Tidal Streams as Galactic Potentiometers

Devdeep Sarkar
Extragalactic Astrophysics

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Tidal Streams

The Origin and all that...

- Natural by-product of hierarchichal structure formation.

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Tidal Streams

The Origin and all that...

- Natural by-product of hierarchichal structure formation.
- Can be produced along the orbit of a satellite galaxy when stars and/or gas are torn from it by tidal forces from its host.

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Tidal Streams

The Origin and all that...

- Natural by-product of hierarchichal structure formation.
- Can be produced along the orbit of a satellite galaxy when stars and/or gas are torn from it by tidal forces from its host.
- The stripped material populates the leading and trailing tidal streams that are aligned with the orbit of the satellite.

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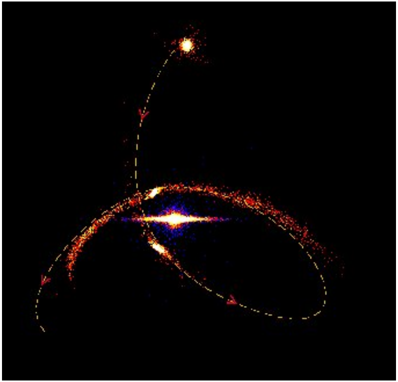
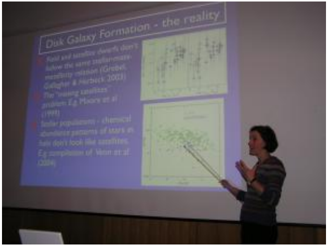
Tidal Streams



Tidal Streams around Milky Way



Kathryn V. Johnston

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Potential Potentiometer?

Motivation From Observations

- Several globular clusters known to possess excess unbound stars outside their tidal radii.

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- Several globular clusters known to possess excess unbound stars outside their tidal radii.
- Moving groups in the halo with no bound counterparts.

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Potential Potentiometer?

Motivation From Observations

- Several globular clusters known to possess excess unbound stars outside their tidal radii.
- Moving groups in the halo with no bound counterparts.
- Discovery of a carbon star trail encircling the Galaxy (Irwin & Totten 1998) provides the first example of data sampling the entire length of a stellar tidal stream.

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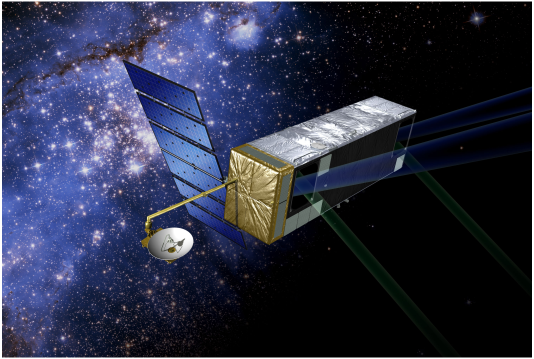
Potential Potentiometer?



(http://planetquest.jpl.nasa.gov/SIM)

Future Observations

Upcoming satellite missions, e.g., SIM, will accurately measure five out of the six phase-space coordinates of a star.

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Why Johnston et al. 1999?

Exploring the possibilities...

This *letter* investigates, through numerical simulations, the extent to which the potential of the Milky Way can be recovered using a data set such as the carbon star stream (Irwin & Totten 1998) and assuming that phase-space positions can be inferred with accuracy of SIM satellite.

