (Levin 2006; Baumgardt et al. 2006) would be directly tested by knowledge of the HVS age distribution. With high-precision proper motion measurements of a sufficient number of HVSs, one could measure not only the Galactic potential, but also the times of ejection for individual stars (Gnedin et al. 2005). Regardless of the relative number of late- to early-type HVSs, measurement of this ratio would be interesting. If the ratio proved small, this observational fact could constrain pictures in which the young stars near Sgr A* are brought to the GC in clusters along with an IMBH, as suggested by Hansen & Milosavljević (2003). It is also possible that late-type HVSs vastly outnumber early-type HVSs, but the difficulty in finding this population has prematurely biased our view of it. Should this be the case, such stars would be vital probes of Galactic structure.

In brief, the true age distribution of HVSs is simply unknown. We therefore turn to the problem of how to find the old population. Clearly, it is not practical at the current time to attempt spectroscopy of all halo stars. In § 2 we analyze the problem of developing optimal selection criteria to search for them. Then in § 3 we comment on the prospects for detecting HVSs in future surveys.

2. NEEDLES IN A HAYSTACK

Old-population HVSs must be much less common than even the relatively low density population of halo stars. Otherwise they would have been discovered in spectroscopic surveys of high proper motion stars. Hence, finding such stars against the much more numerous background of halo stars will require a well thought out search strategy.

If HVSs are ejected isotropically from the Galactic center at a rate Γ, then their density at a Galactocentric distance R is

$$\rho(R) = \frac{\Gamma\langle[v(R)]^{-1}\rangle}{4\pi R^2}, \tag{1}$$

where $v(R)$ is the velocity of the ejected star as a function of R and where the brackets indicate averaging over the inverse velocities. Note that Γ could refer to the HVS population as a whole or to any subclass of stars within it.

2.1. *Zeroth-Order Analysis*

To facilitate the exposition, we make a set of simplifying assumptions. Taken together, these lead to a toy model that, while not realistic, does yield a useful starting point for understanding the problem of finding HVSs. In the next section (§ 2.2) we will sequentially relax these assumptions, allowing the features of the real problem to come into focus.

First, we assume that HVSs do not decelerate as they leave the Galaxy. Equation (1) then simplifies to $\rho(R) \propto R^{-2}$. Second, we assume that the physical density of halo stars also scales as $\rho_{\rm halo} \propto R^{-2}$. Under this very unrealistic assumption, the ratio of HVSs to halo stars would have the same constant value at any position in the Galaxy. Finally, we assume that the color-magnitude relation of the old-population HVSs is identical to that of the halo stars. Together, these assumptions would imply that the ratio of HVSs to halo stars is exactly the same for candidates selected at any color and apparent magnitude and in any direction, provided only that the selection criteria ensured that disk and thick-disk stars were effectively excluded.

2.2. *First-Order Analysis*

As each of the three assumptions is relaxed, the fraction of HVSs increases with increasing R. First, from equation (1), progressive deceleration makes the density of HVSs fall more slowly than R^{-2}. Second, the density of halo stars falls much more quickly than R^{-2}. Locally, halo stars fall roughly as $R^{-3.2}$ (e.g., Gould et al. 1998), and the relation steepens further out. Third, stars near the Galactic center are generally more metal-rich than halo stars, which implies that they are more luminous on the upper main sequence. As we will show below, upper main sequence and turnoff stars dominate the HVS discovery potential. The fact that HVSs are more luminous implies that they lie at farther distances at a fixed magnitude. Hence, they cover a larger range of distance over a fixed magnitude range than do the corresponding halo stars. This enhances their density as a function of apparent magnitude.

