The Planes of Satellite Galaxies Problem, Suggested Solutions, and Open Questions

Marcel S. Pawlowski
Hubble Fellow at
University of California Irvine
Email: marcel.pawlowski@uci.edu
Twitter: @8minutesold
Web: marcelpawlowski.com
The Planes of Satellite Galaxies Problem, Suggested Solutions, and Open Questions

Marcel S. Pawlowski
Hubble Fellow at
University of California Irvine
Email: marcel.pawlowski@uci.edu
Twitter: @8minutesold
Web: marcelpawlowski.com
Is the phase-space distribution of satellite galaxies consistent with ΛCDM expectations?

- Know 40-50 satellite galaxies for Milky Way and Andromeda.
- Can we use the Local Group (and other nearby host galaxies) as a testbed for cosmological models?
- Overall positions and velocities of satellite sub-halos on scales of 100s of kpc should be robust against internal dynamics and feedback processes.
  - Radial distribution is affected.
  
  Ahmed+2017, Garrison-Kimmel+2017
The Vast Polar Structure of the Milky Way (VPOS)

Pawlowski, Pflamm-Altenburg & Kroupa (2012, MNRAS, 423, 1109), Pawlowski & Kroupa (2013, MNRAS, 435, 2116), Pawlowski, McGaugh & Jerjen (2015, MNRAS, 453, 1047)

Majority of MW satellites with measured proper motions co-orbit along VPOS
The Vast Polar Structure of the Milky Way (VPOS)

Pawlowski 2018 (invited brief review in MPLA, arXiv:1802.02579)

Vast Polar Structure (VPOS) of the Milky Way
A Rotationally Supported VPOS: Better PM Measurement Result in Tighter Orbital Pole Distribution

$\Delta_{\text{sph}}$: scatter of 6 most-clustered orbital poles
Coherent velocities: the VPOS is rotating
Pawlowski & Kroupa (2013, MNRAS, 435, 2116)
Coherent velocities: the VPOS is rotating
Pawlowski & Kroupa (2013, MNRAS, 435, 2116)
Coherent velocities: the VPOS is rotating
Pawlowski & Kroupa (2013, MNRAS, 435, 2116)
Coherent velocities: the VPOS is rotating
Pawlowski & Kroupa (2013, MNRAS, 435, 2116)
Coherent velocities: the VPOS is rotating
Pawlowski & Kroupa (2013, MNRAS, 435, 2116)
Coherent velocities: the VPOS is rotating

Pawlowski & Kroupa (2013, MNRAS, 435, 2116)
Coherent velocities: the VPOS is rotating
Pawlowski & Kroupa (2013, MNRAS, 435, 2116)
Coherent velocities: the VPOS is rotating

Pawlowski & Kroupa (2013, MNRAS, 435, 2116)
Coherent velocities: the VPOS is rotating

Pawlowski & Kroupa (2013, MNRAS, 435, 2116)

8 of 11 satellites orbit in VPOS, (1 counter-orbiting)
\( \Delta_{\text{sph}} \): the scatter of the \( k \) most-concentrated orbital poles
$\Delta_{\text{sph}}$: the scatter of the $k$ most-concentrated orbital poles

- Concentration of $k$ closest orbital poles
- Probability to find this pole concentration in isotropic distr. (incl. $12^\circ$ obscuration)

Graph showing scatter of orbital poles with concentration and probability data.
$\Delta_{\text{sph}}$: the scatter of the $k$ most-concentrated orbital poles
Δ_sph: the scatter of the $k$ most-concentrated orbital poles
Δ_sph: the scatter of the k most-concentrated orbital poles

Concentration of k closest orbital poles

Probability in isotropic distr. [%]

Concentration of k closest orbital poles

Probability to find this pole concentration in isotropic distr. (incl. 12º obscuration)

k: number of combined orbital poles
$\Delta_{\text{sph}}$: the scatter of the $k$ most-concentrated orbital poles

Concentration of $k$ closest orbital poles

Probability in isotropic distr. [%]

Concentration of $k$ closest orbital poles

Probability to find this pole concentration in isotropic distr. (incl. 12° obscuration)

$k$: number of combined orbital poles
$\Delta_{\text{sph}}$: the scatter of the $k$ most-concentrated orbital poles

