Hypervelocity Stars as Tools for Galactic Astrophysics

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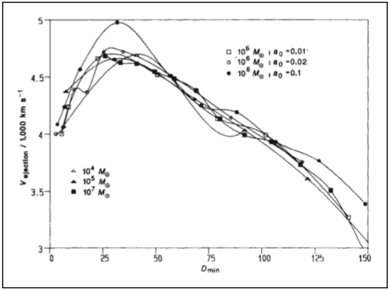
Outline

Hypervelocity Stars

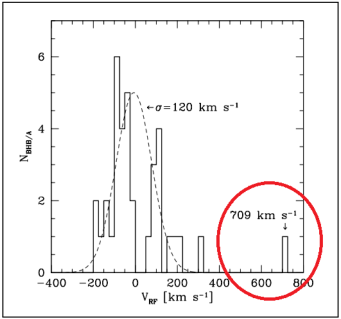
Hypervelocity Stars (HVSs): unbound stars escaping the host Galaxy (Brown 2015)

Theoretical prediction:
Hills 1988



Hills, Nature, 331, 687, 1988

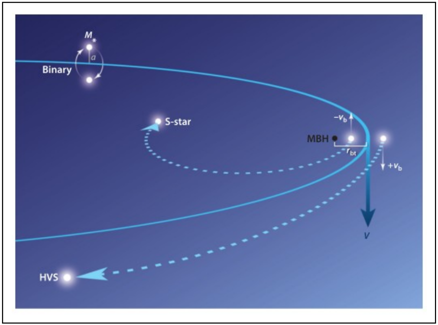
Observational evidence:
Brown+ 2005



Brown, Geller, Kenyon. ApJ, 622, L33, 2005

Hills Mechanism

Binary disruption by a super massive black hole (Hills 1988; Yu & Tremaine 03; Kenyon+ 2008; Kenyon+ 2014; Sari+ 2010)



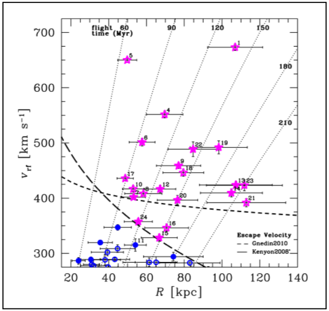
Brown, Annu. Rev. Astron. Astrophys., 53, 157, 2015

Mean ejection velocity (Bromley+ 2006)

$$v_{ej} \approx 1.8 \times 10^3 \ \mathrm{km\ s}^{-1} \times \times \left(\frac{0.1\ \mathrm{AU}}{a}\right)^{1/2} \left(\frac{m_b}{2\ \mathrm{M}_\odot}\right)^{1/3} \times \times \left(\frac{M_{BH}}{4 \times 10^6\ \mathrm{M}_\odot}\right)^{1/6}$$

a = binary separation
m_b = total binary mass
M_{BH} = black hole mass

Multiple Mirror Telescope Survey



21 HVSs (Brown+ 2005, 2007, 2010, 2014)
+ US708 Helium-rich subdwarf O star (Hirsch+ 2005)
+ HE0437-5439 MS 9 $M_\odot$ (Edelmann+ 2005)

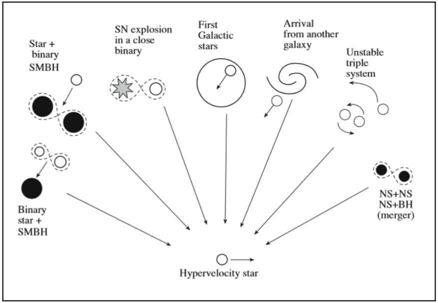
- spectroscopic survey of stars with colors of $2.5 \div 4\ M_\odot$ late B-type stars
- only radial velocity
- outer halo ($\gtrsim 20$ kpc) and $|b| \gtrsim 30°$
- ejection rate 10^{-5}-10^{-4} yr^{-1}
- low density

$$n(r) \approx \frac{8}{(r/\mathrm{kpc})^2}\ \mathrm{kpc}^{-3}$$

- *Gaia* satellite expected to find ≈ 100 HVSs

Production Mechanisms

HVSs have both slow and rapid rotations suggesting different acceleration mechanisms (Hansen 2007; Lopez-Morales & Bonanos 2008)