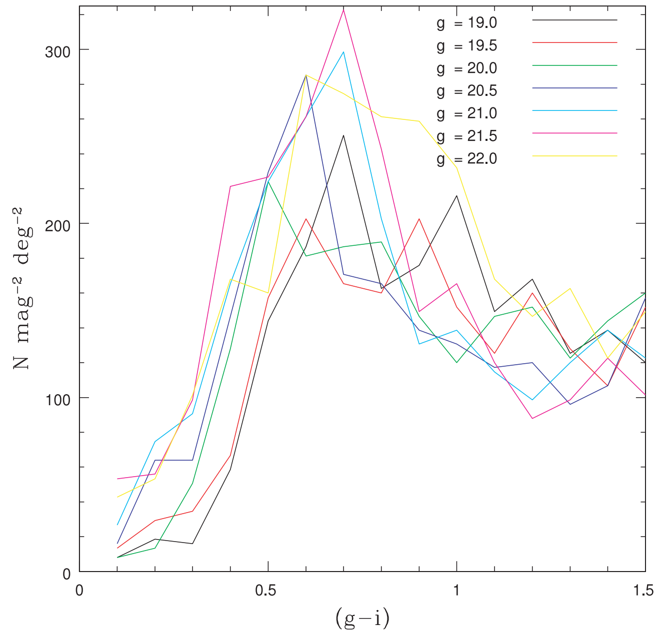

FIG. 1.—Density (in units of mag^{-2} deg^{-2}) of stars in the color-magnitude diagram of the SDSS high-latitude anticenter field toward $(l, b) = (196°, -40°)$. Curves correspond to constant-magnitude bins at half-magnitude intervals from $g = 19$ to $g = 22$. To a first approximation, all the curves are the same. Moreover, they are roughly flat redward of the turnoff (at $g - i \sim 0.65$), and even on the turnoff, they are only about double the plateau value.

Thus, other factors being equal, one should try to search for HVSs as far from the Galactic center as possible. Within a given field, "other factors" are obviously not equal, as it is easier to search among bright than faint stars. So this issue will require additional analysis. However, we are at least driven to the conclusion that the search for HVSs will be easiest toward high-latitude, Galactic-anticenter fields: high latitude to avoid contamination from disk stars, and anticenter to reach the maximum R at fixed apparent magnitude.

2.3. *Characteristics of the Background*

Because the selection criteria for HVS candidates can only be color and apparent magnitude, we must begin by analyzing the background in terms of these two variables. We adopt a purely empirical approach, tabulating the density of stars toward a SDSS field centered at approximately R.A.(J2000.0) = $4^{\rm h}$, decl.(J2000.0) = $-6°$ ($l = 196°$, $b = -40°$). Figure 1 shows the stellar density as a function of $g - i$ color for seven different magnitude bins centered on $g = 19.0, 19.5, \ldots, 22.0$. The key point is that in this magnitude range and in the region from the turnoff redward, this density varies by less than a factor of 4 altogether and only by a factor of 2 in the basic trend with color.

Moreover, the color profiles at each g magnitude are approximately the same. These characteristics imply that the background does not play a crucial role in devising selection procedures for HVS candidates, as it would have, were the curves clearly separated: rather, the color/magnitude selection must be based primarily on maximizing the total number of HVSs and minimizing the amount of observing time required to identify them as HVSs. We return to the issue of turnoff versus giant and lower main sequence stars in § 2.4.

2.4. *Color Selection*

Under certain simplifying assumptions, the color/magnitude selection actually factors into separate selections in color and magnitude. We first introduce and motivate these assumptions and later evaluate how their relaxation would impact our conclusions.

First, we assume that deceleration is negligible, such that, as mentioned in § 2.1, $\rho \propto R^{-2}$. In fact, for an isothermal sphere of circular velocity $v_{\rm circ} = 220$ km s^{-1}, the squared velocity falls by $\Delta v^2 = 2v_{\rm circ}^2 \ln(R_2/R_1)$ between R_1 and R_2. For example, a star traveling at 800 km s^{-1} at 15 kpc will slow by 15% to 675 km s^{-1} at 100 kpc. This is not completely negligible, but it is modest compared to other factors in the problem. Under this assumption, the number of HVSs with a fixed absolute magnitude (and so by assumption a fixed color) and a narrow range of apparent magnitudes Δg is

$$N = \frac{\ln 10}{5} \frac{\Gamma \langle v^{-1} \rangle}{4\pi} \Omega \Delta g \frac{r^3}{R^2}, \qquad (2)$$

where Ω is the angular size of the field and r is the distance from the observer to a star at the center of the magnitude bin.

