Hypervelocity Stars
A New Probe for Near-Field Cosmology

Omar Contigiani

Student Colloquium, 20/06/2017, Leiden

Co-supervisor: Msc. T. Marchetti

Supervisor: Dr. E.M. Rossi
Near-Field Cosmology

And why a new probe would useful
Near-Field Cosmology - Structure Formation

MILKY WAY
Near-Field Cosmology - Structure Formation

DM HALO DENSITY PROFILE
Navarro–Frenk–White

\[ \rho(r) = \frac{M_h}{4\pi} \frac{1}{r(r + rh)^2} \]

Oblate/Prolate
Near-Field Cosmology - Structure Formation

DM HALO DENSITY PROFILE
Navarro–Frenk–White

\[ \rho(r) = \frac{M_h}{4\pi} \frac{1}{r^2 + \frac{r h}{2} \frac{1}{2}} \]

Oblate/Prolate

PREDICTIONS, e.g.

- Self interacting DM ⇒ Inner spherical halo (Peter+ 2013)

- Light MW halo ⇒ No more “missing satellites” (Wang+ 2011)
Near-Field Cosmology - Structure Formation

**DM HALO DENSITY PROFILE**
Navarro–Frenk–White

\[ \rho(r) = \frac{M_h}{4\pi r} \frac{1}{r + r_h}\]

DYNAMICAL TRACERS, e.g.:
- Stellar streams
- Globular clusters
- Stellar streams

Credit: ESO, F. Ferraro // NASA/JPL-Caltech
Near-Field Cosmology - Measurements To Date

\[ \rho(r) = \frac{M_h}{4\pi r (r + r_h)^2} \]

Credit: Wang+ 2015
Near-Field Cosmology - Measurements To Date

\[ \rho(r) = \frac{M_h}{4\pi r(r + r_h^2)} \]

Streams
- Spherical (Bovy 2016)

Halo stars
- Oblate (Loebman+ 2014)

Tracers
- Prolate (Bowden+ 2016)

Credit: Wang+ 2015
Near-Field Cosmology - Measurements To Date

Systematic biases

Thorough statistical analysis required

$\rho(r) = \frac{M_h}{4\pi r(r + rh^2)}$

Credit: Wang+ 2015
Hypervelocity Stars

And why they are a hot topic right now

- High velocity: $v \gg \sigma_v$
- Orbits crossing Galactic center

Credit: Brown 2015
Hypervelocity Stars - Observations To Date

[2005]

DISCOVERY OF AN UNBOUND HYPERVELOCITY STAR IN THE MILKY WAY HALO

WARREN R. BROWN, MARGARET J. GELLER, SCOTT J. KENYON, AND MICHAEL J. KURTZ
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Received 2005 January 7; accepted 2005 February 3; published 2005 February 21

![Graph showing radial velocity distribution with peaks at 709 km s⁻¹ and a dispersion of 120 km s⁻¹]
Hypervelocity Stars - Observations To Date

[2005]

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[2014]

MMT HYPERVELOCITY STAR SURVEY. III. THE COMPLETE SURVEY
WARREN R. BROWN, MARGARET J. GELLER, AND SCOTT J. KENYON
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mgeller@cfa.harvard.edu, skenyon@cfa.harvard.edu
Received 2013 December 5; accepted 2014 April 9; published 2014 May 6

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**Figure:**
- Diagram showing the distribution of hypervelocity stars with radial velocity and distance from the galactic center.
- The text provides statistical information such as the dispersion of velocities ($\sigma = 120$ km s$^{-1}$) and a prominent velocity of 709 km s$^{-1}$.
Hypervelocity Stars - Leading mechanism [1988]

Hyper-velocity and tidal stars from binaries disrupted by a massive Galactic black hole

J. G. Hills

- Three body interaction binary system and MBH

Credit: Brown 2015
Hypervelocity Stars - Leading mechanism [1988]

Hyper-velocity and tidal stars from binaries disrupted by a massive Galactic black hole

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- Three body interaction binary system and MBH
- S-star is left behind
Hypervelocity Stars - Leading mechanism [1988]

Hyper-velocity and tidal stars from binaries disrupted by a massive Galactic black hole

J. G. Hills

- Three body interaction, binary system and MBH
- S-star is left behind
- Hypervelocity star is ejected

$V \sim 1000 \text{ km/s}$
PROBING THE SHAPE OF THE GALACTIC HALO WITH HYPERVELOCITY STARS

OLEG Y. Gnedin,1 ANDREW GOULD,1 JORDI MIRALDA-ESCUDÉ,1 AND ANDREW R. ZENTNER2

Received 2005 June 30; accepted 2005 August 4
Hypervelocity Stars - Promising Past