Tutukov & Fedorova. Ast. Rep. 53-9, 839, 2009

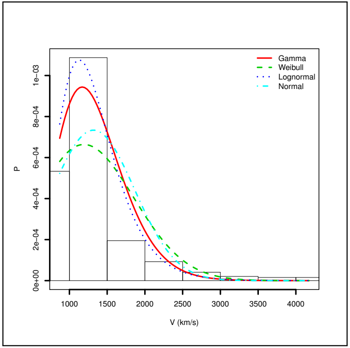
- Composition of the Galactic Centre (Gould & Quillen 2003; Gualandris+ 2005; Antonini+ 2010, 2011)
- Supernovae (Zubovas+ 2013)
- Galactic potential and Dark Matter (Gnedin+ 2005; Yu & Madau 2007)
- Planetary dynamics (Ginsburg+ 2012)
- Disks around Sgr A* (Löckmann+ 2008; Sŭbr & Haas 2016)
- Star clusters (Capuzzo-Dolcetta & Fragione 2015; Fragione & Capuzzo-Dolcetta 2016; Arca-Sedda+ 16)

Young Star Clusters Infall

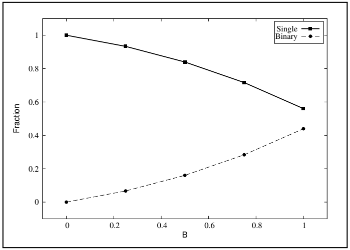
Infall of a young cluster ($\mathrm{M}_{YC} = 10^3\ \mathrm{M}_\odot$) toward the Galactic Centre in elliptical orbit around the Milky Way's BH (Fragione, Capuzzo-Dolcetta & Kroupa, submit. to MNRAS, arXiv:1609.05305, 2016)

- Plummer distribution
- Kroupa initial mass function (Kroupa 2001)
- $m_{max} = 40.54\ \mathrm{M}_\odot$ (Weidner & Kroupa 2004)
- $r_h = 0.1 \times (M_{cl}/\mathrm{M}_\odot)^{0.13}\ \mathrm{pc} = 0.25\ \mathrm{pc}$ (Marks & Kroupa 2012)
- Canonical period distribution (Kroupa 1995)
- e drawn from thermal distribution (Kroupa 2008)
- Black Hole of $M_{BH} = 4 \cdot 10^6\ \mathrm{M}_\odot$ (Gillessen+ 2009, 2016)
- Kenyon+ 2008, 2014 Milky Way potential

Single and Binary HVSs

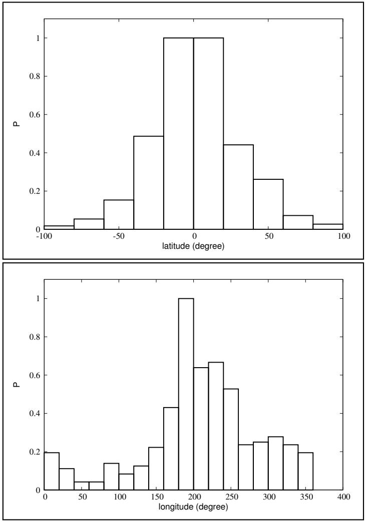


HVSs ejection velocity are distributed as a Gaussian distribution with mean ≈ 1200 km s^{-1}



The relative number of ejected single and binary HVSs depends on the primordial binary fraction B: as B increases, the number of ejected binary HVSs increases