Second, we assume that $R = r$, which reduces the last term in equation (2) from r^3/R^2 to r. That is, $N_{\rm naive} \propto r$. The ratio of this naive estimate to the true number is

$$\frac{N_{\rm naive}}{N} = 1 - 2\cos l \cos b \frac{R_0}{r} + \frac{R_0^2}{r^2} \rightarrow 1 + 1.47 \frac{R_0}{r} + \frac{R_0^2}{r^2}, \qquad (3)$$

where $R_0 = 8$ kpc is the solar Galactocentric radius. Clearly this correction can be fairly large, so we will have to carefully assess its impact after the selection criteria are derived.

Because radial velocity (RV) measurements are most efficiently carried out in the g-band part of the spectrum, the RV precision for a fixed exposure time is basically a function of the g magnitude. This is not exactly true, because the metal lines, from which these determinations are primarily derived for FGK stars, are stronger at lower temperatures. However, this is a modest correction, which we will ignore for the moment but to which we will return below.

Consider now an ensemble of HVSs drawn randomly from a common old-star isochrone and ejected isotropically and stochastically from the Galactic center. We now select stars at a fixed g magnitude (or, rather, in a narrow interval Δg centered at a fixed value of g), which have a variety of absolute magnitudes M_g and therefore (through the color-magnitude relation of the isochrone) a variety of $g - i$ colors (which are what we actually observe). The stars at M_g will be seen over a range of distance $\Delta r = [(\ln 10)/5]10^{0.2(g - M_g + 5)} \Delta g$ pc; i.e., $\Delta r \propto 10^{-0.2 M_g}$. Under the above two assumptions, the relative number of such stars in the sample will be

$$N_{\rm det}(M_g) \propto 10^{-0.2 M_g} \Phi(M_g), \qquad (4)$$

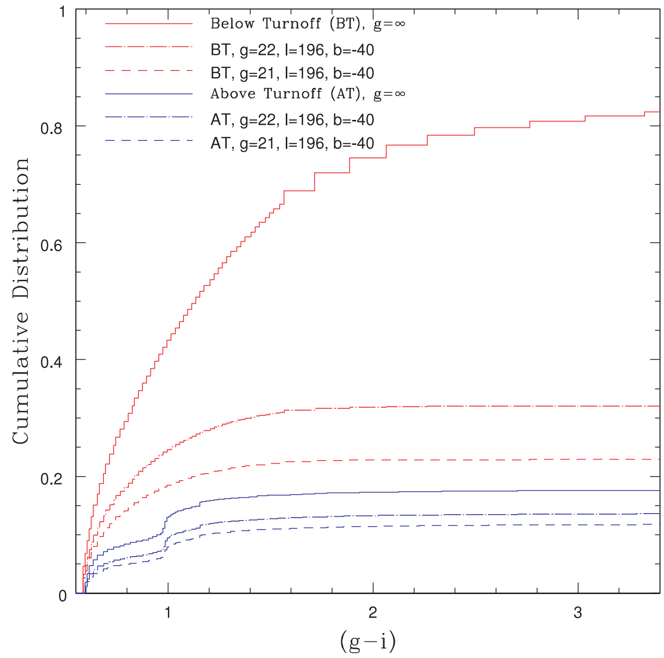

Fig. 2.—Cumulative distribution of expected hypervelocity star detections of apparent magnitude g as a function of $g - i$ color, under the assumption that all stars in the underlying old population are equally likely to be ejected from the Galactic center. The red curves represent stars below the main-sequence turnoff, while the blue curves represent stars above the turnoff. At very faint magnitudes, the result is independent of magnitude and is shown by the two solid curves, whose total is arbitrarily normalized to unity. At realistic magnitudes, $g = 22$ (*dot-dashed curves*) or $g = 21$ (*dashed curves*), the detections are somewhat suppressed by eq. (3), particularly for the branch below the turnoff. For these curves, the great majority of the expected detections are at $g - i < 1.1$.

