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Constraining the Milky Way mass with hypervelocity stars

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HIGHLIGHTS

- Knowing the precise mass of the Milky Way is important for placing our Galaxy in a cosmological context.
- Hypervelocity stars can be used to constrain the mass of the Milky Way.
- Current data favors a mass for the Milky Way in the range $(1.2-1.9)\times10^{12}$ $M_\odot$.

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ABSTRACT

Although a variety of techniques have been employed for determining the Milky Way dark matter halo mass distribution, the range of allowed masses spans both light and heavy values. Knowing the precise mass of our Galaxy is important for placing the Milky Way in a cosmological ΛCDM context. We show that hypervelocity stars (HVSs) ejected from the center of the Milky Way galaxy can be used to constrain the mass of its dark matter halo. We use the asymmetry in the radial velocity distribution of halo stars due to escaping HVSs, which depends on the halo potential (escape speed) as long as the round trip orbital time is shorter than the stellar lifetime, to discriminate between different models for the Milky Way gravitational potential. Adopting a characteristic HVS travel time of 330 Myr, which corresponds to the average mass of main sequence HVSs, we find that current data favors a mass for the Milky Way in the range $(1.2-1.9)\times10^{12}$ $M_\odot$.

1. Introduction

Hypervelocity Stars (HVSs) are defined as stars able to escape the gravitational well of the Milky Way (MW). Theoretically predicted by Hills (1988) as the consequence of interactions of binary stars with the massive Black Hole (BH) in the Galactic Centre (GC), HVSs were first observed by Brown et al. (2005). More than 20 HVSs at distances between 50 and 120 kpc from the GC, and velocities up to $\approx$ 700 km s^{-1}, have been found (Multiple Mirror Telescope (MMT) spectroscopic survey (Brown et al., 2010; 2014)). A similar number of bound HVSs, i.e. stars ejected by the same mechanism of unbound stars, but with velocities below the Galactic escape speed, have been observed (Brown et al., 2007a; 2007b; 2014). The MMT targets stars with the magnitudes and colors of $2.5-4$ $M_\odot$ late B-type stars, since they should not exist at faint magnitudes in the outer halo far from star-forming regions unless they were ejected to that location. Given the MMT target selection (Brown et al., 2014), the sample stars could be either Main Sequence (MS) B stars, evolved Blue Horizontal Branch (BHB) stars or blue stragglers, while only a few of them have a defined stellar type. Recent studies have started to investigate low-mass HVS candidates (Palladino, 2014; Li, 2015; Ziegerer et al., 2015). The physical mechanisms responsible for the production of the observed HVSs are still debated. However, due to their extreme velocities, the origin of HVSs involves strong dynamical interactions probably with a single or binary BHs in the GC (Yu and Tremaine, 2003; Ginsburg and Loeb, 2006; 2007; O'Leary and Loeb, 2008; Sari et al., 2010; Ginsburg et al., 2012; Capuzzo-Dolcetta and Fragione, 2015; Fragione and Capuzzo-Dolcetta, 2016; Fragione and Ginsburg, 2017; Fragione et al., 2016) or in a nearby galaxy (Gualandris and Portegies Zwart, 2007; Sherwin et al., 2008; Boubert and Evans, 2016).

The study of HVSs can provide clues about the process responsible for their production in the Galactic Centre region (Gould and Quillen, 2003). As their orbits are completely determined by the MW potential, Gnedin et al. (2005) and Yu and Madau (2007) suggested to use the kinematics of HVSs to probe the Galactic potential triaxiality. Moreover, HVSs can be used to constrain the mass distribution of our Galaxy, which is still highly uncertain. Gnedin et al. (2010) used the MMT sample to constrain the Galactic mass profile out to 80 kpc. In this paper we apply the method

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proposed by Perets (2009) to discriminate among different Galactic potential models, with a focus on measuring the total dark halo mass.

A variety of techniques have been employed for determining the MW dark matter halo mass distribution (Gnedin et al., 2010; McMillan, 2011; Eadie et al., 2015; Wang et al., 2015), but, nevertheless, the range of allowed values spans both light ($\lesssim 10^{12}$ M$_\odot$) and heavy ($\gtrsim 2 \times 10^{12}$ M$_\odot$) values (Wang et al., 2015). Several classes of kinematic tracers have been used for this purpose, but suffer from systematics caused by the lack of reliable tangential velocity and distance measurements (Gibbons et al., 2014). Küpper et al. (2015) and Bovy et al. (2016) used the tidal stream of the Milky Way's star clusters Palomar 5 and GD-1 to probe the shape of the Galactic potential. Tidal streams are useful tracers of the Galactic mass in the inner halo. On the other hand, HVSs could be highly valuable in discriminating among different mass models out to very large Galactocentric distances, in particular once precise data on their proper motions will be available from *Gaia* (Perets, 2009).

Knowing the precise mass of our Galaxy is important for placing the MW in a cosmological ΛCDM context. Although the difference in mass between light and heavy halo masses is just **by a** factor of $2-3$, such a factor leads to a major difference in the **conversion efficiency** of baryons into stars (higher for lighter haloes), places the Large Magellanic Cloud (Kallivayalil et al., 2013) and the Leo I dwarf spheroidal (Boylan-Kolchin et al., 2013) on unbound (light halo) or bound (heavy halo) orbits and can or cannot solve the Too-Big-to-Fail problem (Taylor et al., 2016). This latter problem is one of the two prominent challenges concerning the satellite galaxies in the MW and consists in the fact that the most massive subhaloes of numerical simulations, which in typical galaxy formation models would host the most luminous satellites, are too dense to be dynamically consistent with observations of any of the known MW companions (Boylan-Kolchin et al., 2011). The other challenge is the so-called Missing Satellite Problem, as ΛCDM model predicts hundred of subhaloes but a smaller set of galaxies is observed (Klypin et al., 1999). Several possible solutions have been suggested, including uncertainties in the mass of the MW halo (Guo et al., 2015; Kang et al., 2016).