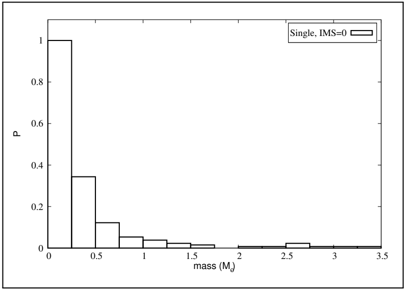
Ejection Geometry

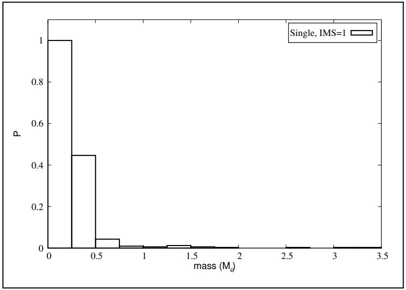


- stars ejected nearly in the cluster orbital plane
- stars ejected preferentially when the cluster passes near the pericentre
- HVSs in burst-like events nearly in the cluster orbital plane and in the direction of the cluster orbital motion, whose binary fraction depends on the initial binary fraction in the progenitor cluster

Role of the Initial Mass Segregation

The initial degree of mass segregation S affects the mass distribution of HVSs



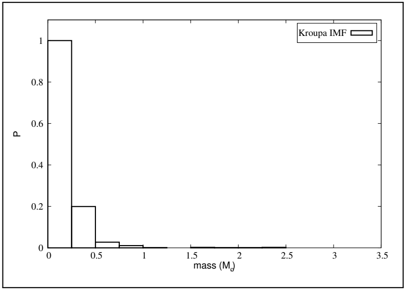


Unsegregated young cluster ($S = 0$): $\approx$ 20% of HVSs have $m_* \gtrsim 0.5\ \mathrm{M}_\odot$

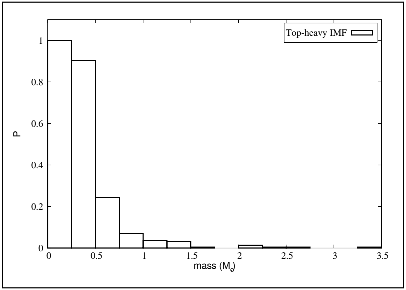
Segregated young cluster ($S = 1$): $\approx$ 97% of HVSs have $m_* \lesssim 0.5\ \mathrm{M}_\odot$

Role of the Initial Mass Function

The initial mass function affects the mass distribution of HVSs



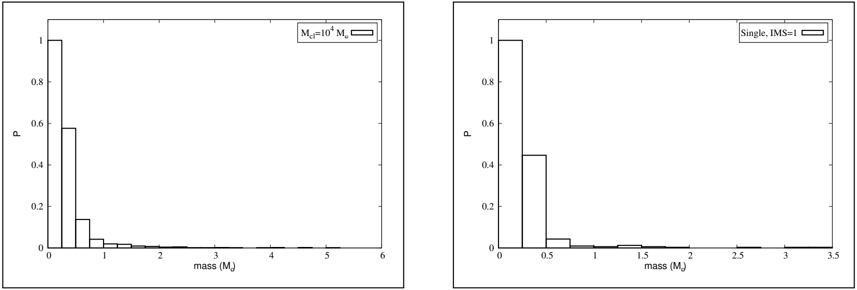
Segregated young cluster with Kroupa IMF:
$\approx$ 97% of HVSs have $m_* \lesssim 0.5\ \mathrm{M}_\odot$



Segregated young cluster with Top-heavy IMF:
$\approx$ 18% of HVSs have $m_* \gtrsim 0.5\ \mathrm{M}_\odot$

Role of the Initial Total Mass

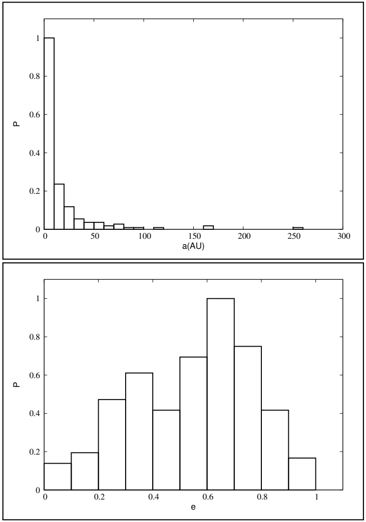
The initial total mass affects the mass distribution of HVSs