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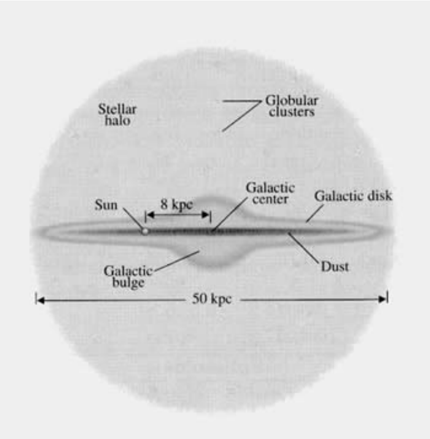
Modeling The Galaxy



Three Component Model for MW

- The Disk
- The Spheroid
- The Halo

Modeling The Galaxy

The Spheroid (Hernquist 1990)

$$\Phi_{spheroid} = -\frac{GM_{speroid}}{r + c}$$

The (Old!) Halo

$$\Phi_{halo} = v_{halo}^2 \ln(r^2 + d^2)$$

The Disk (Miyamoto-Nagai 1975)

$$\Phi_{disk} = \frac{GM_{disk}}{\sqrt{R^2 + \left(a + \sqrt{z^2 + b^2}\right)^2}}$$

- The Three-Component Model as Presented in Spergel 1996 and Johnston et al. 1996.

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Modeling The Galaxy

The (NEW!) *Oblate* and *Triaxial* Halo

$$\Phi_{halo}(x, y, z) = \frac{v_{circ}^2}{2} \ln\left(x^2 + \frac{y^2}{p^2} + \frac{z^2}{q^2} + c^2\right)$$

The Disk (Miyamoto-Nagai 1975)

$$\Phi_{disk} = \frac{GM_{disk}}{\sqrt{R^2 + \left(a + \sqrt{z^2 + b^2}\right)^2}}$$

The Spheroid (Hernquist 1990)

$$\Phi_{spheroid} = -\frac{GM_{speroid}}{r + c}$$

- The Model as Presented in Johnston et al. 1999.

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Modeling The Satellites

Assumptions

1. Since the satellite mass is much smaller than the MW, *dynamical friction* and *energy exchange* are assumed negligible.

(Johnston et al. 1996)

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Modeling The Satellites

Assumptions

1. Since the satellite mass is much smaller than the MW, *dynamical friction* and *energy exchange* are assumed negligible.
2. Interactions between the satellites will occur infrequently so that the evolution of each satellite can be considered independently.

(Johnston et al. 1996)

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Modeling The Satellites

Evolution of 10^4 Particles

- Each satellite is modeled with a collection of 10^4 self-gravitationg particles whose mutual interactions are calculated using a self-consistent field code (Hernquist & Ostriker 1992).
- The particles are initially distributed as a Plummer model and let evolve in a MW-potential for 10 Gyr.

Plummer (1911) Model

$$\Phi = -\frac{GM}{\sqrt{r^2 + r_0^2}}$$

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Energy Distances

Tidal Radius

$$r_{tide} = R\left(\frac{m_{sat}}{M_R}\right)^{1/3}$$

Orbital Energies E of Material

$$\epsilon = r_{tide}\frac{d\Phi}{dR} = r_{tide}\frac{GM_R}{R^2}$$

of satellite's orbital energy E_{sat}.

Pericenter!

These equations should be evaluated at the pericenter of the satellite's orbit since most of the mass loss will occur where the tidal field of the Milky Way is strongest.

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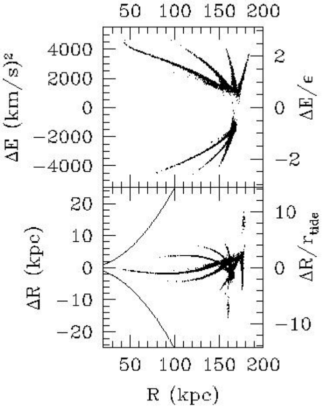
Energy Distances



(Johnston et al. 1999)

Distance Estimates

$$E = \frac{1}{2}\left[v_{los}^2 + d^2\left(\mu_l^2 + \mu_b^2\right)\right] + \Phi_{MW}$$

Result from Simulation 11

Energy offset $\mp 5\epsilon/4$ from E_{sat}.
Distance estimate to within few r_{tide}.

