OLD-POPULATION HYPERVELOCITY STARS FROM THE GALACTIC CENTER: LIMITS FROM THE SLOAN DIGITAL SKY SURVEY

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ABSTRACT

We present limits on the ejection of solar-metallicity (“metal-rich”) old-population hypervelocity stars (HVS) from a sample of over 290,000 stars selected from the Sloan Digital Sky Survey. We derive the speed at the solar circle from the measured positions and radial velocities (RVs) by assuming a radial orbit and adopting a simple isothermal model of the Galactic halo, which enables us to identify candidate bound and unbound ejectees. We examine the kinematics and metallicity distribution of this sample and find no metal-rich ejectees, from which our limits are derived. However, while tuned for metal-rich stars, our experiment is also sensitive to metal-poor ejectees. We find four candidate bound metal-poor F-stars from this sample, all with negative Galactocentric RV (i.e., returning toward the Galactic center (GC)). We additionally find two candidate metal-poor unbound stars (one F and one G). However, existing proper-motion measurements of these two stars make them unlikely to be emerging from the GC. The metal-rich nondetection places a limit on the rate of ejection of old-population stars from the GC of <35 Myr⁻¹. Comparing to the rate for more massive B-star ejectees of ~0.6 Myr⁻¹, our limit on the rate of ejection of old-population HVS shows that the mass function at the GC is not bottom-heavy and is consistent with being normal to top-heavy. Future targeted surveys of old-population HVS could determine if it is indeed top-heavy.

Key words: Galaxy: center – Galaxy: halo – Galaxy: kinematics and dynamics – Galaxy: stellar content – stars: luminosity function, mass function

1. INTRODUCTION

The search for hypervelocity stars (HVS) in the stellar halo was originally proposed in order to indirectly probe the Galactic center (GC) at optical wavelengths (Hills 1988). In his seminal paper, Hills first suggested that these objects would constitute a “minor impurity of metal-rich stars” in the otherwise metal-poor Galactic halos that host supermassive black holes (SMBHs) at their centers. These stars, having been ejected from the GC via binary-exchange collisions with a putative SMBH at speeds in excess of Galactic escape would have provided the dynamical evidence for such an object at a time when direct detection seemed remote. Indeed, while Hills advocated proper-motion surveys at that time, he was also the first to recognize that these objects could be discovered by their velocities noting that their radial velocities (RVs) would be “hard to rationalize away” (Hills 1988). Nearly two decades after this prediction, HVS were first discovered serendipitously in spectroscopic surveys of blue stars in the Galactic halo owing to their very large RVs (Brown et al. 2005; Edelmann et al. 2005; Hirsch et al. 2005). Efficient color-selection methods for the spectroscopic targeting of blue stars in the halo have proven extremely effective to increase samples of young HVS (Brown et al. 2007a, 2007b, 2009). To date, however, no low-mass (F/G) HVS have been detected, perhaps owing to their lack of existence or perhaps simply due to the difficulty in detecting these objects in the old stellar halo.

Despite the tremendous advances in infrared instrumentation since Hills’ prediction (and the associated confirmation of the SMBH at the GC), it remains extraordinarily difficult to image any but the brightest, youngest stars at the center of the Galaxy—the “S-stars” (e.g., Genzel et al. 1997; Ghez et al. 1998, 2000; Schödel 2002). The existence of these young stars is a major mystery since one would naively expect that the conditions near an SMBH are sufficiently hostile to prevent in situ star formation of any kind. A key question is whether or not these stars represent the “tip of the iceberg” in an otherwise normal star-forming region or whether star formation is fundamentally different at the GC. Gould & Quillen (2003) first suggested that blue stars were being ejected from the GC as a natural consequence of the process (presumed to be binary disruption) that bound the blue S stars to SgrA*. Because HVS are relatively rare, it was previously not feasible to amass sufficiently large numbers of spectra of old halo stars to use HVS to go beyond the Gould & Quillen (2003) prediction that there should be young, blue stars in the halo. In the era of deep, wide-field spectroscopic surveys, it is now conceivable to transform Hills’ original idea to find the “impurity of metal-rich” HVS in the Galactic halo to obtain, among other things, detailed information about star formation at the GC, which is otherwise obscured from direct view, to at least a factor of 2.5 lower in mass than the young population currently being probed (Brown et al. 2005, 2007a, 2007b, 2009).