10^4 $M_\odot$ young cluster:
$\approx$ 15% of HVSs have $m_* \gtrsim 0.5$ $M_\odot$

10^3 $M_\odot$ young cluster:
$\approx$ 97% of HVSs have $m_* \lesssim 0.5$ $M_\odot$

Blue Stragglers HVSs



Binary eigenevolution (Kroupa 95)

$$\frac{\dot{e}}{e} = -\dot{\rho}$$

$$\rho = \left(\frac{\lambda R_{\odot}}{R_{per}}\right)^{\chi}$$

$$q_{fin} = q_{in} + (1 - q_{in})\rho^*$$

$$\rho^* = \begin{cases} \rho & \rho \leq 1 \\ 1 & \rho > 1 \end{cases}$$

$$m_{2,fin} = q_{fin} m_{1,in} \ ; \ m_{1,fin} = m_{1,in}$$

$$P_{b,fin} = P_{b,in} \left(\frac{m_{tot,in}}{m_{tot,fin}}\right)^{1/2} \left(\frac{1 - e_{in}}{1 - e_{fin}}\right)^{3/2}$$

$$\lambda = 28 \ , \ \chi = 0.75 \ ; \ \lambda_{ms} = 24.7 \ , \ \chi_{ms} = 8$$

- $\approx 7\%$ of binary HVSs merge becoming blue stragglers HVSs

Observations vs Theory

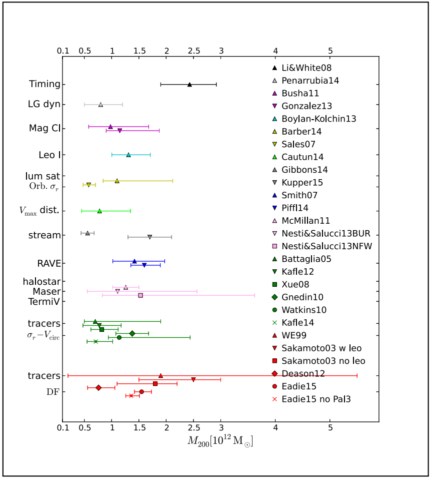
Observations

- HVSs mass $2.5\ \mathrm{M}_\odot \lesssim M_{HVS} \lesssim 4\ \mathrm{M}_\odot$ (Brown+ 14)
- HVSs clumped in the direction of Leo constellation (Brown+ 14)
- Binary HVS (Németh+ 16)
- Blue straggler HVS (Edelmann+ 05)

Theory

- Low initial degree of mass segregation/top-heavy IMF/massive cluster
- HVSs ejected in the cluster orbital plane and in the direction of its motion
- Binary HVSs produced by binary-rich clusters
- Blue stragglers HVSs from merged binary HVSs

Milky Way Dark Matter Halo



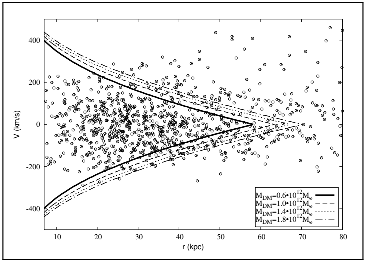
Wang et al, MNRAS, 377, 687, 2015

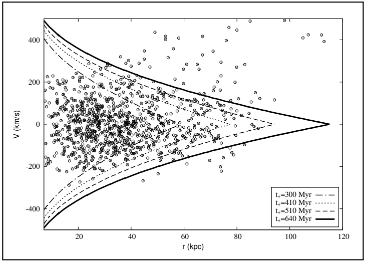
Cosmological problems of the Milky Way (Taylor+ 16)

- Efficiency conversion of baryons into stars
- Large Magellanic Cloud and the Leo I orbit
- Too-big-to-fail problem
- Missing satellite problem

