Making Counter-Orbiting Tidal Debris. The Origin of the MW Satellites?

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Milky Way satellites

Missing Satellites:
- MW-Observation:
  ~ 24 satellite galaxies
- \(\Lambda\text{CDM}\)-prediction:
  ~1000 DM subhalos

Distribution:
- Disc of Satellites (DoS)

Kroupa et al. (2010)

Diemand et al. (2008)
Disc of Satellites (DoS)

- 11 ‘classical’ bright satellites (Metz et al. 2007)

DoS (11 classical satellites)

MW North Pole

Galactic coordinates

MW equator = disc plane

DoS described by normal vector
Disc of Satellites (DoS)

- 11 ‘classical’ bright satellites (Metz et al. 2007)
- 13 faint satellites (mostly discovered in SDSS) (Kroupa et al. 2010)
Disc of Satellites (DoS) + Orbital Poles

- Proper motions measures for 8 satellites
  ➡ Orbital poles \( (\mathbf{L} = \mathbf{r} \times \mathbf{v}) \) Metz et al. (2008)
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- 6 satellites co-orbit in the DoS
  ➡ Extremely unlikely if drawn from CDM simulations

- Sculptor: counter-orbiting \((\mathbf{L} \text{ offset by } \sim 180^\circ)\) in the DoS

Sagittarius: close to MW precession or scattered
Disc of Satellites (DoS) + Orbital Poles + Disc of GCs

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Disc defined by Young Halo GCs
(see Stefan Keller’s poster!)
Another possible origin

Common positions and velocities hint at common origin.

Tidal Dwarf Galaxies (TDGs)?
Another possible origin

Common positions and velocities hint at common origin.

Tidal Dwarf Galaxies (TDGs)?

Tidal debris form in the plane of a galaxy interaction

→ TDGs distributed in a disc

Can \textit{counter-orbiting} tidal debris form in a galaxy collision?

Method: numerical calculations
The Idea

Merger

Target Galaxy

Infalling Galaxy

retrograde

prograde
The Idea
The Setup

- Nbody models with SUPERBOX++
- Scaled MW (10 Gyr ago)
  - exponential disc
  - $M_{\text{disc}} = 8 \times 10^9$ $M_{\odot}$
  - $R_{\text{scale}} = 1.6$ kpc
  - $v_{\text{rot}} = 125$ km/s
  - $N = 5 \times 10^5$ particles
  - Hernquist halo, $10 \times M_{\text{disc}}$
- Similar to M33 today
- Parameter study
  - Mass ratios Target to Infalling
    1:1 and 4:1
  - 74 models (>200 CPU-days)
Do counter-orbiting tidal debris form?
Fly-by example
Fly-By Movie

Projection into the plane of the interaction
= disc of tidal debris seen face-on

2 Phases:
retrograde first
tail sweeps over target
then prograde
Target Galaxy
(edge-on)

Prograde Particles
Retrograde Particles

Movies: on
http://www.astro.uni-bonn.de/~mpawlow
Fly-By
Orbital Poles

Fly-by model 5deg200vel

$\phi$ in degrees

Prograde

Retrograde

$\theta$ in degrees
Fly-By
Orbital Poles

Fly-by model 5deg200vel

Θ in degrees

φ in degrees

Prograde
Retrograde

Dra
UM
LMC
SMC
Car
For
Sco
Sg
Fly-by
Radial Distribution

Fly-by model 5deg200vel

- all
- prograde
- retrograde

$r$ in kpc

$N$

Friday, April 8, 2011
Fly-By
Radial Distribution

• Two phases:
  ➡ Retrograde material more concentrated
  ➡ Maximum distance for retrograde material
  ➡ $P_{\text{retro}}$ high in center, zero further out

• Prograde material along tidal tail connecting the galaxies

$P_{\text{retro}} := \frac{N_{\text{retro}}}{N_{\text{pro}} + N_{\text{retro}}}$

$r$ in kpc
Fly-By
Comparison to MW satellite system

Model

MW Satellites

Arbitrarily picked particles
Fly-By
Comparison to MW satellite system

Model
Arbitrarily picked particles

MW Satellites
Rotated by 90 degrees
Is it possible to reconstruct the early MW-encounter?
Fly-by parameter scan

• Same 2-phase origin in all models.

• Maximum velocities $\sim 300-350$ km/s

• $P_{\text{retro}}$ depends on initial velocity, almost independent of perigalacticon $r_{\min}$
  ➔ Useful for reconstructions of galaxy interactions.

• $P_{\text{retro}}$ drops for particle-subset of higher apogalactica $r_{\text{apo}}$
  ➔ 2-phase origin, retrograde more concentrated.

\[
P_{\text{retro}} := \frac{N_{\text{retro}}}{N_{\text{pro}} + N_{\text{retro}}}
\]
LMC as origin of the DoS?

- Suggested by Lynden-Bell (1976).
- LMC lies and orbits within the DoS, \( v_{\text{LMC}} \sim 380 \text{ km/s} \) (Kallivayalil et al. 2006) comparable to infalling galaxies.

Compare to fly-by parameter scan:

- LMC co-orbiting
  - low \( P_{\text{retro}} \) (1:7)
  - in agreement with most models (no fine-tuning)
- Sculptor counter-orbiting, thus retrograde
  - rather low apogalacticon (~120 kpc, Platek et al. 2006)
  - like retrograde particles

![Graph showing equal-mass fly-by models]

- Initial velocity
  - 155 km/s
  - 175 km/s
  - 190 km/s
  - 210 km/s

\( r_{\text{apo}} > 60 \text{ kpc} \)
What did we learn?
Conclusions

• Creation of pro- and retrograde tidal debris is a natural outcome of galaxy interactions!

• True for both mergers and fly-by interactions of different mass-ratios.

• Here: Fly-Bys
  • number/mass-ratios: in general low $P_{\text{retro}}$
  • radial distribution: retrograde tidal debris more concentrated

• Tidal material resembles Disc of Satellites around the MW.

• TDGs will occupy phase-space region of tidal debris
  ➡ Reconstruction of early MW interaction that shaped MW-interaction
  ➡ Interesting agreements with LMC progenitor