The Observed Structure of the Milky Way Spheroid

Heidi Newberg
Rensselaer Polytechnic Institute
Overview

(1) The Milky Way spheroid is spatially lumpy
   (a) Tidal debris and the Sgr dwarf galaxy
   (b) dwarf galaxies and globular clusters
   (c) oblate, prolate, or spherical?
   (d) asymmetry
   (e) maximum likelihood technique

(2) Velocity Substructure
   (a) The Sloan Extension for Galactic Understanding and Exploration (SEGUE)
   (b) The overdensity in Virgo and the triaxial spheroid

(3) The need for a larger spectroscopic survey of Milky Way Stars (RAVE, GAIA, LAMOST?)
Techniques for finding spatial substructures

1. Select a tracer of known luminosity to use as a distance tracer.
2. Select a tracer that can be used statistically to measure distance to a structure.
3. Convolve with a presumed color-magnitude distribution.

Pal 5 globular cluster

Yanny et al. 2000
Vivas overdensity, or Virgo Stellar Stream

Monoceros stream,
Stream in the Galactic Plane,
Galactic Anticenter Stellar Stream,
Canis Major Stream,
Argo Navis Stream

Stellar Spheroid?

Sagittarius Dwarf Tidal Stream

Pal 5
Squashed halo

Spherical halo

Prolate halo

Exponential disk

Newberg et al. 2002
Kathryn Johnston
Tidal Stream in the Plane of the Milky Way

If it’s within 30° of the Galactic plane, it is tentatively assigned to this structure.

Explanations:
(1) One or more pieces of tidal debris; could have puffed up, or have become the thick disk.
(2) Disk warp or flare
(3) Dark matter caustic deflects orbits into ring

Blue – model Milky Way
Pink – model planar stream

Monoceros, stream in the Galactic plane, Galactic Anti-center Stellar Stream (GASS)

Canis Major or Argo Navis

Sun

TriAnd, TriAnd2
The “Field of Streams”

Binned spatial density of SDSS stars \( g-r < 0.4 \). The color plot is an RGB composite with blue for the most nearby stars with \( 20 < r < 20.66 \), green for stars with \( 20.66 < r < 21.33 \), and red for the most distant stars with \( 21.33 < r < 22.0 \).
Newberg, Yanny et al. 2007

Sgr stream

\[ 20 < g_0 < 21 \]
\[ 18 \text{ kpc} \]

\[ 19 < g_0 < 20 \]
\[ 11 \text{ kpc} \]

\[ 21 < g_0 < 22 \]
\[ 29 \text{ kpc} \]

Sgr stream fainter than S297+63-20.5
Smoothed, summed weight image of the SDSS star counts after subtraction of both an exponential and a 4th order polynomial surface fit.

Anticenter stream
“complex”

Cold stellar stream

Sgr tidal stream
Areal density of SDSS stars with $0.1 < g - i < 0.7$ and $20 < i < 22.5$ in Galactic coordinates. The color plot is an RGB composite with colors representing regions of the CMD as shown in the inset. The estimated distance to the cloud is 10-20 kpc.
Areal density of SDSS stars with 0.1<g-i<0.7 and 20<i<22.5 in Galactic coordinates. The color plot is an RGB composite with colors representing regions of the CMD as shown in the inset. The estimated distance to the cloud is 10-20 kpc.
Asymmetric Spheroid

Star Counts Per Square Degree

Galactic Longitude

Newberg & Yanny 2005
Summary of Spheroid Substructure

Dwarf galaxy streams:
(2) Canis Major/Argo Navis? Monoceros (Newberg et al. 2002, Yanny et al. 2003), GASS (Frinchaboy et al. 2004), TriAnd (Majewski et al. 2004), TriAnd2 (Martin, Ibata & Irwin 2007), tributaries (Grillmair 2006)
(3) Orphan stream, Grillmair 2006, Belokurov et al. 2006

Globular cluster streams:
(1) Pal 5: Odenkirchen et al. 2003
(2) Grillmair & Dionatos 2006
(3) NGC 5466: Grillmair & Johnson 2006

Other:
(1) Hercules-Aquila Cloud
Doubling the known dwarf galaxies

Belokurov et al. 2007

Canis Major/Argo dwarf galaxy in Galactic plane; Martin et al. 2004, Rocha-Pinto et al. 2006


Fig. 7.— The locations of Milky Way satellites in Galactic coordinates. Filled circles are satellites discovered by SDSS, unfilled circles are previously known Milky Way dSphs. The light grey shows the area of sky covered by the Sloan survey and its extensions to date. The dashed and dotted lines show the orbital planes of the Sagittarius and Orphan Streams, respectively, taken from Fellhauer et al. (2006a) and Fellhauer et al. (2006b).
Now that we know the spheroid is lumpy, why do we care?

(3) We can wonder whether there is a smooth component to the spheroid, and what it would look like if we could find it. Newberg & Yanny estimated 20% of spheroid stars are in large tidal debris streams. Bell et al. 2007 say $\sigma/\text{total} = 40\%$.