The Sloan Digital Sky Survey (SDSS) provides an exceptional database to search for HVS that would otherwise be missed from targeted surveys. The SDSS has obtained over 300,000 stellar spectra since it began operations (York et al. 2000; Gunn et al. 1998, 2006). The data are reduced by an automated pipeline that produces reliable spectral classifications and RVs. With this enormous database of stellar spectra it is already possible to detect HVS among a broad class of stars. In particular, the size of the SDSS stellar sample makes SDSS sensitive to F and G type HVS, which require a substantially different search strategy than their O and B counterparts (Kollmeier & Gould 2007). However, in contrast to the photometric survey, the SDSS RV catalog is not complete in any dimension. In this work, we examine the
Figure 1. Distribution of stars that meet the photometric criteria outlined in Section 3. Panels clockwise from upper left shows the distribution of stars in Galactocentric RV, RV error (1σ), dereddened (g − i) color, and dereddened g magnitude. Blue points on the diagram show the position of our metal-poor candidate ejectees for reference.

colors and RVs of a large sample of halo stars in order to place limits on the ejection of metal-rich F/G stars from the GC. As we will describe, we do not explicitly cut on metallicity until the final step, although our search criteria (which are based on the photometric and kinematic properties of our sample stars) are specifically formulated based on the assumption that we are searching for metal-rich stars. This means that interesting high-velocity metal-poor stars can survive the penultimate step. We take note of these even though they are ultimately excluded from our well defined final metal-rich sample.

The paper is organized as follows. In Section 2, we summarize the stellar spectra and the sample selection for stars that will be used for this analysis. In Section 3, we present limits on the ejection of old-population HVS. We compare this limit with young-population HVS in Section 4. In Section 5, we discuss candidate metal-poor HVS uncovered in our study. We present our discussion and conclusions in Section 6. Detailed derivations are put in the Appendix for the interested reader.

2. THE SAMPLE

The sample used here is part of an ongoing study to find high-velocity stars within the SDSS (G. K. Knapp et al. 2009, in preparation). All RVs for stars acquired by the SDSS as of 2007 January 15 were extracted from the SDSS database. Selected objects were required to have RV errors not exceeding 100 km s\(^{-1}\), as determined from the automated stellar template fitting procedure, and required to be free of pipeline flags indicating likely problems in the automated velocity determination. This yielded a sample of 291,111 objects. Velocities were converted to Galactocentric velocity assuming that the local rotation speed is 220 km s\(^{-1}\) and that the Sun moves at (+9,+12,+7) km s\(^{-1}\) relative to the local standard of rest in the direction of the GC, Galactic rotation, and the north Galactic pole, respectively. All spectra with Galactocentric RVs in excess of |V\(_G\)| ≥ 350 km s\(^{-1}\) were examined to ensure the sample was free of catastrophic velocity errors. In Figure 1, we show the distribution of stars from this sample that match our photometric criteria (which are discussed below). We show the distributions of color, magnitude, Galactocentric RV, and velocity error to give a sense of the overall properties of the sample. The blue points in the figure will be discussed in Section 5.

3. METAL-RICH F AND G STAR EJECTEES

Kollmeier & Gould (2007) argued that large RV samples, such as SDSS, could probe an as yet undiscovered old population of stars ejected from the GC and would be most sensitive to stars near the main-sequence turnoff within this population. Moreover, they argued that such surveys would be more sensitive to the bound rather than unbound members of this population, simply because the bound stars accumulate over the lifetime of the Galaxy and can be seen still orbiting, while the unbound stars can only be viewed during their exit. In this section, we analyze the sensitivity of SDSS to both classes of ejectees, and we tabulate the candidates derived from this database. We present detailed derivations of our sensitivity calculation in the Appendix for the interested reader.

