Searching for Milky Way Satellite Galaxies with DECam

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DPF 2017
July 31, 2017
What are Dwarf Galaxies?
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The Milky Way

Small Magellanic Cloud
What are Dwarf Galaxies?

- The Milky Way
- Small Magellanic Cloud
- Fornax
- Sculptor
- Draco

Small Magellanic Cloud
Why are dwarf galaxies important?

Dwarf galaxies are the most dark-matter-dominated objects known.

Wolf et al. (2010)
Deviations from Cold Dark Matter could be detected in the abundance and densities of the smallest structures.
Smallest Structures Probe Fundamental Characteristics of Dark Matter

Cold Dark Matter

Warm Dark Matter

Simulations

Cold Dark Matter

Self-Interacting Dark Matter

Lovell et al. (2012)

Vogelsberger et al. (2016)
Observational Challenges to Cold Dark Matter

The “Missing Satellites” Problem

Fewer satellites are observed compared to simulations

The “Too Big to Fail” Problem

Observed satellites are under-dense compared to simulations
Observational Challenges to Cold Dark Matter

The “Missing Satellites” Problem

Fewer satellites are observed compared to simulations

Garrison-Kimmel et al. (2014)

The “Too Big to Fail” Problem

Observed satellites are under-dense compared to simulations

Garrison-Kimmel et al. (2014)
The Milky Way

Naked Eye Visible

Large Magellanic Cloud (LMC)

Small Magellanic Cloud (SMC)
NOTE: We can’t measure dark matter content from photometry alone...

Spectroscopy talk by Ting Li

Paust et al. (2007)

Measure:
- Age
- Metallicity
- Distance
Dwarf Galaxy Discovery Timeline

SDSS Begins

- Confirmed
- Candidate
Matched-Filter Searches

1) Start with a large catalog of stars

2) Apply a selection in color-magnitude space based on a stellar isochrone

3) Convolve with a spatial kernel

Stellar Isochrone

Koposov et al. (2008)
Walsh et al. (2009)
Willman et al. (2010)
Dwarf Galaxy Discovery Timeline

SDSS Begins

Confirmed
Candidate
The SDSS DR8 imaging footprint is shown in grey. Dashed line marks the tentative orbit of the Sgr dwarf galaxy. Galactic satellites are published by Okamoto et al. (2012) and Sand et al. (2009).

The accuracy and the stability of the SDSS photometry makes it possible to identify the most extreme faint systems, detectable to about magnitude $M_V = -4$. The exact limits for detection are set by the differential sky brightness and the capability to distinguish between individual stars.

With the piercing gaze of the HST: all three objects studied by Simon and Geha (2007) and Kirby et al. (2008) are confirmed with HST/STIS images. The CMDs of the UFDs have revealed no secrets even under medium and high resolution spectroscopy.

The CMDs of the UFDs can appear very simple. Differential photometry is then essential to secure the detection of the very faint and extended UFDs.

The CMDs of the UFDs show the usual for their Classical counter-parts signs of the MSTO and/or RGB. However, the rest of the population of these objects is too insignificant and can only be unearthed via an automated over-density detection procedure.

The CMDs of the UFDs are characterized by a relatively narrow width with a single peak. Moreover, the CMDs of the ultra-faint dwarfs are found to be horizontal and stretched, as their high ellipticities as first glimpse at discovery probably due to the influence of the Milky Way tides.

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The SDSS DR8 imaging footprint is shown in grey. Dashed line marks the tentative orbit of the Sgr dwarf galaxy. Galactic and wide photometric studies of a significant fraction of the new sizes, ellipticities and their stellar content. The most recent, deep accuracy using the same data. Deep follow-up imaging on telescopes identified in the SDSS as groups of only few tens of stars, their tionally faint levels of surface brightness across gigantic areas of possible for the over-density detection algorithms to reach excep-sky.

The ease with which these systems reveal themselves in a stellar picture with a naked eye, the rest of the population of these objects of all presently known SDSS ultra-faint satellites on the Galactic Grillmair, 2009; Belokurov et al., 2010 Walsh et al., 2007; Belokurov et al., 2008; Belokurov et al., 2009; Belokurov et al., 2007c; Irwin et al., 2007; Koposov et al., 2007; series have been reported in quick succession (for new Milky Way satellites and more than a dozen of new discov-eries, including Boo I, Boo III, CVn I and UMa II, are seen in this so-called ultra-faint satellites of the Milky Way. Although several star clusters and classical dwarf galaxies, while the very faint and The brightest of these ''hot pixels'' correspond to the well-known Galactic satellites that give the impression of being still intact. and 5

Fig. 6. Distribution of the classical dwarf galaxies (blue filled circles) and the SDSS ultra-faint satellites (red filled circles), including three ultra-f
The Dark Energy Survey

570 megapixel Dark Energy Camera (DECam)

~3 deg² field-of-view

<20s readout time

Unprecedented sensitivity up to 1µm

Mounted on the 4m Blanco telescope at CTIO in Chile
A likelihood analysis to simultaneously combine spatial and spectral information

\[ p_i = \frac{\lambda u_i}{\lambda u_i + b_i} \]

\[ \lambda = \frac{1}{f} \sum_{i \in \text{Stars}} p_i \]

\[ \log L = - \sum_{i \in \text{Stars}} \log(1 - p_i) - f\lambda \]

\( u_i \) = signal probability
\( b_i \) = background probability
\( \lambda \) = number of stars in the dwarf
\( f \) = observable fraction of stars

This technique naturally yields a membership probability for each star; important for spectroscopic targeting.
The Figure 2. magnitude and magnitude error in each of two of our elliptical Plummer population of the candidate does not bias the estimate. The resulting distribution represents the predicted magnitude from Bressan et al. 2001 PDF with a set of representative isochrones for old, metal-poor cells algorithm and are weighted by the inverse solid angle of the annulus is chosen to be sufficient.

