The Milky Way halo revolution

Vasily Belokurov
IoA, Cambridge
Universal structure formation

Initial conditions
Cosmic Microwave Background

Prediction for today’s Milky Way dark matter density distribution

40 kpc

500 kpc
Stellar and Dark halos are linked

Dark Matter halo $>90\%$ mass

Stellar halo $<0.1\%$ mass

Andrew Cooper
Galactic halo formation in Cold Dark Matter Cosmology

Aquarius Collaboration

Helmi & de Zeeuw et al 2000
Galactic halo formation in Cold Dark Matter Cosmology

Helmi & de Zeeuw et al 2000

Aquarius Collaboration
shells/clouds
massive satellites
radial orbits

streams
lower-mass satellites
tangential orbits

satellites
Information content

- **Satellites:** baryonic physics in high-z Universe, constraints on the low end of the DM mass function, **targets for indirect DM searches**

- **Streams:** properties of galaxies nonexistent at z=0, shape of the DM distribution, granularity of the DM distribution **unique probes of DM**

- **Shells/clouds:** accretion history, major merger events in the life of the Milky Way, **likely to dominate local density, important for direct detection**
1. Satellites
MW satellites revolution

SDSS, PS1, DES, VST, SMASH etc Willman et al. 2005a,b, Zucker et al. 2006b,a; Belokurov et al. 2006, 2007; Sakamoto & Hasegawa 2006; Irwin et al. 2007; Walsh, Jerjen & Willman 2007; Belokurov et al. 2008, 2009, 2010; Bechtol et al. 2015; Koposov et al. 2015a, 2018; Drlica-Wagner et al. 2015, 2016; Martin et al. 2015; Kim et al. 2015a; Kim & Jerjen 2015; Laevens et al. 2015b,a; Torrealba et al. 2016b, 2018; Homma et al. 2016, 2018, Torrealba et al 2019

Simon 2019
the ascii list is on /data/apm7_a/mike/subaru/sdsscands/stacks/
as usual only visible from certain solarius machines eg. cass02
these are not adjusted onto SDSS photom system yet
the ascii list is on /data/apm7_a/mike/subaru/sdscands/stacks/
as usual only visible from certain solaris machines eg. cass02
these are not adjusted onto SDSS photom system yet

Mike Irwin
To: Vasily Belokurov, Daniel Zucker
Re: Obj3,4,5,6

-----well b' me they are ALL satellites of the MW !!

Take a look at provisional CMDs in /home/mike/obj*.gif and note how
distant obj5 is.

These are simply the whole Subaru field so can easily clean them up later
to get rid of some of foreground.

Still need to refine the calibration but can't be far off since I'm using
default Subaru values.
CATS AND DOGS, HAIR AND A HERO: A QUINTET OF NEW MILKY WAY COMPANIONS


Received 2006 August 20; accepted 2006 September 20

ABSTRACT

We present five new satellites of the Milky Way discovered in Sloan Digital Sky Survey (SDSS) imaging data, four of which were followed up with either the Subaru or the Isaac Newton Telescopes. They include four probable new dwarf galaxies—one each in the constellations of Coma Berenices, Canes Venatici, Leo, and Hercules—together with one unusually extended globular cluster, Segue 1. We provide distances, absolute magnitudes, half-light radii, and color-magnitude diagrams for all five satellites. The morphological features of the color-magnitude diagrams are generally well described by the ridge line of the old, metal-poor globular cluster M92. In the past two years, a total of 10 new Milky Way satellites with effective surface brightness $\mu_v \gtrsim 28$ mag arcsec$^{-2}$ have been discovered in SDSS data. They are less luminous, more irregular, and apparently more metal-poor than the previously known nine Milky Way dwarf spheroidals. The relationship between these objects and other populations is discussed. We note that there is a paucity of objects with half-light radii between $\sim 40$ and $\sim 100$ pc. We conjecture that this may represent the division between star clusters and dwarf galaxies.