Concentration of $k$ closest orbital poles

| Probability in isotropic distr. [%] | 0 | 1 | 1.5 | 2 | 3.5 | 5 | 7 | 10 | 11 |
|-----------------------------------|---|---|-----|---|-----|---|---|-----|----|
| k: number of combined orbital poles | 5 | 6 | 7 | 8 | 9 | 10 | 11 |

Probability to find this pole concentration in isotropic distr. (incl. $12^\circ$ obscuration)
$\Delta_{\text{sph}}$: the scatter of the $k$ most-concentrated orbital poles

Sculptor orbits in the opposite direction but is well aligned with the VPOS. $\Delta_{\text{sph}}$ ignores this!
Minimum pole concentration and proper motion uncertainties

Assign each satellite tangential velocity which makes it orbit as close as possible to sat. plane.
Minimum pole concentration and proper motion uncertainties

Assign each satellite tangential velocity which makes it orbit **as close as possible** to sat. plane.

- Minimum possible pole concentrations of 10-20°.
Minimum pole concentration and proper motion uncertainties

Assign each satellite tangential velocity which makes it orbit as close as possible to sat. plane.

- Minimum possible pole concentrations of 10-20°.
- If only Sculptor counter-orbits, $\Delta_{sph}$ for all 11 sats is already 53°, vs 61° observed.

  ➡ Using $\Delta_{sph}$ of all 11 satellites is not a good measure of orbital coherence!
Minimum pole concentration and proper motion uncertainties

Assign each satellite tangential velocity which makes it orbit **as close as possible** to sat. plane.

- Minimum possible pole concentrations of 10-20º.
- If only Sculptor counter-orbits, $\Delta_{sph}$ for all 11 sats is already 53º, vs 61º observed.
  
  $\Rightarrow$ Using $\Delta_{sph}$ of all 11 satellites is not a good measure of orbital coherence!

- Now add **random uncertainties** as reported for observed proper motions ($\leq 0.1$ mas/yr):
  
  $\Rightarrow$ Poles on average much less concentrated
Assign each satellite tangential velocity which makes it orbit as close as possible to sat. plane.

- Minimum possible pole concentrations of 10-20°.
- If only Sculptor counter-orbits, $\Delta_{sph}$ for all 11 sats is already 53°, vs 61° observed.
  - Using $\Delta_{sph}$ of all 11 satellites is not a good measure of orbital coherence!

- Now add random uncertainties as reported for observed proper motions ($\leq 0.1$ mas/yr):
  - Poles on average much less concentrated

- What if total PM uncertainties are underestimated by only 50%?
  - Average observed $\Delta_{sph}$ are consistent with perfect alignment + uncertainties!
Significance: Could the VPOS be a pure chance alignment? Pawlowski (2016, MNRAS, 456, 448)

Probability to find at least as extreme structure in isotropic distribution

11 classical satellites in narrow plane ($\Delta_{\text{rms}} = 19.6$ kpc height)
(consider $12^\circ$ obscuration by Milky Way)

$P = 1.3 \times 10^{-2}$
(~ $2.5 \sigma$)
Significance: Could the VPOS be a pure chance alignment? Pawlowski (2016, MNRAS, 456, 448)

Probability to find at least as extreme structure in isotropic distribution

**11 classical satellites** in narrow plane ($\Delta_{\text{rms}} = 19.6$ kpc height) 
(consider 12° obscuration by Milky Way)

+ of these **8 co-orbit** ($\Delta_{\text{sph}} = 27.2$° orbital pole concentration)

![Diagram of orbital poles](image)

$$P = 1.3 \times 10^{-2} \quad (~2.5 \sigma)$$

$$P = 0.7 \times 10^{-4} \quad (~4.0 \sigma)$$
Significance: Could the VPOS be a pure chance alignment? Pawlowski (2016, MNRAS, 456, 448)

Probability to find at least as extreme structure in isotropic distribution

11 classical satellites in narrow plane ($\Delta_{\text{rms}} = 19.6$ kpc height)  
(consider $12^\circ$ obscuration by Milky Way)

\[ P = 1.3 \times 10^{-2} \quad (\sim 2.5 \sigma) \]

