Gaps in tidal streams

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Stellar halos across the cosmos,
MPIA, July 4th 2018
Milky Way Substructure

Aquarius, Springel et al. 2008

Image credit: ESA/Hubble & NASA

Halo mass function

Stars

No Stars

$10^4$ $10^5$ $10^6$ $10^7$ $10^8$ $10^9$ $10^{10}$

Mass (M$_\odot$)

$10^{-10}$ $10^{-8}$ $10^{-6}$ $10^{-4}$ $10^{-2}$ $10^0$

$\frac{dN}{dM_{\text{halo}}}$ [M$_\odot^{-1}$]

Aq-A-1
Aq-A-2
Aq-A-3
Aq-A-4
Aq-A-5
Tidal Streams from Globular Clusters

Smooth Potential

Lumpy Potential

Interaction with substructure

Ibata et al. 2002, Johnston et al. 2002
Outline

• How do gaps grow/evolve?

• How many gaps are expected in the known streams around the Milky Way?

• Gaps in known streams
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Analytic Toy Model for Gaps

Setup

• Stream on circular orbit
• No position/velocity dispersion
• Plummer sphere perturber
• Arbitrary spherical host potential
• Arbitrary impact geometry

Approach

• Impulse approximation for velocity kicks
• Compute resulting orbits at first order
• Compute resulting stream shape
• Similar to Carlberg 2013, Yoon, Johnston, Hogg 2011

Erkal & Belokurov 2015a
Cartoon of Gap Formation

Orbital Mechanics 101
aka Football in Space

Gap Formation (also in Space)

1) Flyby

2) Compression

3) Expansion

4) Gap

5) Caustic

Tangential Throw

Radial Throw

Oscillations!
N-body example

- Stream generated by progenitor on circular orbit at 10kpc
- NFW host potential
- $10^8 M_\odot$ Plummer sphere, 250pc scale radius
- Direct impact on stream

Density along stream

Gap density

Gap size ($^\circ$)

Sky angle ($^\circ$)

Time in Gyr

~$1/t$

~$t$

~$t^{1/2}$
Same picture roughly holds for realistic streams

- Simple model misses two important aspects:
  - Streams are not generally on circular orbits
  - Stream material has a distribution in E,L

\[ \text{Gap size} \sim t^{1/2} \]

\[ \text{Gap density} \sim 1/t \]

Sanders, Bovy, Erkal 2016
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Streams around the MW

~ 15 globular cluster streams around MW

Pal 5, Odenkirchen et al. 2002
Ibata et al. 2016

Tri/Psc - Bonaca et al. 2012
Martin et al. 2014

GD1, Grillmair & Dinatos 2006
Streams around the MW

Streams in DES

Shipp + 2018
How many subhaloes fly near the stream?

- Flux through cylinder around stream (same approach as Yoon et al. 2011, Carlberg 2012)

$$N_{\text{enc}} \propto n_{\text{sub}} l b_{\text{max}} \sigma t$$

$$N_{\text{enc}} \sim (\text{number density}) \times (\text{stream length}) \times (\text{stream age})$$

- Also get velocity distribution

Erkal, Belokurov, Bovy, Sanders 2016
How many subhaloes fly near the stream?

- Pal 5
  - ~3.4 Gyr old (Kuepper et al. 2015)
  - # density of subhaloes scaled down from Aquarius (Springel et al. 2009)
  - length from observations (Odenkirchen et al. 2002)
  - disk depletes substructure by 3 (D’Onghia et al. 2010, Penarrubia et al. 2010, Sawala et al. 2016)

\[
\begin{align*}
10^5-10^6 \, M_{\odot} & : \sim 26 \text{ within } 2 \, r_s \\
10^6-10^7 \, M_{\odot} & : \sim 10 \text{ within } 2 \, r_s \\
10^7-10^8 \, M_{\odot} & : \sim 4 \text{ within } 2 \, r_s
\end{align*}
\]

Erkal, Belokurov, Bovy, Sanders 2016
How many gaps are created?

• Use gap size and gap depth from model

• Subhalo properties from VLII (Diemand et al. 2008)
  • Match $M-v_{\text{max}}$ relation with Plummer spheres

• Know number of interactions, sample properties of flyby, get distribution of gap properties

Erkal, Belokurov, Bovy, Sanders 2016
Properties of Gaps

• Distribution of gap sizes for LCDM spectrum from $10^5$-$10^8$ $M_\odot$

Guides the scale on which to search for gaps

Erkal, Belokurov, Bovy, Sanders 2016
So... how many gaps?