where $\Phi(M_g)$ is the fraction of stars from the isochrone in the M_g bin. Note in particular that this relative number does not depend on g, the apparent magnitude at which they are selected.

Figure 2 shows the cumulative distribution of these relative numbers as a function of color (the observed quantity) for an isochrone of solar metallicity and an age of 10 Gyr (Demarque et al. 2004). Since these are given in the Johnson-Cousins system, we convert to SDSS bands using the transformations by R. Lupton given on the SDSS Web site.[4] When the isochrone is viewed as a "function" of color, it is double-valued. To illustrate the role of the two branches, we plot their cumulative distributions separately, although of course these could not be distinguished from color/magnitude data alone. The solid curves illustrate the result under the assumption that $r = R$; i.e., effectively that $g = \infty$. The dashed and dot-dashed curves show the more realistic cases of $g = 22$ and $g = 21$ in the direction $(l, b) = (196°, -40°)$.

There are several important features of this diagram. First, and by far most important, the great majority of potential sensitivity to old-population HVSs comes from stars with $g - i$ colors within 0.5 mag of the turnoff; i.e., with $g - i < 1.1$. This is already basically true for the naive $g = \infty$ case, but strictly applies in realistic cases, $g \lesssim 22$. By contrast, both the M and late-K dwarfs on the lower branch and the M and late-K giants on the upper branch contribute very little, the former because they are so close and the latter because they are so rare. Note that the dominance of turnoff stars is a specific result of the $L^{1/2}$ luminosity dependence in equation (4). If $N \propto L^{3/2}$ (as in a magnitude-limited sample of uniform density population), then giants would dominate. If

[4] See http://www.sdss.org/dr5/algorithms/sdssUBVRITransform.html.

$N \propto L^0$ (as in a magnitude-limited sample of an r^{-3} halo-star–like population), then dwarfs would dominate. Second, the lower branch contributes a bit more than double to the detection rate than the upper branch for realistic cases. That is, the sample is dominated by stars just below the turnoff, with a significant, although clearly secondary, contribution from stars just above the turnoff. This implies that the validity of our approximations is basically determined by how well they hold up at the turnoff. Third, the small contribution from late-type giants obviates another potential complication. Depending on the precise form of the ejection mechanisms, it is possible that giant star ejection is suppressed relative to smaller stars. For example, some or all of the ejections might take place from disruption of relatively tight binaries that are too close to permit giant star survival. Had Figure 2 implied that giants dominated the HVS distribution, this would lead to significant uncertainty. However, the small contribution of giants, particularly late-type giants, implies that any such suppression would also have a small impact. The one exception to this is the clump giants, which are not included in the Yale Isochrones (Demarque et al. 2004) and hence are not represented in this figure. They would contribute a small bump in the "above turnoff" curve, similar in amplitude to the bump at $g - i \sim 1$ that is actually seen in this curve, which is due to first-ascent giants. With radii of 10 times solar, these stars are themselves relatively small. However, with ages of only 100 Myr, they are younger than the transport time to their current location, roughly 200 Myr at $g = 21$ and velocity $v = 700$ km s^{-1}. Hence, the progenitors of these stars would have had to have been ejected when they were very distended. In any event, they are not included in the figure. We note that the slightly greater RV precision (at fixed g and fixed exposure time) of cooler stars also has negligible impact, again because of the small contribution of these stars. One final point to consider is that stars initially ejected as turnoff stars could go through a giant phase during their transit out of the Galaxy. Conservatively, we estimate that at a $g = 21$ limit, a giant with $M_g = 1$ could be detected at a distance of $d = 100$ kpc. This would imply a flight time of approximately 170 Myr, which would be marginally sufficient for the giant to have been ejected as a turnoff star. This condition holds even more strongly for stars at the tip of the giant branch ($M_g = -2.5$), which are detected at larger distances and whose flight times are more than sufficient for them to have been ejected as turnoff stars. However, as shown in Figure 2, the contribution of these very late type giants is extremely small.