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Constraining Galactic Potential

The Algorithm

Johnston et al. (1999)

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Constraining Galactic Potential

The Algorithm

- For each assumed potential, integrate the satellite's orbit backward and calculate r_{tide} and ϵ at the pericenter.

Johnston et al. (1999)

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- For each assumed potential, integrate the satellite's orbit backward and calculate r_{tide} and ϵ at the pericenter.
- For each star in the debris with l, b, μ_l, μ_b, and v_{los}:

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- For each star in the debris with l, b, μ_l, μ_b, and v_{los}:
  - create n_{test} particles with energies E in the range $\pm 3\epsilon/4$ about $(E_{sat} \mp 5\epsilon/4)$ if the star is ahead/behind the satellite

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  - estimate the "energy distance" to each particle
  - integrate backward in time for a Galactic lifetime

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Constraining Galactic Potential

The Algorithm (cont'd...)

- For each star in the debris with l, b, μ_l, μ_b, and v_{los}:
  - credit the potential with a "capture" whenever any of these particles is separated by $dr < 1.8r_{tide}$ and a velocity $dv < (Gm_{sat}/dr)^{1/2}$.

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- Assign the potential's "score" as the number of successful captures.
- The potential having the highest score is the most likely one!

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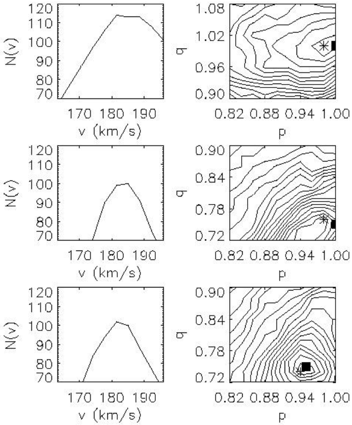
Simulation Results



(Johnston et al. 1999)

Recaptured Particles

Left-hand panels: Maximum number of captured particles for fixed v_{circ} and arbitrary q, p. *Right-hand panels*: Maximum number of rebound particles contoured in the p-q plane for the most likely value of v_{circ} from the left-hand panels.

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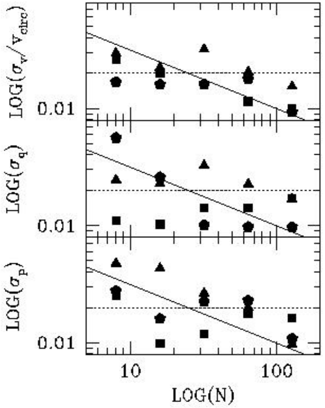
Simulation Results



(Johnston et al. 1999)

Dispersion

$\sigma_w = (< w^2 > - < w >^2)^{1/2}$

Bootstrapped errors in the potential calculated with N stars. The solid line is given by $\sigma_w = 1/10\sqrt{N}$. The dotted line shows the size of one cell of the gridded distribution from which σ_w was calculated.

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What Have We Learnt?

From Johnston et al. (1999)...

- Use of SIM measurements of stars in tidal streams to probe the Galactic potential seems promising.
- The 5D phase-space information for only 100 stars can be used to determine the circular velocity and shape of the Galactic halo with accuracies of a few percent...more than an order-of-magnitude improvement in our knowledge about MW's mass distribution.

cont'd...

However, discussion has been limited to four-parameter model...uncertainty will increase with the number of parameters varied.

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From P241C to ...

- K. V. Johnston, L. Hernquist, & M. Bolte; ApJ, 465, 278 (1996)
- K. V. Johnston, H. Zhao, D. N. Spergel, & L. Hernquist; ApJ, 512, 109 (1999)
- C. Murali & J. Dubinski; ApJ, 118, 911 (1999)
- R. Ibata, G. F. Lewis, M. Irwin, E. Totten, & T. Quinn; ApJ, 551, 294 (2001)
- C. Grillmair & R. Johnson; ApJ, 639, 17 (2006)
- YOU (2007? 2014?)

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