Subject headings: galaxies: dwarf — Local Group
CATS AND DOGS, HAIR AND A HERO: A QUINTET OF NEW MILKY WAY COMPANIONS


Received 2006 August 20; accepted 2006 September 20

No. 2, 2007

QUINTET OF NEW MILKY WAY COMPANIONS

Fig. 2.—CMDs of the central parts of Com, CVn II, Segue 1, and Her (from left to right) from the Subaru/INT follow-up data.
Gaia, the halo explorer

- Uniform quality all-sky coverage
- No weather
- Superb star/galaxy separation
- Spurious object reject via repeated scanning
- Parallax rejection
- Proper motion selection
Satellite detection with Gaia DR2
Gaia’s magic - Antlia 2 discovery
Gaia’s magic - Antlia 2 discovery
Gaia’s magic - Antlia 2 discovery
Gaia’s magic - Antlia 2 discovery

![Graphs showing color-magnitude distributions of all stars and stars not nearby with no motion.](image)
Gaia’s magic - Antlia 2 discovery

“The hidden giant: discovery of an enormous Galactic dwarf satellite in Gaia DR2” by Torrealba et al 2019
Previously unimaginable levels of surface dimness

Torrealba et al 2019
Previously unimaginable levels of surface dimness

Torrealba et al. 2019
Satellite orbits

Simon 2018; Pace & Li 2018 - proper motion study of the UFDs, many on highly tangential orbits, detected near peri-centre
Kallivayalil et al 2018; Fritz et al 2019; Erkal & Belokurov 2019 - using satellite orbits to re-visit the make-up of the Magellanic family
A spectacular demonstration of the hierarchical nature of galaxy formation

Torrealba et al 2019
Erkal & Belokurov et al 2019
A spectacular demonstration of the hierarchical nature of galaxy formation

Torrealba et al. 2019
Erkal & Belokurov et al. 2019
Conclusion+Question

• Ant 2 - a harbinger of a new, previously unseen super-mega-LSB population? If yes, then analogs can be detected with HSC and LSST out to 5 Mpc!

• The outer parts of the MW satellites - pathway to total DM masses, cusp-to-core transformation. A task for the new generation spectroscopy facilities: WEAVE, DESI, 4MOST and PFS
2. Streams
Gaia stream discoveries

Ibata, Malhan, & Martin

New stream detection methods taking advantage of Gaia’s superb proper motions

Myeong et al 2018
Catching DM sub-halos with stellar streams
Gaia’s view of the known streams

Bonaca & Price-Whelan

GD-1 Stream

Observed GD-1 stream
- Gaia proper motions
- PanSTARRS photometry

Model of a perturbed GD-1
- \( t = 495 \) Myr
- \( M = 5 \times 10^6 M_\odot \)
- \( r_c = 10 \) pc
- \( b = 15 \) pc
- \( V = 250 \) km s\(^{-1} \)

Orphan Stream

Erkal, Koposov & OATs

Galactic South

Galactic North

Galactic plane

Spline fit

PM direction
Orphan-LMC interaction

Milky Way + LMC
\( t = -2.00 \) Gyr, \( r(\text{LMC-Orphan}) = 507.6 \) kpc

Erkal et al 2019
Orphan-LMC interaction

Erkal et al 2019

Milky Way + LMC
$t = -2.00$ Gyr, $r(\text{LMC-Orphan}) = 507.6$ kpc
First total galaxy mass measurement

Erkal et al 2019

$M_{\text{LMC}} = 1.5 \times 10^{11} \, M_\odot$

We may have just detected the Magellanic wake, do ask me later
Conclusions/Questions

• Detection of the Orphan stream perturbation and determination of the LMC mass. Implies decoupled MW halo out of equilibrium.

• Looking forward to WEAVE/DESI/4MOST/PFS to complement Gaia’s astrometry.

• Full phase-space information is required to model the streams. Sub 1 km/s precision is required.

• Destroyed satellites in the shape of halo sub-structures keep the chemical record of the first building blocks.
3. Shells/Clouds/Mess
Previous attempts to understand the chemo-dynamics of the Galaxy

Eggen, Lynden-Bell & Sandage 1962

All samples limited to the Solar neighbourhood
Previous attempts to understand the chemo-dynamics of the Galaxy

Eggen, Lynden-Bell & Sandage 1962

Chiba & Beers 2000

All samples limited to the Solar neighbourhood
Previous attempts to understand the chemo-dynamics of the Galaxy

Eggen, Lynden-Bell & Sandage 1962
Chiba & Beers 2000
Carollo et al 2010

All samples limited to the Solar neighbourhood
Transition in halo properties

(b) $[\text{Fe/H}] \leq -1.8$

Chiba & Beers 2000
Hypothesis

“The presence or absence of a break in the stellar halo profile can be related to the accretion history of the galaxy. We find that a break radius is strongly related to the buildup of stars at apocenters. We relate these findings to observations, and find that the “break” in the Milky Way density profile is likely associated with a relatively early (~6–9 Gyr ago) and massive accretion event.”