(2) We can match characteristics of the substructure to models of galaxy formation.
  • We can measure the dark matter potential and substructure. Although we can in principle measure the 3D positions and space velocities for every star in the Milky Way, stars in tidal streams are the only ones for which we know where they were in the past.
Models of the Sgr dwarf tidal stream compared to new data (Helmi, private communication). The prolate model fits better, but there is an inconsistency with the tilt of the tidal tails.
Maximum Likelihood fit to the Celestial Equator

- **F-turnoff stars**
  - $0.1 < (g-r)_0 < 0.3$
  - $16 < g_0 < 22.5$
  - $(u-g)_0 > 0.4$
  - $310^\circ < ra < 59^\circ$
  - 115,907 stars

- Gaussian magnitude distribution with std. deviation of 0.6 and median 4.2
Stripe 82 Separation
We're bringing Galactic structure into the information age.
SEGUE Collaboration

China
LAMOST

Germany
Astrophysical Institute Potsdam
Max-Planck Heidelberg
Max-Planck Garching

Japan
Japan Participation Group

Korea
Korean Scientist Group

UK
Cambridge University

United States
American Museum of Natural History
University of Chicago
Fermilab
Johns Hopkins University
JINA/Michigan State/Notre Dam/Chicago
Los Alamos National Laboratory
New Mexico State University
Ohio State University
Princeton University
US Naval Observatory
University of Washington
Newberg et al. 2002

CMD in the direction of the Virgo Stellar Stream

Spheroid turnoff stars are slightly redder

F turnoff stars in Virgo

Thick disk turnoff is much redder
Counts of F turnoff stars with $0.2 < (g-r)_0 < 0.4$.

We compare one sight line in Virgo with the symmetric point with respect to the Galactic center. In a symmetric spheroid, the star counts in the two directions should be the same.

Models are Galactocentric triaxial Hernquist profiles.
$V_{\text{gsr}} = 130 \pm 10 \text{ km/s}$

$V_{\text{gsr}} = -168 \pm 10 \text{ km/s}$

$13 \text{ kpc}$

$16 \text{ kpc}$

$(300^\circ, 55^\circ)$

VSS field

$40 \pm 11\%$ of the stars are in the peak.

Sum of the two fields: $<10\%$ of the brighter stars are in the peak.

$S297+63-20.5$

$V_{\text{gsr}} = 130 \pm 10 \text{ km/s}$
Vgsr = -76 ± 10 km/s

VSS field

(300°, 55°)

13 kpc

16 kpc

Sum of the two

Y_{gsr}(km/s)

Y_{gsr}(km/s)
Other SEGUE Plates

With only the small amount of analysis we have done with SEGUE spectra, we have found at least one moving group on every SEGUE plate. The statistics are not consistent with Gaussian in any selection of stars limited in stellar population and volume. We find more substructure on every scale we look for it. Clearly, we need at least an order of magnitude more spectroscopic data, and it would be advantageous to have higher resolution.
Following Helmi et al. 1999

Tidal streams separate in angular momentum
– need 3D position and velocity through space.

Stars within 1 kpc of the Sun, with Hipparcos proper motions
A larger spectroscopic survey of the Milky Way

Now I want to identify all of the individual substructures from which the spheroid formed. We can do that if we group stars by angular momentum. For angular momentum we need distances, tangential velocities, and radial velocities for each star.
GAIA Astrometric Satellite
Magnitude limit: 20
1 billion Galactic stars
Astrometry and radial velocities
2011-2020

Currently de-scoped, so they will only get radial velocities for stars fainter than $17^{\text{th}}$ magnitude!

With LAMOST, radial velocities can be obtained for the most interesting magnitude range of $17<V<20$, maybe just for blue stars.
4 meter telescope
4000 fiber spectrograph

First light May 2007,
operations in 2009

Xinglong Observing Station, 3hr north of Beijing

I was there!
Participants in LAMOST, US (PLUS)

Heidi Newberg (Rensselaer), Timothy Beers (Michigan State), Xiaohui Fan (Arizona), Carl Grillmair (IPAC), Raja Guhathakurta (Santa Cruz), Jim Gunn (Princeton), Zeljko Ivezic (U. Washington), Sebastien Lepine (AMNH), Jordan Raddick (education, Johns Hopkins), Alex Szalay (JHU), Beth Willman (CfA), Brian Yanny (FNAL), and Zheng Zheng (IAS).

The collaborating group of Chinese astronomers, under the leadership of Licai Deng (NAOC), includes: Yuqin Chen, Jingyao Hu, Huoming Shi, Yan Xu, Haotong Zhang, Gang Zhao, Xu Zhou (NAOC); Zhanwen Han, Shengbang Qian (Yunnan, NAOC); Yaoquan Chu (USTC); Li Chen, Jinliang Hou (SHAO); Xiaowei Liu, Huawei Zhang (PKU); and Biwei Jiang (BNU).
A 3-5 year survey of 3-5 million Galactic stars

Sample survey footprint, shown as an Aitoff projection in Galactic coordinates. The green area probes the spheroid and thick disk in the NGC, with targets selected from existing SDSS imaging data. The yellow area probes the spheroid and thick disk in the SGC, and depends on imaging in the first year of SDSS III. The blue areas probe the thin disk.
Overview

(1) The Milky Way spheroid is spatially lumpy
   (a) Tidal debris and the Sgr dwarf galaxy
   (b) dwarf galaxies and globular clusters
   (c) oblate, prolate, or spherical?
   (d) asymmetry
   (e) maximum likelihood technique

(2) Velocity Substructure
   (a) The Sloan Extension for Galactic Understanding and Exploration (SEGUE)
   (b) The overdensity in Virgo and the triaxial spheroid

(3) The need for a larger spectroscopic survey of Milky Way Stars (RAVE, GAIA, LAMOST?)