The Plummer profile consists of half-light radius, ellipticity, and position angle, the population of the candidate satellite does not bias the estimate of the field population is 0.01.

Left: false color gri magnitude space. We then convolve the photometric velocities quite similar to that of Ret II. photometric uncertainties could contribute to this offset in isochrone. Since it is near the base of the giant branch, the isochrone of the star is more metal-rich than would be expected for a system as small as Ret II.

Figure 1. The Astrophysical Journal, 2012b. The spatial data for catalog object 0.01, 0.01, 0.01, and densely sample in one bounded degree of freedom.

The likelihood formalism above was applied to the Y1A1 TS 2 log modulus for the candidate blue HB star at (3:35:23.85, 541005.1) was plotted as filled in with red. The four PARSEC isochrones used correspond to the membership probability assigned to each star by the likelihood analysis.

Figure 3. Right: stars in the same region centered on DES J0335.6 are plotted as filled in with red. The four PARSEC isochrones used correspond to the membership probability assigned to each star by the likelihood analysis.

The GIRAFFE target included observed by GMOS is indeed a member of Ret II, the GIRAFFE target included observed by GMOS is indeed a member of Ret II, the GIRAFFE target included observed by GMOS is indeed a member of Ret II.

Colors correspond to the membership probability assigned to each star by the likelihood analysis.
Dwarf Galaxy Discovery Timeline

- SDSS Begins
- DECam Installed
- DES Year 1
- DES Year 2

Cumulative Number

Year

Confirmed
Candidate
Dwarf Galaxy Discovery Timeline

- Confirmed
- Candidate
- \(\Lambda CDM\) Prediction
  (Tollerud et al. 2008)

SDSS Begins

DECam Installed
Fig. 1.— Locations of the eight new dwarf galaxy candidates reported here (red triangles) along with nine previously reported dwarf galaxy candidates in the DES footprint (red circles; Bechtol et al. 2015; Koposov et al. 2015a; Kim & Jerjen 2015b), five recently discovered dwarf galaxy candidates located outside the DES footprint (green diamonds; Laevens et al. 2015a; Martin et al. 2015; Kim et al. 2015a; Laevens et al. 2015b), and twenty-seven Milky Way satellite galaxies known prior to 2015 (blue squares; McConnachie 2012). Systems that have been confirmed as satellite galaxies are individually labeled. The figure is shown in Galactic coordinates (Mollweide projection) with the coordinate grid marking the equatorial coordinate system (solid lines for the equator and zero meridian). The gray scale indicates the logarithmic density of stars with $r < 22$ from SDSS and DES. The two-year coverage of DES is $\sim 5000$ deg$^2$ and nearly fills the planned DES footprint (outlined in red). For comparison, the Pan-STARRS 1 survey covers the region of sky with $2000 > 30$ (Laevens et al. 2015b).

**Blue** - Previously discovered satellites
**Green** - Discovered in 2015 with PanSTARRS, SDSS, etc.

**Red outline** - DES footprint
**Red circles** - DES Y1 satellites
**Red triangles** - DES Y2 satellites
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Satellites of the Magellanic Clouds?

There is \(~3\sigma\) evidence that DES satellites are not isotropically distributed.

This anisotropy could be explained by an association with the Magellanic Clouds.
Magellanic Satellites Survey

(MagLiteS)

DECam Program for 12 nights in 2016-2017
PI: Keith Bechtol
Deputy PI: ADW

Funding through the NASA Guest Investigator Program
PI: ADW

Collaboration of ~45 members across ~20 institutions
Magellanic Satellites Survey (MagLiteS)

12 nights
~1300 deg$^2$
3 tilings

Roughly comparable in depth to DES Y2 in g and r-bands
Simulations predict ~3 dwarf galaxies for an isotropic distribution and ~10 galaxies for a Magellanic Cloud association.

First satellite found in a 1/4th of the MagLiteS data; other candidates being investigated.

Blanco Imaging of the Southern Sky

NOAO DECam Program for 12 nights in 2017A
Co-PIs: Soares-Santos & ADW

3 Science Drivers:
- Dwarf Galaxy Searches
- Gravitational Wave Follow-up
- Search for Planet 9

Cover ~2000 deg² in 2017; eventually cover the entire sky in g,r,i,z bands

Collaboration of ~35 members across ~10 institutions
BLISS also uses all pre-existing DECam Data

g-band
r-band
i-band
z-band

Sum(\text{teff} \times \text{texp})
log-scale from 30s (blue) to 300s (red)
• Most exposures pass cuts on exposure quality
• 2017A data covers ~2200 deg² in any single band
Blanco Imaging of the Southern Sky

- Most exposures pass cuts on exposure quality
- 2017A data covers ~2200 deg$^2$ in any single band
CDM Predictions for Future Dwarf Discoveries

- ΛCDM Prediction (Hargis et al. 2014)
- Confirmed
- Candidate
- MagLiteS (Projected)
- DECam (Projected)
- LSST (Projected)

Logarithmic Scale

Year

1920 1940 1960 1980 2000 2020 2040

10^0 10^1 10^2

Predicted Dwarf Discoveries

“Smoothed” ΛCDM Prediction