A light halo mass ($\leq 10^{12}$ M$_\odot$) can save ΛCDM small-scales predictions

HVSs Asymmetric Distribution



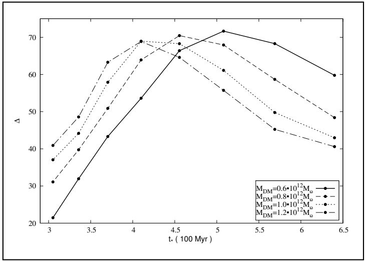


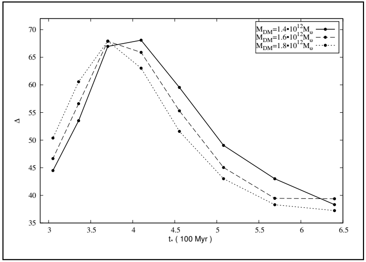
HVSs asymmetric distribution depends on the Milky Way potential and HVSs propagation time (Perets+ 2009)

- Unbound HVSs are only outgoing
- Bound HVSs can be outgoing and ingoing
- Ingoing stars have velocity up to $-v_{esc}(r)$
- Ingoing stars can evolve to a different stellar type because of finite lifetime

Fragione & Loeb, submitted, arXiv:1608.01517, 2016

Constraining Milky Way Mass with HVSs





The HVSs asymmetry Δ must be compatible with the number of stars ($\Gamma = 37$) that give the excess in the velocity distribution (Brown+ 2014)

$$\Phi_{NFW}(r) = -\frac{GM_{DM} \ln(1 + r/r_s)}{r}$$

HVSs favour a light dark matter halo with

$$0.6 \times 10^{12}\ \mathrm{M}_\odot \lesssim M_{DM} \lesssim 1.2 \times 10^{12}\ \mathrm{M}_\odot$$

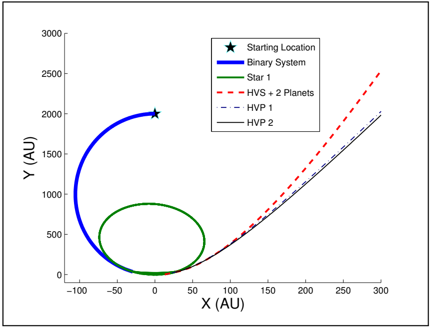
$$12.7\ \mathrm{kpc} \lesssim r_s \lesssim 20.0\ \mathrm{kpc}$$

Total Milky Way mass

$$1.2 \times 10^{12}\ \mathrm{M}_\odot \lesssim M_{DM} \lesssim 1.9 \times 10^{12}\ \mathrm{M}_\odot$$

Hypervelocity Stars and Exoplanets

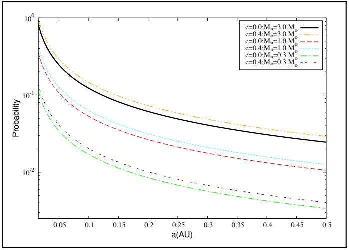
HVSs can be ejected with a planetary system and binary disruption can generate Hypervelocity Planets (Ginsburg+ 12; Fragione in prep.; Fragione & Ginsburg in prep.)

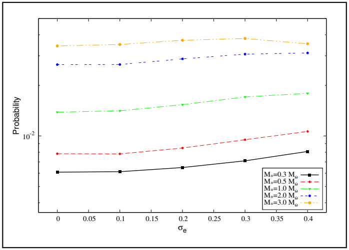


Ginsburg, Loeb & Wegner, MNRAS, 423, 948, 2012

- HVSs can retain compact planets (Ginsburg+ 2012)
- *Kepler* mission (Borucki+ 2010; Lissauer+ 2011)
- *Transiting Exoplanet Survey Satellite* mission by NASA: expected launch 2017-2018 (Sullivan+ 2015)

Geometric Transit Probabilities





Geometric probability for single planets (Murray & Correia 10; Winn 10)

$$p_T \approx \frac{R_*}{a(1-e^2)}$$

R_* = star radius
a = planet semi-major axis
e = planet orbital eccentricity

CORBITS algorithm computes the combined geometric probability of a multi-transit in an exoplanetary system (Brakensiek & Ragozzine 16)

Fragione & Ginsburg, accepted by MNRAS, arXiv:1609.03905, 2017

Observing Real Transits

Probability of observing a transit determined by physical parameters...