3.1. Selection Criteria for Bound Ejectees

We begin by asking what the sensitivity of the SDSS survey is to bound turnoff stars and whether any such candidates are in the sample. Of course, this requires that we establish selection criteria that remove the vast majority of contaminants but still retain significant sensitivity to bound ejectees. We adopt the following two criteria:

\[ v_{r,G} > v_{\text{cut}} = 400 \text{ km s}^{-1}, \]
\[ v_{\odot\text{-circle}} < v_{\text{esc}}, \] (1)
where \( v_{\odot} \) is the observed RV converted to the Galactic frame, \( v_{\odot\text{-circle}} \) is the velocity that the star has when it crosses the solar circle, and \( v_{\text{esc}} \) is the Galactic escape velocity, again measured at the solar circle.

The first criterion is purely observational (apart from the implied assumption of solar motion) and is self-contained. The threshold \( v_{\text{esc}} \) is established empirically from the observed velocity distribution (G. K. Knapp et al. 2009, in preparation).

The second criterion requires that we specify both a model of the Galaxy (to determine the value of \( v_{\text{esc}} \)) and a model of the photometric properties of the target population (metal-rich ejectees), so that we can estimate \( v_{\odot\text{-circle}} \) from its observed \( v_{\odot,G} \) and from the observed fluxes in several bands.

For the Galactic model, we adopt an isothermal sphere characterized by a rotation speed \( v_{\odot} = 220 \text{ km s}^{-1} \), truncated in density at a Galactocentric radius \( R_0 \). For this model \( R_0 = R_\odot \exp[(v_{\odot\text{-circle}}/v_r)^2/2 - 1] \) where \( R_\odot = 8 \text{ kpc} \) is the distance to the GC. We will adopt \( v_{\text{esc}} = 550 \text{ km s}^{-1} \), which implies \( R_0 = 8.37 R_\odot \), as a default, but will also consider other values. This model agrees well with more complex models in the literature at the solar circle. However, at larger radii, triaxiality can significantly affect the trajectories of stars and hence their velocities. Because we do not know the true potential of the Milky Way, we perform our calculations on an exceedingly simple model. We will consider two classes of metal-rich stars, “F stars,” defined observationally as \( 0.5 < (g - i)_0 \leq 0.5 \), and “G stars,” defined as \( 0.5 < (g - i)_0 \leq 0.75 \). We adopt for these absolute magnitudes \( M_g = 3.5 \) and \( M_g = 5.5 \), respectively, which holds for a metal-rich population. It is important to keep in mind that these assumptions apply only to the putative metal-rich ejectee population: the photometric properties of non-metal-rich ejectee stars (including metal-poor ejectees and nonejectees), which obviously dominate the SDSS sample overall, are completely irrelevant.

From the observed extinction corrected magnitude \( g_0 \) of the star (determined from the Schlegel et al. 1998 extinction maps), we can infer its distance, \( d = 10^{0.95 - M_g}/5^2 \) kpc, and hence (from its position on the sky), the angle \( \phi \) between the Sun and the GC, as seen from the star. Then, since the ejectee is assumed to be on a Galactocentric radial orbit, 5 its full three-dimensional velocity is \( v = |v_{\odot,G}\sec \phi| \), and hence its velocity at the solar circle (assuming, as is always the case for F stars in SDSS, that \( R < R_0 \)) is

\[
v_{\odot\text{-circle}} = \sqrt{(v_r/v_\odot\sec \phi)^2 + 2v_\odot^2 \ln(R/R_\odot)}.
\]

It is immediately obvious that this equation places strong constraints on the observational parameter space in which the search can be conducted. For instance, if the star is fairly bright, so that \( r \ll R_0 \), then \( \cos \phi > v_{\odot,G}/v_{\text{esc}} \). Since, for this geometry, \( \cos \phi \sim -\cos \phi \cos \beta \), this constraint eliminates the roughly 73% of the sky that is not sufficiently close to the Galactocentric (or anticentric) directions. At the opposite extreme, a bound star at \( R > R_0 \exp[(v_{\odot\text{-circle}}/v_\odot)^2/2] \sim 2.57 R_0 \) cannot be probed in any direction because its velocity (and hence RV) will fall below the threshold. At intermediate distances, these two effects combine with different relative weights.