Deason et al, 2013
Duality of the local velocity ellipsoid in Gaia DR1

Meatball - Sausage dichotomy

VB et al 2018
Anisotropy-metallicity link

see Myeong et al 2018 for a complementary study of the halo in the action space

VB et al 2018
Anisotropy-metallicity link

consistent with continuous accretion of small dwarfs

see Myeong et al 2018 for a complementary study of the halo int he action space
Anisotropy-metallicity link

Continuous accretion of small dwarfs consistent with extreme radial anisotropy preferred direction, implying head-on collision with a massive dwarf.

See Myeong et al. 2018 for a complementary study of the halo in the action space.
Insights from the Gaia DR2

The nature of the double sequence in GDR2 CMD

Babusiaux et al 2018: Stars with highly tangential motion

Haywood et al 2018: blue - last major merger, red - heated thick disc

Gallart et al 2019: part of the red sequence - prehistoric in-situ halo
Linking orbits and chemistry

A clear alpha-[Fe/H] sequence for the major merger debris selected kinematically

Helmi et al 2018

Mackereth et al 2018

Di Matteo et al 2018
From local samples to the rest of the halo

Deason et al 2018
Linking local halo kinematics with distant tracers.
Halo break = Sausage apo-centre

Lancaster et al 2018
Tracing the halo velocity ellipsoid to 40 kpc. Two components are required within 30 kpc

Cunningham et al 2018
Independent study - distant halo anisotropy with HST

Bird et al 2018

\[ \beta = 1 - \frac{\sigma_\theta^2 + \sigma_\phi^2}{2\sigma_r^2} \]

Requires the combined power of all spectroscopic surveys!
The shape of the MW stellar halo - dominated by one merger

Observed density and model of the Gaia DR2 RR Lyrae

Iorio et al 2018

The bulk of stars inside this triaxial structure show coherent highly eccentric motion (also see Wegg et al 2018 for dynamical modelling)
The shape of the MW stellar halo - dominated by one merger

The bulk of stars inside this triaxial structure show coherent highly eccentric motion (also see Wegg et al 2018 for dynamical modelling)
The shape of the MW stellar halo - dominated by one merger

Observed density and model of the Gaia DR2 RR Lyrae

Elongated, triaxial, tilted

The bulk of stars inside this triaxial structure show coherent highly eccentric motion (also see Wegg et al 2018 for dynamical modelling)
From stellar halo properties to MW accretion history with simulations

“Observing” the Auriga simulations suite

Orbital anisotropy

Fattahi et al 2018

$9 < |z|/\text{kpc} < 15$

$-1 < [\text{Fe/H}] < -0.7$
From stellar halo properties to MW accretion history with simulations

"Observing" the Auriga simulations suite

Orbital anisotropy

Mass assembly

Fattahi et al. 2018
From stellar halo properties to MW accretion history with simulations

"Observing" the Auriga simulations suite

Fattahi et al. 2018
Other accretion events?

Myeong et al 2019
Other accretion events?

Myeong et al 2019
Conclusions/Questions

• Ancient major merger + second possibly contemporaneous event discovered

• Tightly constrains the MW accretion history and properties of the halo, including shape, escape velocity etc

• Need to assess the damage done by the merger to the young MW - disc formation, disc heating, bulge formation, bar formation
Summary

• Many tens of MW satellites being discovered, most at the extreme surface brightness levels. Need efficient spectroscopic follow-up machine... e.g **PFS**

• Detection and characterisation of completely dark DM sub-halos is possible with stellar streams. But requires detection of large number of streams members. A job for **HSC and PFS**

• The inner halo is swamped by the debris of the ancient major merger. To map the rest of the accretion history either need better astrometry or go beyond the halo break. A job for **Gaia+LSST+DESI/WEAVE/4MOST+PFS**
Join the revolution!