From this analysis, we conclude that at a fixed magnitude, selection should start from the turnoff and proceed redward to $g - i = 1.1$. In practice, the old-population HVSs will not come from a single isochrone, but from a superposition of many isochrones with a variety of ages and metallicities. However, all of these are qualitatively similar, with just slightly varying turnoff colors. Indeed, we investigated a 5 Gyr isochrone and found results that were qualitatively similar to those shown in Figure 2. The important practical point is just to sample the field stars beginning at colors blue enough to cover all such turnoffs. The cost of moving the blue boundary further blueward by $\Delta(g - i) = 0.3$ is quite small, since this region of the observed field star color-magnitude diagram has few stars. We therefore advocate a color selection of $0.3 < g - i < 1.1$.

2.5. *Magnitude Selection*

Observations of a fixed exposure time can potentially measure RVs to a given precision down to a certain apparent magnitude limit g. Once this is established, one could in principle measure RVs for all stars within this limit, or (if fibers/slits were scarce) only those within 2 mag of the limit, which would contain >60% of all the HVSs within the magnitude limit. The following arguments apply equally to either strategy.

Let us first suppose that "downtime" (for slewing, readout, and changing slit masks or fiber positions) is negligible compared to the exposure time. Let us compare two observation strategies, the first with a single field exposed for a time Δt and the second with two fields each exposed for $\Delta t/2$. Let us initially assume that the magnitude limit is above sky in both cases. Then the flux limit will be a factor of 2 larger in the second case to maintain the same signal-to-noise ratio (S/N). The maximum observable distance will therefore be reduced by $2^{-1/2}$, which will decrease the number of HVSs detected in each field by the same factor. However, since there are twice as many fields, the total number of detected HVSs will increase by $2^{1/2}$. Hence, it is always better to go to shorter exposures of more fields. If both limits are below sky, then the flux limit increases by $2^{1/2}$, so the distance limit decreases by $2^{-1/4}$, and the number of HVSs from both fields increases by $2^{3/4}$. That is, the same argument applies even more strongly.

Now consider the opposite limit, in which the exposure time is negligible compared to the downtime. Shortening the exposure time then still increases the flux limit and so reduces the number of HVSs detected by $2^{-1/2}$, but in this case there is no compensating increase in the number of fields covered. Comparing the two cases, it is clear that the exposure times should be set approximately equal to the downtime. It can be shown that the optimal exposure time is exactly equal to the downtime if the magnitude limit is above sky and is equal to 1/3 of the downtime if it is below the sky.

This argument somewhat overstates the case: it would be strictly valid if the cumulative distributions illustrated in Figure 2 were identical for the limiting magnitudes corresponding to the two different exposure times. These curves are nearly identical for the upper branch, but less so for the lower branch. However, the argument remains qualitatively valid, the correction being toward exposures that are somewhat longer than the downtime.

2.6. *Observing Strategy: General Considerations*

Before analyzing the characteristics of specific spectrographs, there are two general points to consider. First, from Figure 1, the stellar density in our recommended color range, $0.3 < g - i < 1.1$, is about 150 mag^{-1} deg^{-2}. Hence, if one is to cover 2 or 3 mag in g, this requires monitoring 300–500 stars per square degree. Note that in another direction, $(l, b) = (275°, 62°)$, we find stellar densities in this color-magnitude range that are about 2.5 times higher, confirming that it is substantially easier (in terms of the sheer number of background contaminants) to search for old-population HVSs in high-latitude anticenter fields.