### 3.2. Candidate Bound Metal-rich Ejectees

Of the stars in the G. K. Knapp et al. (2009, in preparation) sample, four F stars (and no G stars) survive as bound ejectees (see Table 1) based on their kinematics. We examine the metallicities of these stars using the latest version of the SDSS/SEGUE Stellar Parameters Pipeline (Lee et al. 2008a, 2008b; Allende-Prieto et al. 2008) and find all of these candidates to be metal-poor. Therefore, we find no metal-rich candidate bound ejectees. We discuss the metal-poor ejectees in Section 5, but they do not enter into our derived limits. We now address the following question: What is the significance of having detected zero bound ejectees? To answer this, we must determine the sensitivity of SDSS to the putative bound population.

### 3.3. Bound-ejectee Sensitivity of SDSS

To calculate the sensitivity of the SDSS spectroscopic survey, we first evaluate \( n_i \), the number density of stars per steradian, per magnitude satisfying our color criteria, for our two classes of stars as a function of magnitude and position on the sky using the SDSS photometric catalog. This was done using 20 individual patches of sky, each with area 1 deg\(^2\), and interpolating these values to obtain \( n_i \) for other parts of the sky. The fraction of ejected stars probed by a single observation of the \( i \)th star is given by (see the Appendix for derivation)

\[
f_i = \frac{\ln 10}{2.5} \frac{r_i^3}{4\pi R_i^2 v_P n_i}.
\]

We sum Equation (3) over all stars in the SDSS spectroscopic catalog that meet our color criteria. Figure 2 shows the result for several cases. The three bold curves (blue) are for F stars under the assumption of \( v_{\text{esc}} = 550 \text{ km s}^{-1} \) and for three different thresholds, \( v_{\text{cut}} = 400, 410, \) and 420. The solid (red) curve is for F stars with \( v_{\text{cut}} = 400 \text{ km s}^{-1} \), \( v_{\text{esc}} = 520 \text{ km s}^{-1} \), while the dashed (green) curve is for G stars with \( v_{\text{cut}} = 400 \text{ km s}^{-1} \), \( v_{\text{esc}} = 550 \text{ km s}^{-1} \). The two other curves will be explained later.

Several features are apparent from Figure 2. First, the sensitivity is peaked quite close to the escape velocity. This may seem surprising since the fraction of ejectees probed in this regime declines exponentially with the square of the velocity for \( R_s < R_0 \), and then even more steeply (see Equation (A10) in the Appendix). However, at low \( v \), distant (i.e., faint) stars do not contribute because their declining speeds at large \( R \) bring

### Table 1

| Name | \( V_G \) (km s\(^{-1}\)) | Type | \( g_0 \) | \( (g - i)_0 \) | \( T_{\text{eff}} \) (K) | \( \log(g) \) | [Fe/H] | Plate/Fiber/MJD |
|------|-----------------|-----|-------|-----------------|-----------------|----------------|--------|-----------------|
| SDSSJ061118.63+642618.5 | -412.3 ± 5.5 | F | 18.39 | 0.45 | 6145 | 4.08 | -1.27 | 2299/488/53711 |
| SDSSJ074557.31+181246.7 | -409.0 ± 5.9 | F | 18.96 | 0.34 | 6235 | 3.51 | -1.73 | 2074/113/55437 |
| SDSSJ224525.56+011332.1 | -407.1 ± 16.3 | F | 19.30 | 0.49 | 6168 | 4.02 | -1.37 | 1101/561/52621 |
| SDSSJ221532.02+103456.7 | -404.4 ± 17.2 | F | 20.07 | 0.35 | 6069 | 4.10 | -1.91 | 1891/423/52328 |
| SDSSJ111107.85+585357.2 | +425.4 ± 3.1 | F | 16.16 | 0.36 | 6514 | 3.58 | -1.77 | 950/554/52378 |
| SDSSJ224740.09-004451.6 | +401.8 ± 13.1 | G | 19.97 | 0.72 | 5518 | 4.17 | -1.22 | 1901/7/53261 |
weaker by about the same factor.