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Received 2005 June 30; accepted 2005 August 4

[2005]

Joint constraints on the Galactic dark matter halo and Galactic Centre from hypervelocity stars
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4Theoretical astrophysics 350-17, California Institute of Technology, Pasadena, CA 91125, USA

[2017]
# Hypervelocity Stars - Promising Future

**Quantity**

10^9 stars

**Quality**

Spectroscopic subsample w/ full 3D velocity and position

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Credit: ESA/Gaia/DPAC. A. Moitinho & M. Barros (CENTRA – University of Lisbon)
Statistical Inference

Crash Course

Data
\((X_1, X_2, \ldots, X_n)\)

Model
\(f(X, \theta)\)

\(\mathcal{L}(\theta) = \prod_i f(X_i, \theta)\)

Constraints on model parameters
\(\tilde{\theta}\)
Statistical Inference - Unit (Fisher) Information

\[ I(\theta)_{i,j} = E \left[ \left( \frac{\partial \log f(X|\theta)}{\partial \theta_i} \right) \left( \frac{\partial \log f(X|\theta)}{\partial \theta_j} \right) \right] \]

\[ \text{Cov} (\hat{\theta}) \geq \frac{1}{I(\theta)} \]

Depends only on how sensible the model is to a change of parameters.
Research Project Goals

Study the kinematics of HVS to obtain:
Research Project Goals

Study the kinematics of HVS to obtain:

1) **FISHER FORECAST**
   To assess the potential.
   
   Compute the information and display the contours for DM halo parameters.
**Research Project Goals**

**Study the kinematics of HVS to obtain:**

1) **FISHER FORECAST**
   To assess the potential.
   Compute the information and display the contours for DM halo parameters.

2) **ESTIMATED POPULATIONS**
   How many HVSs could be there?
   Construct mock catalog of the galactic population and infer how many of them will be observed by Gaia.

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Research Project Goals

Study the kinematics of HVS to obtain:

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   To assess the potential. Compute the information and display the contours for DM halo parameters.

2) **ESTIMATED POPULATIONS**
   How many HVSs could be there? Construct mock catalog of the galactic population and infer how many of them will be observed by Gaia.

3) **LIKELIHOOD PIPELINE**
   Develop a technique! Feed the mock catalog into it and obtain realistic constraints.

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Formalism

Starting from the physics

Treat HVS as a statistical ensemble defined in the configuration space

\[
\left( \vec{x}, \vec{v}, m \right)
\]

\( \vec{w} \) Phase-space coordinate

\( f(\vec{w}, m) \) Number density in configuration space

Stellar mass
1) Steady state
Time-independent potential

Time-independent ejection rate

\[ \frac{\partial}{\partial t} = 0 \]
Phase-space distribution - Assumptions

1) Steady state

\[ \frac{\partial}{\partial t} = 0 \]

2) Source

How many HVSs are ejected per unit mass, volume, velocity?

Usually done with Monte Carlo simulations.

In our case, analytic function (Rossi+ 2014) which fits MC.
Phase-space distribution - Assumptions

1) **Steady state**

\[ \frac{\partial}{\partial t} = 0 \]

2) **Source**

Analytic function which fits MC.

3) **Sink**

When to HVS “disappear”?
Phase-space distribution - Assumptions

1) Steady state
\[ \frac{\partial}{\partial t} = 0 \]

2) Source
Analytic function which fits MC.

3) Sink
When to HVS “disappear”?

\[ T_{\text{flight}}(m) = \varepsilon_1 \varepsilon_2 T_{\text{MS}}(m) \]

\[ \varepsilon \quad \text{Uniformly distributed between [0, 1]} \]
Phase-space distribution - Solving continuity equation

\[
\frac{df}{dt}(\vec{w}, m) = R(\vec{w}, m) - S(\vec{w}, m)
\]
Phase-space distribution - Solving continuity equation

\[ f(\vec{w}(t), m) = \int_{0}^{\infty} R(w(t-t'), m) g(t') \, dt' \]

Analytic formula, that can be computed for any assumed

\[ R \quad \& \quad g \]

Ejection rate \hspace{1cm} Dying rate

Unfortunately, it requires the numerical integration of the trajectory

\[ \vec{w}(t) \]
Fisher Forecast

Estimates based on Unit Information - assuming a 1D toy model of the galaxy

\[ I(\vec{\theta})_{i,j} = E \left[ \left( \frac{\partial \log f(X|\vec{\theta})}{\partial \theta_i} \right) \left( \frac{\partial \log f(X|\vec{\theta})}{\partial \theta_j} \right) \right] \]

Credit: Selletin+ 2014
Fisher Forecast - Contours

ASSUMPTIONS:

- 1D toy model
- 5 $M_\odot$ HVSs
BAD NEWS:

Large relative errors.

\[ M_h \left( 10^{12} M_\odot \right) = 0.70^{+1.49}_{-1.49} \]

\[ r_h \, (\text{kpc}) = 16.00^{+12.24}_{-12.24} \]
**BAD NEWS:**
Large relative errors.