In this paper, we study the kinematics of HVSs in the Galaxy as a probe of the MW halo mass. The outline of the paper is as follows. In Section 2, we describe the method we use to discriminate among different halo masses. In Section 3 we present our models for the MW gravitational potential. In Section 4, we perform numerical simulations of HVSs motion to study their kinematics and provide results. Finally, in Section 5, we summarize our main conclusions.

2. Method

Theoretical calculations by Yu and Tremaine (2003) suggest that the HVSs ejection rate, both in case the source at the GC is a single or a binary BH, is $\approx 10^{-5} - 10^{-4}$ yr^{-1}. If HVSs ejections are continuous and isotropic, their number density is (Brown, 2015)

$$n(r) = \frac{dN/dt}{4\pi r^2 dr/dt} \approx \frac{8}{(r/\mathrm{kpc})^2}\ \mathrm{kpc}^{-3}, \tag{1}$$

implying that HVSs are rare objects. The MMT survey (Brown et al., 2014) targeted stars luminous enough to be observed in the Galactic halo where the relative number of HVSs is expected to be higher. Deason et al. (2014) found evidence for a very steep outer halo density profile, implying that the relative frequency of HVSs is much higher in the outer halo than in the inner halo. Moreover, at Galactic latitudes $|b| \gtrsim 30°$, the survey is less likely to be contaminated by the disk and runaway stars (Bromley et al., 2009; Kenyon et al., 2014).

We assume that HVSs are ejected from the GC (Bromley et al., 2006), and escape the MW if the ejection velocity v_{ej} is higher than the local escape speed $v_{esc}(r)$, which depends on the Galactic potential. While unbound stars will leave the MW, bound stars will reach the apocentre of their orbit and then return back to the GC with a negative radial velocity (Bromley et al., 2009; Kenyon et al., 2008; Brown, 2015). The observations reveal a significant asymmetry in the tail of the velocity distribution of the sample stars. In particular, there is a significant lack of stars with $v_r < -275$ km s^{-1} in Galactocentric coordinates (Brown et al., 2007a; 2007b; 2010). We divide the stars of the sample to outgoing stars with positive radial velocities in Galactocentric coordinates, and ingoing stars with negative radial velocities. Perets (2009) proposed a method that uses the observed asymmetry between ingoing and outgoing stars to discriminate among different Galactic potential models. Such asymmetry originates both from the MW gravitational potential as well as from the finite lifetime of HVSs.

Bound stars can be spotted either as outgoing stars or ingoing stars, according to when they are observed in their orbit (Kenyon et al., 2014). However, unbound HVSs can be observed only as outgoing. Therefore, an asymmetry in the distribution of ingoing and outgoing stars is expected if HVSs are continuously ejected from the GC (Perets, 2009). Whereas bound stars are expected to be symmetrically divided between ingoing and outgoing stars, unbound HVSs can have only positive velocities. Furthermore, while unbound HVSs are not limited in ejection velocity, except for the limitations of the assumed ejection model, the bound stars must satisfy $v_{ej} < v_{esc}(r)$. At a given Galactocentric distance r, ingoing stars can be observed with a negative velocity whose amplitude is at maximum $v_{esc}(r)$, which depends on the Galactic gravitational potential. As consequence, for a given MW model, no ingoing stars are expected to be found below the curve $-v(r) = -v_{esc}(r)$ in the v-r plane. Therefore, the asymmetric distance-velocity distribution can be used to directly constrain the Galactic potential (Perets, 2009).

However, some stars may disappear from view because they evolve to a different stellar type (Kenyon et al., 2008; Bromley et al., 2009). For example, the finite lifetime of MS stars **goes like** $t_* \propto m^{-\alpha}$, with $\alpha \approx 3$, implies that massive stars ejected from the GC cannot reach large Galactocentric distances and fall back toward the GC before leaving the MS (Bromley et al., 2006). The MMT targeted stars that could be late-type MS B stars with masses in the range $2.5-4$ M$_\odot$, for which the maximum travel time would be $t_* \approx 1-6 \cdot 10^8$ yr (Brown et al., 2010; 2014). The asymmetry in the velocity-distance distribution is still expected but the cutoff $-v(r)$ will also depend on the finite travel time. Moreover, stars of different types have different travel times and will lead to distinct distance-velocity cutoffs, providing independent probes of the Galactic potential (Perets, 2009).

In conclusion, different Galactic potential models give different $v_{esc}(r)$, which, combined together with different travel times, lead to peculiar cutoffs in the v-r plane. In this paper we apply the method proposed by Perets (2009) to current data on halo stars, with a focus on measuring the dark halo mass. We draw critical lines for HVSs both as function of the dark halo mass M_{DM} and of the stars travel time t_*. Whereas Perets (2009) look for the best fit model that shows the largest asymmetry, we consider the one that gives compatible asymmetric distribution of stars Δ and number of high-velocity outliers Γ in the MMT sample (see Section 4 for details) to constrain the MW mass.

3. Models for the MW gravitational potential

As described in the previous section, HVSs data can be used to constrain the MW potential. We describe the MW potential with a 4-component model $\Phi(r) = \Phi_{BH} + \Phi_{bul}(r) + \Phi_{disk}(r) + \Phi_{NFW}(r)$