Inferring the Galactic gravitational potential with Gaia and friends

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Review of action-angle variables

R.E. Sanderson • LG Astrostatistics • 1 June 2015
Review of action-angle variables
The accreted stellar halo is clumpy in action space

View in Galactic coordinates

View in action space (using input potential)

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Actions are most clustered in the correct potential

\[ J_r = \frac{GM}{\sqrt{-2E}} - \frac{1}{2} \left( L + \sqrt{L^2 + 4GMb} \right) \]

Potential parameters

Observations

Both

\[ M_{\text{true}} = 2.7 \times 10^{12} \, M_\odot \]
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Both

\[ M = 2.63 \times 10^{12} \, M_\odot \]

\[ M_{\text{true}} = 2.7 \times 10^{12} \, M_\odot \]
The Kullback-Leibler divergence measures clustering

\[ D_{KL}(p||q) = \int \ln \left( \frac{p(x)}{q(x)} \right) p(x) \, dx \]

Clumpier distribution = larger relative entropy
\[ D_{KL} = 1.1 \]

Smoother distribution = smaller relative entropy
\[ D_{KL} = 0.4 \]
Testing the action-clustering method

1. Make a mock halo in a known potential (start with accreted component only)
2. “Observe” halo with Gaia
3. Find the potential that maximizes the KLD
4. Determine confidence intervals (“error bars”)
5. Compare the answer to input values
6. Variations: incorrect/different functional forms, +smooth component, different error models, etc.

Errors blur, but do not destroy the information

Without errors          With Gaia (pre-launch) errors

Sanderson, Helmi, & Hogg, 2015
Results of tests with a mock *isochrone* halo

$\log_{10}$ conditional probability

**Without errors**

**With pre-launch Gaia errors**

67, 95, 99% confidence equivalents

$d_{GC} < 20$ kpc

Sanderson, Helmi, & Hogg, 2015
Simulated stellar halo in cosmological potential
15 thin streams chosen by hand from tagged Aquarius halo Aq-A
(Cooper+2010, Helmi+2011)

Sanderson, Hartke, & Helmi, in prep
Best-fit halo matches present-day mass profile

Model: smooth, spherical NFW

Sanderson, Hartke, & Helmi, in prep

*Membership info not used in fit*
Best-fit halo matches present-day mass profile
Model: smooth, spherical NFW

*Derived from \((r_\text{-}2, \rho_\text{-}2)\) of DM*

Sanderson, Hartke, & Helmi, in prep
Follow-up observations

**RVs**

- **Northern Hemisphere**: WEAVE on William Herschel Telescope (INT/IAC, La Palma, Canary Islands)

- **Southern Hemisphere**: 4MOST on VISTA telescope in Chile (ESO, Cerro Paranal, Chile)

- 4m telescope with multiple-fiber instrument

- ~10$^6$ halo stars (per survey)

- RV errors <2 km s$^{-1}$ to V=20-22

- Adds RVs to stars with Gaia proper motions

**RR Lyrae**

- **Distances** to 2%, RV errors 5-10 km s$^{-1}$
Improved distances increase information, but decrease sampling

KIII giants, Gaia parallaxes

RRLe distances
Observations with larger average $d_{\text{GC}}$ do better

Sanderson, in prep

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Advantages

• No need to assign membership of stars in streams (membership probability is an output)
• Robust to adiabatic time-evolution of host, substructure, some chaotic diffusion
• Can use any informative parameter (i.e. abundances)

Disadvantages

• Needs 6D phase space info
• Not a forward model (no way to treat uncertainties)
• Derailed by large (>50%) smooth component
• Limited to integrable potentials
Metallicities as a $4^{th}$ dimension

Metallicities and spreads from empirical relations of Kirby et al. (2011), constant $M/L$

$Z/Z_\odot$ might be better (e.g. Leaman 2012)
Metallicities as a fourth dimension

With \([\text{Fe/H}]\) (4D)
\[
\text{max } D_{KL} = 2.27
\]
\[
N = 30,860
\]
\[
\sqrt[3]{N} \sim 30
\]
\[
\sqrt[4]{N} \sim 13
\]

Without \([\text{Fe/H}]\) (3D)
\[
\text{max } D_{KL} = 2.34
\]
The takeaway

- Tidal streams are sensitive to the potential of the Galactic dark matter halo
- Streams form clumps in action space that still look clumpy at Gaia precision ($\delta \pi / \pi < 0.2$)
- Maximizing $D_{KL}$ of action distribution identifies the potential parameters
- Relation between $D_{KL}$ and posterior probability lets us set confidence intervals
- Expected number of MW streams is enough
- Stream membership info not required
The future

- Metallicity/abundances as extra dimensions
- More realistic potentials: flattening, triaxiality
- Halo-to-halo stochasticity
- Uses for the recovered action space