**GOOD NEWS:**
Strong degeneracy, worth investigating.
Mock catalogs

Simulation of the HVS Galactic and Gaia populations

Previous Results

Predicted ejection rate
theory (Yu+Tremaine 2013) & observations (Kollmeier+ 2010)

$10^{-4}$ yr$^{-1}$

Predicted pop. of 2.5-4 M$_\odot$ within 100 kpc

Observations (Brown 2015)

300
Mock catalogs - Ingredients

1) Ejection Rate & Flight time distribution
Previously modelled

\[ T_{\text{flight}}(m) = \varepsilon_1 \varepsilon_2 T_{\text{MS}}(m) \]
Mock catalogs - Ingredients

1) Ejection Rate & Flight time distribution
   Previously modelled

   \[ T_{\text{flight}}(m) = \varepsilon_1 \varepsilon_2 T_{\text{MS}}(m) \]

2) Galactic Model
   Kenyon+ 2008 (Potential)
   Halo + Bulge (spherical)
   Disc (axisymmetric)

   Bovy+ 2015a (3D Dustmap)
   Green+ 15, Marshall+ 06, Drimmel+ 03

   \[ f_{v,M} \propto M^{-1.7} |\vec{v}|^{-1} \]
   \[ \log |\vec{v}| = \log(1200M_\odot/M) + 0.6 \text{ km/s} \]
**Mock catalogs - Ingredients**

1) **Ejection Rate & Flight time distribution**
   Previously modelled

   \[ T_{\text{flight}}(m) = \varepsilon_1 \varepsilon_2 T_{\text{MS}}(m) \]

2) **Galactic Model**
   - Kenyon+ 2008 (Potential)
   - Bovy+ 2015a (Dustmap)

3) **Gaia Selection Function**
   \[ G_{\text{RVS}} < 16 \]
   
   `pyGaia` (A. Brown) to reconstruct Errorbars on proper motions / parallax / radial velocity
Mock catalogs - HVS Galactic population

Total Galactic population

60% unbound
Mock catalogs- HVS Galactic population

Gaia 3d velocities and positions

10% unbound
Mock catalogs- HVS Galactic population

Gaia 3d velocities and positions (high velocity)

~200 stars
Full likelihood

Finally!

\[ \mathcal{L}(\vec{\theta}) = \prod_{i} f(X_i, \vec{\theta}) \]

“Observed” data from mock catalogs

Formalism can predict different PDF for different parameters

\[ f(X_i, \vec{\theta}) \]

\[ M_h, r_h, c/a \]
Full Likelihood
Full Likelihood

GOOD NEWS

1) No bias

2) \( \frac{c}{a} = 0.98^{+0.04}_{-0.02} \)
**Full Likelihood**

**GOOD NEWS**

1) No bias

2) \( \frac{c}{a} = 0.98^{+0.04}_{-0.02} \)

**MIXED NEWS**

Effective constraint:

\[ \frac{M_h}{r_h^2} \pm 8\% \]
Summary

1) FISHER FORECAST
To assess the potential.

2) ESTIMATED POPULATIONS
How many HVSs are expected.

3) LIKELIHOOD PIPELINE
Develop a technique!

FORMALISM

🔍

Scientific Outlook

1) BARYONIC POTENTIAL
Can HVSs constrain the disk/bulge?

2) CHECK CONTAMINATION
Weighted likelihood?

3) BREAK DEGENERACY
More contours!
Mock catalogs- HVSs Galactic population vs Gaia
Fisher Forecast - P-S distribution

ASSUMPTIONS:
- 2D toy model
- 5 $M_\odot$ HVSs
Fisher Forecast - P-S distribution
Statistical Inference - Likelihood

Likelihood Principle:
All knowledge about the real parameters is in the likelihood.

Maximum Likelihood Estimation:
The point of maximum of the likelihood is a *good* estimator of the real parameters.

\[
\mathcal{L}(\vec{\theta}) = \prod_i f(X_i, \vec{\theta})
\]