+ of these 8 co-orbit ($\Delta_{\text{sph}} = 27.2^\circ$ orbital pole concentration)

\[ P = 0.7 \times 10^{-4} \quad (\sim 4.0 \sigma) \]

+ 16 SDSS satellites define narrow plane ($\Delta_{\text{rms}} = 25.9$ kpc)  
aligned with classical satellites ($22^\circ$)  
(consider exact SDSS DR10 footprint and 2x MW obscuration)

\[ P = 3.7 \times 10^{-7} \quad (\sim 5.1 \sigma) \]
SDSS footprint biases away from alignment with plane fitted to 11 classical sats. Pawlowski (MNRAS, 456, 448)

Distribution of normal vectors for $N_{\text{iso}} = 27$ (isotropic only)
How many MW satellites can be part of an isotropic distribution?  

Pawlowski (2016, MNRAS, 456, 448)

Set up artificial MW satellite distributions following SDSS survey footprint:

- Preserve Galactocentric distances.
- \( N_{iso} \): 0 to 27 satellites in isotropic distribution.
- The others in planar, polar distribution with input rms height of 5 to 50 kpc.

\[ \Rightarrow \text{Expect 1 to 6 of the considered satellites to not be part of satellite plane.} \]

\[ \Rightarrow > 50\% \text{ in isotropic distribution excluded at } \geq 95\%. \]
How does the VPOS compare to $\Lambda$CDM expectations?

Frequency of similarly extreme satellite arrangements in cosmological simulations is $\leq 0.1\%$

(11 classical satellites only!)

Pawlowski (2018, MPLA, 33, 1830004)
Do Baryons help?
Pawlowski et al. (2015, ApJ, 815, 19), Pawlowski et al. (2017, AN, 338, 854)

Sawala et al. (2015): APOSTLE hydro simulations solve small-scale problems incl. satellite planes.

- Only measure flattening of satellite system projected onto unit sphere:
  - Does not test for planar alignment.
Do Baryons help?

Pawlowski et al. (2015, ApJ, 815, 19), Pawlowski et al. (2017, AN, 338, 854)

Sawala et al. (2015): APOSTLE hydro simulations solve small-scale problems incl. satellite planes.

- Only measure flattening of satellite system projected onto unit sphere:
  - Does not test for planar alignment.
  - Resulting flattening same as that for ELVIS DM-only simulations.
Do Baryons help?

Pawlowski et al. (2015, ApJ, 815, 19), Pawlowski et al. (2017, AN, 338, 854)

Sawala et al. (2015): APOSTLE hydro simulations solve small-scale problems incl. satellite planes.

- Only measure flattening of satellite system projected onto unit sphere:
  - Does not test for planar alignment.
  - Resulting flattening same as that for ELVIS DM-only simulations.

- Do not test coherence of orbits and alignment with best-fit plane.
  - Their orbital pole distribution is consistent with isotropic one.
Do Baryons help?
Pawlowski et al. (2015, ApJ, 815, 19), Pawlowski et al. (2017, AN, 338, 854)

Sawala et al. (2015): APOSTLE hydro simulations solve small-scale problems incl. satellite planes.

- Only measure flattening of satellite system projected onto unit sphere:
  - Does not test for planar alignment.
  - Resulting flattening same as that for ELVIS DM-only simulations.

- Do not test coherence of orbits and alignment with best-fit plane.
  - Their orbital pole distribution is consistent with isotropic one.

- Satellite systems in hydro-simulations (Ahmed et al. 17) not more flattened than in DMO-simulations.

No indication that baryons help address satellite planes problem.
Is the Milky Way special? The Great Plane of Andromeda (GPoA) Ibata+2013

Pawlowski (2018, MPLA, 33, 1830004)
The Vast Polar Structure / Great Plane of Andromeda have:

- Similar heights:
  - **VPOS**: 20-30 kpc
  - **GPoA**: 14 kpc
- Similar diameters: 400 kpc
- Similar spin directions

- Additional alignments:
  - **VPOS**: YH GCs, 50% streams
  - **GPoA**: Giant Stream, NW-S1
The GPoA is also in tension with $\Lambda$CDM expectations!