- Transit duration (Winn 10)

$$T \approx 6 \, \frac{P}{1\ \mathrm{day}} \frac{R_*}{a} \sqrt{1-e^2}\ \mathrm{hr}$$

- Drop in brightness (Winn 10)

$$f(t) = \frac{F(t)}{F_*} \propto \left(\frac{R_p}{R_*}\right)^2$$

- Signal to Noise ratio (Burke+ 15)

$$\mathrm{S/N} = \sqrt{N_{tr}} \, \frac{\Delta}{\sigma}$$

...but also observational strategy

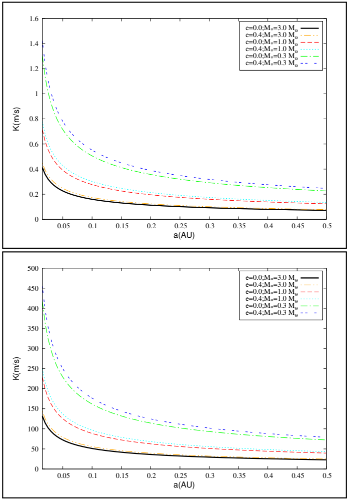
- Probability of detection (Fressin+ 13, Burke+ 15)

$$P_{det} = \frac{1}{2} + \frac{1}{2} \,\mathrm{erf}\left(\frac{\mathrm{S/N} - 7.1}{\sqrt{2}}\right)$$

- Window function: probability that a requisite number of transits required for detection occurs in the observational data as a function of planetary orbital period

$10^{-3} \lesssim P \lesssim 10^{-1}$ geometrical probabilities implies that at least one transit can be spotted with $\gtrsim 90\%$ probability around a low-mass ($\lesssim 1\ \mathrm{M}_\odot$) HVSs

Radial Velocities



Stellar velocity amplitude induced by the planet (Cummings+ 08)

$$
\begin{aligned}
K &= \frac{28.4\ \mathrm{m/s}}{\sqrt{1-e^2}} \frac{M_p \sin i}{\mathrm{M_J}} \times \\
&\times \left(\frac{a}{1\ \mathrm{AU}}\right)^{-1/2} \left(\frac{M_*}{\mathrm{M}_\odot}\right)^{-1/2}
\end{aligned}
$$

M_* = star mass
M_p = planet mass
a = planet semi-major axis
e = planet orbital eccentricity

Radial Velocity surveys are able to observe massive planets and Earth-sized planets provided that the duration of the survey is large enough

Conclusions

- Physical and kinematic feature of HVSs can be used to constrain the physical properties of star clusters infallen onto the massive black hole
- An unsegregated/top-heavy IMF/massive young stellar cluster may have originated part of present HVSs (Fragione, Capuzzo-Dolcetta & Kroupa 2016)
- HVSs data can constrain the dark content of the Milky Way
- HVSs data suggest a light dark matter halo $\lesssim 1.2 \times 10^{12}$ $M_\odot$ (Fragione & Loeb 2016)
- Possibility of studying planetary dynamics after strong gravitational perturbations
- New-generation telescopes are expected to spot planets around HVSs (Fragione & Ginsburg 2016)

A Bright Future for Hypervelocity Stars

Brown 2015: We are at an exciting time in the study of HVSs. New HVS candidates will soon come from Southern Hemisphere imaging surveys. The distribution of HVSs in large, uniform surveys will test proposed HVS ejection mechanisms. *Gaia* proper motions may directly link HVSs to their MBH origin. **The future of HVSs appears unbounded**.