Since the peak of the G-star curve in Figure 2 is lower than the v_r_circ below the first selection cut in Equation (1). Most distant Galactic model. Bold, blue curves show the sensitivity for bound F stars assuming v_esc = 550 km s^{-1} and for three different thresholds, v_cut = 400, 410, and 420 from bottom to top. Solid red curve shows the case for bound F stars with v_cut = 400 km s^{-1}, v_esc = 520 km s^{-1}, while the dashed (green) curve is for bound G stars with v_cut = 400 km s^{-1}, v_esc = 550 km s^{-1}. The sensitivity to unbound F stars (bold-dashed, magenta) and unbound G stars (dotted, cyan) for the case v_esc = 550 km s^{-1}, v_cut = 400 km s^{-1} are also shown.

them below the first selection cut in Equation (1). Most distant stars gain by r^3, at least for r < R0. Second, the sensitivity falls quite steeply with increasing v_cut, approximately a factor of 2 for each 10 km s^{-1}. This is basically a consequence of the same volume effect just analyzed. The same effect also accounts for the dramatic falloff in sensitivity if the escape velocity proves lower than our default

Figure 2. Sensitivity of SDSS to old-star ejectees as a function of type and Galactic model. Bold, blue curves show the sensitivity for bound F stars assuming v_esc = 550 km s^{-1} and for three different thresholds, v_cut = 400, 410, and 420 from bottom to top. Solid red curve shows the case for bound F stars with v_cut = 400 km s^{-1}, v_esc = 520 km s^{-1}, while the dashed (green) curve is for bound G stars with v_cut = 400 km s^{-1}, v_esc = 550 km s^{-1}. The sensitivity to unbound F stars (bold-dashed, magenta) and unbound G stars (dotted, cyan) for the case v_esc = 550 km s^{-1}, v_cut = 400 km s^{-1} are also shown.

we select candidate unbound-ejected stars with exactly the criteria as bound stars (Equation (1)), except reversing the sign on the second condition, v_{\odot-circle} \geq v_{\text{esc}}, and of course demanding that they be exiting rather than entering the Galaxy. Then, following a very similar derivation to the one given for the bound case (see Equations (A3) and (A9) in the Appendix for derivations of these), we immediately derive their analogs for the unbound case,

\[ \Gamma_{\text{unbound}}^{-1} = \frac{3}{(\Gamma_{\text{thresh}})^3} \frac{35 \text{ km s}^{-1}}{0.75 \times 4 \text{ Myr km s}^{-1}} < 35 \text{ Myr}^{-1} \]

\[ (505 \text{ km s}^{-1} < v_{\odot-circle} < 540 \text{ km s}^{-1}). \]

Since the peak of the G-star curve in Figure 2 is lower than the F-star peak by a factor of \sim 2.5, the limit on G-star ejectees is weaker by about the same factor.

3.4. Unbound Ejectees

The Brown et al. (2007a, 2007b) survey in essence covered an entire volume of the Galaxy (defined by magnitude limits) rather than a scattering of targets within the Galaxy, such as SDSS. Thus, to calculate \Gamma_{\text{thresh}} one should perform a volume integral. An argument similar to the one given in the Appendix leads to the equation

\[ \Gamma_{\text{thresh}} = \int_{\text{area-covered}} \frac{d sin b dl}{4\pi} \int_{r_{\text{min}}}^{r_{\text{max}}} \frac{d r^2}{[R(r,l,b)]^2 \left( \frac{v^2 - 2v^2 \ln(R/R0)}{v^2} \right)^{1/2}}. \]  