(15 of 27 satellites form plane)

Frequency of similarly extreme satellite arrangements in cosmological simulations is $\leq 1\%$, $\leq 0.1\%$ if considering radial distribution.

Pawlowski (2018, MPLA, 33, 1830004)
Is the Local Group special?
The Centaurus A Satellite Plane (CASP)

- Tully et al. (2015) had suggested double-planar structure of satellite galaxies.
Is the Local Group special?  
The Centaurus A Satellite Plane (CASP)

- Tully et al. (2015) had suggested double-planar structure of satellite galaxies.
- With additional candidates, we see less evidence for two planes, but increased significance of single-plane interpretation.

Müller, Jerjen, Pawlowski, Binggeli (2016) A&A, 595, 119
Is the Local Group special?  
The Centaurus A Satellite Plane (CASP)

• Tully et al. (2015) had suggested double-planar structure of satellite galaxies.

• With additional candidates, we see less evidence for two planes, but increased significance of single-plane interpretation.

• Does the satellite plane rotate? YES!

Müller, Pawlowski, Jerjen & Lelli (2018)  
Science, Volume 359, Issue 6375, 534
The Centaurus A Satellite Plane (CASP):
A coherent line-of-sight velocity trend indicative of rotation

14/16 satellites follow kinematic trend;
~0.4% chance to find this at random
Analogs of the CASP are very rare in cosmological simulations

- Pick hosts similar to Centaurus A:
  1. Viral mass $M_{\text{vir}} = 4.0 \times 10^{12} \, M_\odot$
  2. Isolated: no halo of $M_{\text{vir}} \geq 1.0 \times 10^{12} \, M_\odot$ within $d \leq 1.4 \, \text{Mpc}$
- Mock-observe at Cen A distance from 10 random direction.
- Draw 16 out of top 30 satellites, or chose top 16 (results no different).
- Apply simplified criteria to define satellite structure (avoids look-elsewhere effect):
  
  $b/a$: Projected on-sky flattening $b/a$ (x-axis).
  
  $N_{\text{corr}}$: Number of correlated velocities (y-axis).

**Dark Matter Only**

- $f_{\text{flat}} = 19.5\%$
- $f_{\text{both}} = 0.1\%$
- $f_{\text{corr}} = 1.2\%$
Analogs of the CASP are very rare in cosmological simulations and baryons don’t help!

**Dark Matter Only**

A

\[ f_{\text{flat}} = 19.5\% \]

\[ f_{\text{both}} = 0.1\% \]

\[ f_{\text{corr}} = 1.2\% \]

**Hydrodynamics + Feedback**

B

\[ f_{\text{flat}} = 14.4\% \]

\[ f_{\text{both}} = 0.5\% \]

\[ f_{\text{corr}} = 1.6\% \]
Suggested origins of planes of satellite galaxies

- Filamentary Accretion
- Group Infall
- Tidal Dwarf Galaxies

Self-consistently included in cosmological simulations (Any way to boost these?)

TDGs should be dark matter free. (Might require radical changes, e.g. MOND?)

Pawlowski (2018, MPLA, 33, 1830004)
Why filamentary accretion does not solve the satellite plane problem

• Intuitively convincing: Sub-halos are accreted mostly along filaments, i.e. from preferred directions. Thus, they end up anisotropically distributed around host.

• The GPoA & CASP align with the large-scale shear field. (Libeskind+2015)
Why filamentary accretion does NOT solve the satellite plane problem

**BUT:**

- Intuitively convincing: Sub-halos are accreted mostly along filaments, i.e. from preferred directions. Thus, they end up anisotropically distributed around host.
- The GPoA & CASP align with the large-scale shear field. (Libeskind+2015)

- Effect of filaments included self-consistently in cosmological simulations!
- Significant anisotropy ≠ sufficiently strong planar alignment
- Cosmic filaments too wide to account for narrow satellite planes.
- Coherent angular momentum of satellites in plane not expected from radial accretion along filament.
- The VPOS does not align with the large-scale shear field.
Why group infall does not solve the satellite plane problem

- Some sub-halos in simulations are accreted in groups.
- Satellites in one group share similar orbit, disperse along common plane.
- Thus, satellites accreted in the same group should for long time co-orbit along a common plane.

(Images: Pawlowski in prep.)