Second, the RV precision requirements to distinguish escaping HVSs from halo stars are not very severe: $\sigma = 50$ km s^{-1} would be quite adequate. This precision is not difficult to achieve even in very noisy spectra, particularly for FGK stars, which have many spectral features. Typical HVSs have RVs of $v_r \sim 700$ km s^{-1}, well separated from halo stars, whose dispersion as measured locally is only $\sigma(v_r) \sim O(170$ km s$^{-1})$ (Popowski & Gould 1998). There are, of course, halo stars moving closer to the escape velocity, but the extreme tail of this distribution is quite thinly populated.

However, the most recent work by Brown et al. (2007) reveals the existence of a "bound" population of HVSs. In order to distinguish this population from high-velocity outliers in the normal halo population, one might want to aim for higher precision RV measurements. Of course, it is impossible to definitively identify "bound HVSs" on a star-by-star basis from RV data alone: proper motions would be required to determine whether their orbits point back to the Galactic center. Hence, the question is what RV precision is required to identify strong candidates above the tail of the halo-star background. We therefore will return to this question of identifying "bound HVSs" in § 3 after evaluating the expected density of these stars relative to the background.

2.7. *Specific Evaluations*

From this point forward, concrete development of an observing strategy obviously depends on the detailed characteristics of the multiobject spectrograph, which cannot be treated completely generally. However, to give some broad guidance and to help understand the sensitivity of the search under realistic conditions, we consider two specific multiobject spectrographs with radically different characteristics.

First, we consider the resolution $\mathcal{R} = 2000$ SDSS spectrograph, which has 640 3″ diameter fibers spanning a 7 $\deg^2$ field on a 2.5 m telescope. The fiber plug plates require about 10 minutes to change. In principle, one should consider the time required for repointing the telescope, but this will be relatively infrequent because, even in the anticenter fields, there are about 2000 viable targets (for a 2 mag interval) and only 640 fibers, so there should be about three plug plates per pointing. If we strictly applied the "exposure time equals downtime" rule, the resulting 10 minute exposure would yield a per pixel S/N of 10 at about $g = 19.5$. Given the 3″ fibers, this is about 1 mag below dark sky. In practice, it is probably impractical to change plug plates so frequently, so 45 minute exposures (in keeping with current SDSS practice) would appear to be more realistic. Taking account of sky, this yields a per pixel S/N of 8 at $g = 20.5$ and S/N = 4 at $g = 21.5$. This latter is probably adequate for $\sigma = 50$ km s^{-1} measurements, but this should be tested directly. Hence, in one 9 hr night, the SDSS telescope could cover a total of 21 $\deg^2$ over $19.5 < g < 21.5$ and $0.3 < g - i < 1.1$; i.e., 3 45 minute exposures (one for each of three plug plates) on each of three fields.

Second, we consider the $\mathcal{R} = 20{,}000$ IMACS F/4 spectrograph, which accommodates up to 1000 slits spanning a 0.067 $\deg^2$ field on the Magellan 6.5 m telescope. Changing slit masks requires about 15 minutes, but in fact this is not the relevant scale of "downtime," because each field has only of order 20–30 available targets, far fewer than the available slits. Rather, each mask could be cut to serve of order 10 fields (with a total of 200–300 targets). Hence, the downtime is primarily set by the time required to acquire a new field (without changing the mask). This is roughly 5 minutes, which by the guideline derived in § 2.5 would indicate an exposure time also of 5 minutes. Taking account of sky noise and assuming a $4e^-$ read noise, this leads to an estimate of the per pixel S/N of 1.2 at $g = 21.5$. To evaluate the utility of such signal levels, we construct synthetic spectra, add noise, and then fit the results to a (four-parameter) quadratic polynomial plus a template spectrum, offset by various velocities from the constructed spectrum. We find that this S/N is sufficient for an accurate RV measurement, provided that at least 80 Å are sampled, centered on $\lambda = 5175$ Å. In fact, the formal error in the measurement is less than 10 km s^{-1}, so it would appear that even lower values of the S/N would be tolerable. However, we find that if the S/N is further reduced, while the width of the correlation peak does not increase dramatically, multiple minima (each quite narrow) begin to appear, undermining the measurement. Similarly, if the wavelength coverage is reduced at constant S/N, then multiple minima also appear. In any event, if appropriate blocking filters permit this 80 Å (800 pixel) window or larger, then the field can be reliably probed to $g = 21.5$. Of order 50 fields could be searched during a 9 hr night, covering about 3.3 $\deg^2$.