where we have for convenience assumed the form of the Galactic potential within R < R_b. We estimate this expression for the Brown et al. (2007a, 2007b) survey by noting that it was 80% complete over an area \Delta \Omega \sim 5000 \text{ deg}^2 and that most of the sensitivity was in regions where R \sim r, by adopting an average value for the velocity in the denominator of \langle v \rangle = 600 \text{ km s}^{-1}, and approximating \Delta r = r_{\text{max}} - r_{\text{min}} = 40 \text{ kpc}. We then obtain \Gamma_{\text{thresh}} = 80\% \times (\Delta \Omega/4\pi)(\Delta r/\langle v \rangle) = 6.4 \text{ Myr}. Hence, the four detections imply \Gamma_{\text{unbound}}^{-1} = 4\Gamma_{\text{thresh}} = 0.625 \text{ Myr}^{-1}.

Thus, the upper limit given by Equation (6) shows that F-star ejectees are no more than 100 times more common than B-star ejectees. Since F stars themselves are about 100 times more common than B stars in the Galaxy as a whole, this result is already of some interest. Nevertheless, it would certainly be better to achieve at least a few times better sensitivity.

5. METAL-POOR EJECTEES

While our photometric criteria are tuned for metal-rich stars, they are sufficiently broad that they do not exclude metal-poor stars. We therefore find some metal-poor candidate ejectees in our sample, including five metal-poor F star ejectees and one metal-poor G star ejectee. Because they are contaminants of our selection and not targets, they do not enter into our derived limits. However, they are of interest and should be followed up, so we present them here.
5.1. Bound Metal-poor Ejectees

We find four candidate bound metal-poor F star ejectees (and no G stars). It is a curious fact that all four are coming toward us, however there is a 1/8 random probability that all four would be going in the same direction, which is too high to warrant further analysis. These candidates could either be members of a metal-poor population ejected from the GC or simply halo stars. Obtaining proper-motion measurements for the candidates would discriminate between the two scenarios. We show the locations of these stars in color, magnitude, velocity, and velocity error along with the larger sample in Figure 1.

5.2. Unbound Metal-poor Ejectees

There is one metal-poor F star candidate that survives our selection criteria and one metal-poor G star. The proper motions for both of these stars are inconsistent with a Galactocentric origin, as we now show. Were it ejected from the GC, based on its current position, a star should exhibit a proper motion in the direction

\[ \tan(\theta) = \tan(\iota) \sin(b), \]

where \( \theta \) is measured from Galactic north through east. The F star candidate has a measured proper motion from USNO-B \( \cap \) SDSS (Monet et al. 2003; Pier et al. 2003; Munn et al. 2004) of 34 mas yr\(^{-1}\) at 55\(^\circ\) (with small errors)—significantly in conflict with the predicted value \( \theta = 330^\circ \).

Unlike the F star, the G star candidate cannot be discarded based on its proper-motion direction alone. The measured proper motion of 6 mas yr\(^{-1}\) is sufficiently small that the measured direction of 183\(^\circ\) is poorly determined, given the errors. We therefore compare the predicted and observed vector proper motions, which (unlike the case of the F star) require a distance estimate. From its color, magnitude, and metallicity, we estimate a distance of 5.0 kpc, and it is therefore expected to be moving at 41 mas yr\(^{-1}\) at 244\(^\circ\). Since the typical Munn et al. (2004) errors are ~4 mas yr\(^{-1}\), it is extremely unlikely that this star is an unbound ejectee.

6. DISCUSSION

We have presented the first limit on old-population ejectees from the GC based on data obtained with the SDSS. We have shown that the ejection of F/G stars is no more than 100 times more common than O/B star ejectees. We note that this limit is obtained simply from analyzing the stellar spectra obtained by SDSS as part of its main projects, not via a survey designed to preferentially select these objects. Already, this limit suggests that the mass function at the GC is not weighted toward low mass star formation—a fact impossible to determine by direct imaging of the GC alone. It is also possible that the ejection mechanism is dramatically less effective for low-mass stars as suggested by, e.g., Perets et al. (2007). We additionally find a population of candidate ejectees that are metal-poor (see Table 1). While they do not figure into our limits, these objects may represent a population of metal-poor stars at the GC. These stars may represent a low-metallicity population at the GC. Another possibility is that our candidates are low-metallicity runaway stars ejected from the disk. Proper-motion measurements would determine whether they are indeed ejectees from the GC. Ongoing surveys, such as the second epoch of the Sloan Extension for Galactic Understanding and Exploration (SEGUE-2; Yanny et al. 2009), will determine conclusively if star formation at the GC is indeed weighted heavily toward young, massive stars.

