The impact of Sagittarius on the disk of the Milky Way

James Bullock (UC Irvine)
The impact of Sagittarius on the disk of the Milky Way

Chris Purcell (Irvine ➔ U Pittsburgh)

Erik Tollerud (Irvine)
Near-Field Cosmology

Detailed observations of MW & Local Group to inform general models of galaxy formation.

How do we make thin disks like the MW in LCDM?

Bars? Spirality? (Even harder questions)
Missing Satellites Problem
Halo Streams & Substructure

Milky Way looks hierarchical

Bullock & Johnston 2005
Substructure within ~20 kpc of Galactic Center!

Juric 08

Virgo overdensity

Monocoros: R~20kpc, z~4kpc

Structure w/in ~20 kpc of Galactic Center!

Bullock & Johnston 2005

Wednesday, August 18, 2010
Ghosts of past mergers...

Milky Way (David Law)

Rigid (growing) disk potential

Bullock & Johnston 05
What do all of these mergers do to the disk?
Accreted dark halo mass ($M_{\odot}$)

Ave # mergers per halo

$10^{12} M_{\odot}$ halo

Accreted dark halo mass ($M_{\odot}$)

Stewart et al. 08
Cosmological Context

Stewart et al. 08

$>2 \times 10^{11} \, M_\text{sun}$ mergers
- HAVE NOT happened

Ave # mergers per halo

$10^{12} \, M_\text{sun}$ halo

Accreted dark halo mass ($M_\text{sun}$)
Cosmological Context

Stewart et al. 08

10^{11} M_{\text{sun}} mergers

~70% of the time

~1 over last 10 Gyr

Accreted dark halo mass (M_{\text{sun}})

10^{12} M_{\text{sun}} halo

Ave # mergers per halo
Cosmological Context

Stewart et al. 08

$10^{11} \, M_{\text{sun}}$ mergers

- Heat disks, don’t destroy them
- Milky Way is probably too cold to have had one. MW uncommonly quiescent. (Purcell, JSB, Kazantzidis 09).

Accreted dark halo mass ($M_{\text{sun}}$)

Initial

Remnant

Purcell et al. 09

$10^{12} \, M_{\text{sun}}$ halo

Ave # mergers per halo
Cosmological Context

Accreted dark halo mass ($M_{\text{sun}}$)

Stewart et al. 08

~$10^{10} M_{\text{sun}}$ mergers
  - ALWAYS happen
  - Typically ~6 in last 10 Gyr

Ave # mergers per halo

Accreted dark halo mass ($M_{\text{sun}}$)

$10^{12} M_{\text{sun}}$ halo
Accreted dark halo mass ($M_{\text{sun}}$)

Ave # mergers per halo

$\sim 10^{10} M_{\text{sun}}$ mergers
- ALWAYS happen
- Typically $\sim 6$ in last 10 Gry

Stewart et al. 08

Kazantzidis, JSB et al. 08

Initial Disk
Accreted dark halo mass ($M_{\text{sun}}$)

- Ave # mergers per halo

- Stewart et al. 08
  - $\sim 10^{10} M_{\text{sun}}$ mergers
  - ALWAYS happen
  - Typically $\sim 6$ in last 10 Gyr

- Kazantzidis, JSB et al. 08
  - Create interesting disk structures
  - Rings, spirals, flares
  - Detailed predictions depend on orbits, masses, timing, etc.
Sgr Dwarf Progenitor?

Nierderste-Ostholt et al. 2010:
(~70% of light in stream)

\[ L_{\text{Sgr}} \approx 10^8 \, L_\odot \]

\[ M_* \approx 2 \times 10^8 \, M_\odot \]

Wednesday, August 18, 2010
Sgr Dwarf Progenitor?

Nierderste-Ostholt et al. 2010:
(~70% of light in stream)

\[ L_{\text{total}}^{\text{Sgr}} \sim 10^8 L_\odot \]

\[ \rightarrow M_* \sim 2 \times 10^8 M_\odot \]
Sgr Dwarf Progenitor?

Nierderste-Ostholt et al. 2010:
(~70% of light in stream)

\[ L_{\text{Sgr}} \simeq 10^8 L_\odot \]

\[ M_* \simeq 2 \times 10^8 M_\odot \]

\[ M_{\text{vir}} \gtrsim 3 \times 10^{10} M_\odot \]
Sgr Dwarf Progenitor?

Nierderste-Ostholt et al. 2010:
(~70% of light in stream)

\[
L_{\text{Sgr}}^{\text{total}} \approx 10^8 L_{\odot}
\]

\[
M_* \approx 2 \times 10^8 M_{\odot}
\]

\[
M_{\text{vir}} \gtrsim 3 \times 10^{10} M_{\odot}
\]

\[
M_{\text{Sgr}}^{\text{total}} \approx M_{\text{MW disk}}^{\text{MW}}
\]
30 million particle disk + live halo

Purcell, JSB, Tollerud 2010
Stable to secular instabilities

Purcell, JSB, Tollerud 2010
‘Light’ Sgr Model

M_v = 1.5e10 M_{sun}

post-Sgr: t = 0.000 Gyr

Purcell, JSB, Tollerud 2010
'Light' Sgr Model

$M_v = 1.5 \times 10^{10} \, M_{\odot}$

post-Sgr: $t = 2.644 \, \text{Gyr}$

Purcell, JSB, Tollerud 2010

Wednesday, August 18, 2010
The impact of Sagittarius on the disk of the Milky Way

Law et al.

Purcell et al.

Rigid halo, rigid disk, no dark matter in Sgr

Fully self-consistent
Intermediate-scale spiral structure, similar to MW

Purcell, JSB, Tollerud 2010
Intermediate-scale spiral structure, similar to MW

Purcell, JSB, Tollerud 2010
Intermediate-scale spiral structure, similar to MW

Purcell, JSB, Tollerud 2010
Intermediate-scale spiral structure, similar to MW

Purcell, JSB, Tollerud 2010
Heavy Sag, $M=3.10^9 M_{\text{sun}}$

Purcell, JSB, Tollerud 2010
Scale height $\sim 400$ pc

Velocity Ellipsoid $\sim (35, 32, 20)$ km/s

Scale height $= 500$ pc

Velocity Ellipsoid $= (37, 27, 20)$ km/s
Did the Sag impact Create Monoceros Ring?

Light Sag $M = 1.5 \times 10^{10} \, M_{\odot}$  |  Heavy Sag $M = 3.0 \times 10^{10} \, M_{\odot}$
Conclusions

Sagittarius = an architect of structure in the Galaxy

Purcell, JSB, Tollerud 2010
Galactic anti-Center:
cone radius = 5°

log ρ (M☉/pc^3)

heliocentric distance (kpc)

exp. disk, R_⊙ = 2.6 kpc
Halo Streams & Substructure

Halo substructure compares well to LCDM
e.g. Bell et al. (2008)

MW data + models engineered to match data

Random LCDM realization
Light Sag $M = 1.5 \times 10^{10} \, M_{\text{sun}}$ Simulation

Heavy Sag $M = 3 \times 10^{10} \, M_{\text{sun}}$ Simulation
Heavy Sag $M = 3.10\, M_{\text{sun}}$ Simulation

Scale height = 510 pc
Velocity Ellipsoid = (37, 27, 20) km/s

Milky Way Disk

Scale height ~ 400 pc
Velocity Ellipsoid ~ (35, 32, 20) km/s
Near-Field Cosmology

What do all of these mergers do to the disk?
Halo Streams & Substructure

Bullock & Johnston 2005