Thus, while these two spectrographs differ in aperture, resolution, and field size by factors of 7, 10, and 100, respectively, they are capable of broadly similar searches for HVSs. We conclude that it is feasible to conduct the search over tens of square degrees on a variety of telescopes without exorbitant effort.

3. DISCUSSION

How likely is it that such a survey of several tens of square degrees will detect old-population HVSs? At one level, as emphasized in § 1, we have no idea: based on what we know now, old-population HVSs could equally well be very common or nonexistent. However, in the absence of any hard information, we might guess that the ratio of old-population to B-type HVSs might be similar to the ratio of the underlying populations near the GC. This itself is not known, but as a proxy we evaluate the same ratio in the solar neighborhood. In fact, what is required is the ratio of turnoff stars to B stars, since our proposed survey is most sensitive to turnoff stars, while B stars form the only population of HVSs that have been reliably tabulated. The distance ranges are similar: the B stars have typically been detected at 60 kpc, while turnoff stars at $g = 21.5$ lie at about 25 kpc (a factor of 2.5 advantage for the B stars). Moreover, the sizes of the magnitude intervals to be searched are about the same.

We estimate the ratio of B stars to turnoff stars in the solar neighborhood as follows. We analyze samples of each stellar class drawn from the *Hipparcos* catalog (Perryman et al. 1997), restricted to $V < 7.3$ (the *Hipparcos* completeness limit), a distance of $r < 300$ pc (to ensure good parallaxes and low extinction), and a distance from the Galactic plane of less than 50 pc. We define turnoff stars as having absolute magnitudes of $3.5 < M_V < 4.5$ and near-turnoff colors of $0.3 < B_T - V_T < 0.8$. For B stars, we probe the 2 mag interval $-2.0 < M_V < 0.0$, which approximately corresponds to the Brown et al. (2006a, 2006b, 2007) $g - r$ selection criterion, and we enforce $-0.5 < B_T - V_T < 0.2$ to distinguish these from giants. For each class of star, we tabulate $\sum_i (V_{\text{eff},\,i})^{-1}$, where $V_{\text{eff},\,i}$ is the effective volume over which that star could have been found. That is, $V_{\text{eff}} = 4\pi r_{\max}^3$, where $r_{\max}$ is the maximum distance at which that star could have been detected given its observed absolute magnitude, its known direction, and the two constraints on distance given above. We find effective densities of 0.91×10^{-5} pc^{-3} and 60.7×10^{-5} pc^{-3} for the two classes, indicating that turnoff stars are about 67 times more common than B stars.

Applying this rather crudely derived multiplier to the B-star HVS density found by Brown et al. (2007), and taking account of the factor of 2.5 B-star advantage just derived, we estimate that there could be 1 turnoff HVS per 45 $\deg^2$. Hence, a survey of 100 $\deg^2$ could probe the existence of this putative population.