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APPENDIX

GENERAL FORMULAE FOR BOUND-EJECTEE SENSITIVITY

Initially, consider a spectroscopic survey that obtains RVs of all stars in a small angular area \( \Omega \) over a narrow magnitude range \( g_0 \pm \Delta g_0/2 \), and over a specified narrow range of colors. Consider a star in this sample that is ejected from the GC, with current Galactocentric RV \( v_r \), and assume that it has an absolute magnitude (estimated from its color) \( M_g \). The star then has distance from us \( r \approx 10^{(g_0-M_g)/5} \approx 2 \) kpc, so the volume of such a survey is

\[ \Delta V = \frac{\ln 10}{5} \Delta g_0 \Omega r^3. \]  

(A1)

It then has a three-dimensional Galactocentric velocity \( v = v_r, \) \( \cos \phi \), where \( \phi \) is the angle between us and the GC, as seen from the star.

As seen from the GC, the probed volume covers an area \( A \) and has a thickness \( \Delta w \). Of course, \( \Delta V = A \Delta w \). A fraction \( \Delta A/4\pi R^2 \) of all ejected stars will pass through this volume at some time (assuming isotropic ejection), where \( R \) is the star’s
Galactocentric distance, and it will spend a fraction $2\Delta w/v_P$ of its time in this volume, where $P$ is the orbital period, and where the factor of 2 arises from ingoing+outgoing radial orbits. Hence, observations of this volume will probe a fraction

$$f_{\text{vol}} = \frac{2\Delta w}{4\pi R^2 v_P} = \frac{\ln 10}{2.5} \frac{\Delta g_0 \Omega r^3}{4\pi R^2 v_P}$$

(A2)

of all ejected stars. Now consider that we do not observe all stars in this volume, but only one. Clearly, the fraction of ejected stars that we probe falls by a factor of 2 as we consider smaller volumes. The total sensitivity of the survey is then simply the sum

$$f_{\text{tot}} = \sum_i f_i$$

over all stars. If there are $N_{\text{tot}}$ bound stars orbiting, then the expected number of detections will simply be

$$N_{\text{exp}} = f_{\text{tot}} N_{\text{tot}}.$$  

It will prove useful to express the same result as

$$\Gamma_{\text{thresh}}^{-1} = \tau_{\text{MW}} \sum_i f_i,$$  

(A9)

where $\tau_{\text{MW}} = 10$ Gyr is the lifetime of the Milky Way. In this formulation, $N_{\text{exp}} = \Gamma / \Gamma_{\text{thresh}}$, where $\Gamma$ is the mean bound-ejection rate averaged over the lifetime of the Galaxy.

To understand the basic properties of $f_i$, let us initially restrict attention to the first case, $R_* \leq R_b$. Then

$$f_i = \frac{\ln 10}{5} \left( \frac{r_i}{R_i} \right)^3 \frac{\exp(-z_i^2/2)}{z_i}, \quad z \equiv \frac{v}{v_c}.$$  

(A10)

If we consider some typical values for relatively faint turnoff stars in SDSS ($g_0 \sim 18.5, r \sim 10$ kpc, $R \sim 16$ kpc, $z = 2$, and $n = 100$ deg$^{-2}$), then $f_i \sim 1.5 \times 10^{-3}$. Hence, by obtaining RVs for about $10^4$ stars, one could probe a bound population of F stars ejected from the GC provided it had at least $10^5$ members. This corresponds to $\Gamma_{\text{thresh}} = 10$ Myr$^{-1}$.

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