Pal 5
0.7 gaps with $f < 75\%$

GD1
0.6 gaps with $f < 75\%$

Tri/Psc
1.6 gaps with $f < 75\%$

~3 gaps expected in all three streams
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Gaps in Pal 5

- Nearby cold/long stream (~ 1km/s dispersion, ~10 kpc long)
- Progenitor still intact
- Deep data with CFHT (Ibata et al 2016)
- Proper motion for progenitor (Fritz & Kallivayalil 2015)
- Radial velocities along stream (Odenkirchen et al 2009, Kuzma et al 2015)
Gaps in Pal 5

- How should unperturbed stream look?
- Equal amounts of material in leading and trailing arm
- Symmetric density since no significant distance gradient (Ibata et al. 2016)
- Relatively smooth density along stream with little small scale structure
- Epicyclic over densities near progenitor

Erkal, Koposov, Belokurov 2017
Gaps in Pal 5

- 2 gaps
  - ~ 2 degrees (10^6-10^7 M\odot)
  - ~ 9 degrees (10^7-10^8 M\odot)
- Observed width is more uniform

Expected 0.7 gaps so
~3x LCDM

10^6-10^7 M\odot ~ 9-18 keV thermal relic WDM

Erkal, Koposov, Belokurov 2017
Gaps in Pal 5

- Alternative mechanisms
  - GMCs (Amorisco+ 2016): $10^6$-$10^7$ M$\odot$ within solar circle (Rice + 2016), 0.65 gaps expected
  - Globular clusters: < 1/6 rate expected from subhaloes (Erkal, Koposov, Belokurov 2017)
  - MW Bar: Rotating bar creates differential torque along stream (Erkal, Koposov, Belokurov 2017, Pearson+2017)
  - MOND can create asymmetries in tidal streams (Thomas+2018, Wu+2010)

Erkal, Koposov, Belokurov 2017
Gaps in Pal 5

- Alternative statistical approach
  - Measure power spectrum/bispectrum of density fluctuations (Bovy, Erkal, Sanders 2017)
  - Streams and perturbations generated in action-angle space (Sanders, Bovy, Erkal 2016)
- Idea (ABC)
  - Select normalization of LCDM subhaloes
  - Perturb stream with subhalo flybys
  - Keep if power/bispectrum on large scales matches data
  - Get constraint on LCDM normalization

Bovy, Erkal, Sanders 2017
Gaps in Pal 5

- Tested with N-body streams

- Pal 5 consistent with 1.5-9 LCDM, consistent with gap counting

Bovy, Erkal, Sanders 2017
Gaps in GD-1

CFHT data

Simulation

Stream on sky

Stream density

Angle along stream

- Hard to interpret since no progenitor
- Wiggles and density variations
- Still working on interpretation

de Boer + 2018
Gaps in GD-1

Gaps confirmed with Gaia

Price-Whelan & Bonaca 2018

3 gaps in GD-1

Wiggles in the stream track, stars off-stream
Gaps in GD-1

Progenitor disruption creates a gap

Stream density

Stream observables

Erkal & Gieles in prep.
Recovering Subhalo Properties

- Gap properties depend on 7d parameter space:
  - Subhalo mass
  - Scale radius
  - 3 velocities
  - Impact parameter
  - Time since impact

- Can we constrain these from observations of a gap?

Erkal & Belokurov 2015b
Stream observables

- Analytic model predicts 6d shape of perturbed stream

$10^7 \, M_\odot$, $r_s=250 \, \text{pc}$

Distance
Declination angle
Radial velocity
Tangential velocity
Vertical velocity
Density

Angle along stream
Inference with emcee

LSST Errors

$10^7 M_\odot, r_s = 250$ pc

Erkal & Belokurov 2015b

Velocity

$M$ ($10^7 M_\odot$) $w_r$ (km/s) $w_s'$ (km/s) $w_z$ (km/s) $r_s$ (kpc) $b$ (kpc) $t$ (Myr)

$r_s$

$b$

time
Observational Strategy

- Measure density and centroid along stream  
  Pal 5  GD-1  ✓  ✓
- Look for density variation with accompanying wiggle  
  Pal 5  GD-1  ✓-  ✓-
- Follow up with radial velocities  
  In progress
- Develop tools to model gaps in real streams  
  In progress
- Fit gap!
Conclusions

• Kicks from subhaloes change orbital periods and create gaps

• Expect ~1 deep gap per long stream

• Pal 5 contains 2 gaps and is consistent with ~ 3x LCDM

• Small gap consistent with $10^6$-$10^7$ M$\odot$ subhalo, > 9-18 keV WDM

• GD-1 has 3 gaps (1 from progenitor?), ~ 3x LCDM

• Next step: perform inference for observed gaps

• Can be used for constraints on any DM model