The bound turnoff HVS population should be substantially enhanced simply because bound turnoff HVSs remain in the Galaxy for their entire lifetimes, while bound B-type HVSs go supernova before they have even have a chance to turn around: hence, all detected bound B-type HVSs have positive RVs. Brown et al. (2007) found 11 bound B-type HVS candidates with velocities between 280 and 450 km s^{-1}. If we use the naive scaling for the escaping HVSs derived just above and include an additional factor of 100 for the longer lifetime of turnoff stars relative to B stars, this implies a surface density of about 6 $\deg^{-2}$. The question is: could these stars actually be found against the huge background population of halo turnoff stars? This depends sensitively on the velocity distribution of the background. For a background surface density of 300 deg^{-2} and Gaussian velocity dispersion σ, the background (per σ) is about 2.5 deg^{-2} at 3 σ and 0.1 deg^{-2} at 4 σ. Hence, if we assume a dispersion of $\sigma = 105\ \mathrm{km\ s^{-1}}$ as found for B stars by Brown et al. (2007) at somewhat larger distances (and, for the moment, ignore measurement errors), then the high end ($\sim$450 $\mathrm{km\ s^{-1}}$) of the bound population found by Brown et al. (2007) could be reliably detected in turnoff stars by observing only a few square degrees, while the low end ($\sim$280 $\mathrm{km\ s^{-1}}$) would show up statistically against the background in observations of about 15 deg^2. If the observations were degraded by $\sim$50 $\mathrm{km\ s^{-1}}$ errors, then this would only raise the observed dispersion of the background to $\sigma \sim 115\ \mathrm{km\ s^{-1}}$ and so would not qualitatively change these estimates. It is also the case that a small fraction of the bound HVSs would then scatter into the tail of the background, but this also would not qualitatively alter the estimates. Thus, while higher RV precision would obviously be better, it should not be sought at the expense of covering large areas.

We thank Alan Dressler and Mike Gladders for discussions at OCIW morning tea that stimulated the genesis of this paper. We thank our referee, Warren Brown, for a careful and helpful report that improved our paper. We are also grateful to Scott Gaudi, Jennifer Johnson, Steve Shectman, and Ian Thompson for helpful discussions. J. A. K. was supported by NASA through a Hubble Fellowship. A. G. was supported by grant AST 04-2758 from the NSF. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF.

REFERENCES

Baumgardt, H., Gualandris, A., & Portegies Zwart, S. 2006, J. Phys. Conf. Ser., 54, 301
Brown, W. R., Geller, M. J., Kenyon, S. J., & Kurtz, M. J. 2005, ApJ, 622, L33
———. 2006a, ApJ, 640, L35
———. 2006b, ApJ, 647, 303
Brown, W. R., Geller, M. J., Kenyon, S. J., Kurtz, M. J., & Bromley, B. C. 2007, ApJ, 660, 311
Demarque, P., Woo, J.-H., Kim, Y.-C., & Yi, S. K. 2004, ApJS, 155, 667
Edelmann, H., Napiwotzki, R., Heber, U., Christlieb, N., & Reimers, D. 2005, ApJ, 634, L181
Fuentes, C. I., Stanek, K. Z., Gaudi, B. S., McLeod, B. A., Bogdanov, S., Hartman, J. D., Hickox, R. C., & Holman, M. J. 2006, ApJ, 636, L37
Gnedin, O. Y., Gould, A., Miralda-Escudé, J., & Zentner, A. R. 2005, ApJ, 634, 344
Gould, A., Flynn, C., & Bahcall, J. N. 1998, ApJ, 503, 798
Hansen, B. M. S., & Milosavljević, M. 2003, ApJ, 593, L77
Hills, J. G. 1988, Nature, 331, 687
Hirsch, H. A., Heber, U., O'Toole, S. J., & Bresolin, F. 2005, A&A, 444, L61
Levin, Y. 2006, ApJ, 653, 1203
Perets, H. B., Hopman, C., & Alexander, T. 2007, ApJ, 656, 709
Perryman, M. A. C., et al. 1997, The *Hipparcos* and Tycho Catalogues (SP-1200; Noordwijk: ESA)
Popowski, P., & Gould, A. 1998, ApJ, 506, 271
Yu, Q., & Tremaine, S. 2003, ApJ, 599, 1129