Effect of group infall included self-consistently in cosmological simulations! Too many groups fall in over the lifetime of a halo, and groups consist of small number of galaxies only. In conflict with observational constraints: Infalling groups need to be compact, but all observed dwarf associations are wider. (Metz+2009)
Why group infall does **not** solve the satellite plane problem

- Some sub-halos in simulations are accreted in groups.
- Satellites in one group share similar orbit, disperse along common plane.
- Thus, satellites accreted in the same group should for long time co-orbit along a common plane.

**BUT:**
- Effect of group infall included self-consistently in cosmological simulations!
- Too many groups fall in over the lifetime of a halo, and groups consist of small number of galaxies only.
- In conflict with observational constraints: Infalling groups need to be compact, but all observed dwarf associations are wider. (Metz+2009)
Why Tidal Dwarf Galaxies (TDGs) do not solve the satellite plane problem

- Second-generation galaxies formed in the debris of galaxy collisions.
- Survive their formation phase.
  (Duc+2011; Recchi+2007; Plöckinger+2014)
- Naturally result in planar, phase-space correlated dwarf galaxy populations!
  Even explains counter-orbiting satellite.
  (Pawlowski+2011, 2012a,b)

- TDGs should be DM free!
  (or non-eq. dyn., modifying DM/gravity?)
- TDGs should deviate from mass-metallicity relation.
  (But if very old, material less pre-enriched)
- On- and off-plane M31 satellites not systematically different
  (Collins+2015)
  (But what if all are TDGs?)
- Major open questions: Do enough TDGs form? With the right mass-function? And SFHs consistent with observed ones?
Why Tidal Dwarf Galaxies (TDGs) do **not** solve the satellite plane problem

**BUT:**

- Second-generation galaxies formed in the debris of galaxy collisions.
  
  (Duc+2011; Recchi+2007; Plöckinger+2014)

- Survive their formation phase.
  
  (Duc+2011; Recchi+2007; Plöckinger+2014)

- Naturally result in planar, phase-space correlated dwarf galaxy populations! Even explains counter-orbiting satellite.
  
  (Pawlowski+2011, 2012a,b)

- **TDGs should be DM free!**
  
  (or non-eq. dyn., modifying DM/gravity?)

- **TDGs should deviate from mass-metallicity relation.**
  
  (But if very old, material less pre-enriched)

- **On- and off-plane M31 satellites not systematically different** (Collins+2015)
  
  (But what if all are TDGs?)

- Major open questions: Do enough TDGs form? With the right mass-function? And SFHs consistent with observed ones?
Conclusions

• The phase-space distribution of satellite galaxies is a powerful test of cosmological models: it does not strongly depend on baryonic physics.

• Co-rotating Planes of Satellite Galaxies have been found for at least three systems: Milky Way, Andromeda & Centaurus A.

• Satellite galaxy planes are in severe tension with ΛCDM simulations, where similarly extreme structures should occur with a frequency of only 1 in ~1000 hosts.

• None of the suggested solutions to the Planes of Satellites Problem can satisfactorily address the issue.

• More details? See recent review: Pawlowski (2018, MPLA, 33, 1830004)
A whirling plane of satellite galaxies around Centaurus A challenges cold dark matter cosmology

Oliver Müller, Marcel S. Pawlowski, Helmut Jerjen, Federico Lelli

The Milky Way and Andromeda galaxies are each surrounded by a thin plane of satellite dwarf galaxies that may be corotating. Cosmological simulations predict that most satellite galaxy systems are close to isotropic with random motions, so those two well-studied systems are often interpreted as rare statistical outliers. We test this assumption using the kinematics of satellite galaxies around the Centaurus A galaxy. Our statistical analysis reveals evidence for corotation in a narrow plane. Of the 15 Centaurus A satellites with kinematic data, 14 follow a coherent velocity pattern aligned with the long axis of their spatial distribution. In standard cosmological simulations, <0.5% of Centaurus A–like systems show such behavior. Corotating satellite systems may be common in the universe, challenging small-scale structure formation in the prevailing cosmological paradigm.

Invited review on the Planes of Satellites Galaxies Problem in MPLA
arXiv:1802.02579

See also Mike BK’s Perspectives article in the same issue!