Halo Substructure as seen by RR Lyrae Stars

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Are there enough sub-structures in the MW halo as predicted by LCDM models
Still a lot of work to do from the observations point of view.
A case study: The Virgo Overdensity

★ Large overdensity of stars seen in SDSS spanning at least 2000 sq deg of the sky (maybe more if it extends to the South) (Bonaca et al 2012)
★ Distances (based on main sequence photometric parallaxes) go from ~6 to 20 kpc (Juric et al 2008)
★ Cloud-like (not the typical stellar stream)
★ Rough estimate of the luminosity = $10^6$ stars over the whole area (Bonaca et al 2012)
★ Not clear yet what the origin is. Destroyed galaxy? Destroyed galaxies? Halo ellipsoid tilt?
The Virgo Overdensity

Jerjen et al (2013) identified a main sequence at 23 kpc with properties similar to the stellar population of Sgr. No features detected at closer distances.

Spectroscopy of main sequence candidates by Brink et al 2010 (over small fields) show different kinematic features. Again some of them beyond ~20 kpc.

Detailed studies are difficult since they are confined to small areas of the sky and this is a very large feature (with very low surface brightness).
The Role of RR Lyrae Stars

- Old stars (>10Gyr)
- Standard candles. Distances good to ~5%
- Solid classification
- Several wide field surveys covering most of the sky now available (eg. Catalina Sky Surveys)

Overdensities of RR Lyrae stars in the QUEST survey (Vivas et al 2001, 2006)
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Velocities of RR Lyrae stars ~19 kpc show a strong kinematical signature at $V_{gsr} = 128$ km/s → the Virgo Stellar Stream (Duffau et al 2014, revised value from Duffau et al 2006)
New Surveys of RR Lyrae Stars

La Silla-QUEST survey (Zinn et al 2014)
- 112 CCD camera at the 1m Schmidt telescope in La Silla Observatory
- FOV = 10 deg²
- Single broad-band filter
- Coverage = 840 deg²
- ~ 1300 RR Lyrae stars up to ~80 kpc (V ~ 20.5)

Density of RR Lyrae stars clearly shows an enhancement due to the Virgo overdensity (Zinn et al 2014)
Goal: Understand the origin of the Virgo overdensity by studying their kinematic properties

274 RR Lyrae stars in the Virgo region (La Silla-QUEST: circles; QUEST: stars; Catalina Sky Survey: squares; LINEAR: asterisks; SEKBO: green)

Sample contains observations obtained with SOAR, WIYN, Magellan + stars in the SDSS database (only suitable spectra) + stars reported in Duffau et al 2014 and Prior et al 2009 → Sample >3x larger than previous works, covering 5x the area
Finding sub-structures

Find pair of stars close in the sky and with similar velocities. Pairs interconected formed a group.

In practice, $4d_{ij} < \text{critical value}$

\[(4d_{ij})^2 = \omega_{3d_{ij}}^2 (3d_{ij})^2 + \omega_v (v_i - v_j)^2 \quad (3)\]

where $3d_{ij}$ is the three-dimensional distance between two stars calculated from their galactocentric cartesian coordinates $(x, y, z)$:

\[3d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}. \quad (4)\]

Modification of the definition in Starkenburg et al 2009 (details in Duffau et al 2014)
Several groups are found using this algorithm in the Virgo region

- Are all of them real?
- Can a smooth halo produce groups like these ones?
Simulations

- Number of stars from integrating the density power law of the halo of Zinn et al (2014)
- Random position in the region of study
- Distance drawn from a distribution following the Zinn et al (2014) halo profile
- Velocity drawn from a Gaussian distribution (with dispersion dependent on distance).
- Observational errors added
- 10,000 simulations
Properties of Fake Groups
Significant Groups

Sagittarius Stream

Multiple features in the range of distance of the VOD

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Virgo Z

Dwarf galaxy candidate discovered by Walsh et al (2009) at 40 kpc

Jerjen et al (2013) found a strong main sequence in the location of Vir Z but at 23 kpc

Barbuy et al (2013) suggested it is a cluster of galaxies, not a dwarf.
RR Lyrae stars in Vir Z

Tentatively, stars 532 and 550 are associated with Vir Z which then will be located at 26.5 kpc.
Origin of the VOD

- VOD composed of multiple kinematical groups, with the most prominent group being the VSS at a velocity of ~130 km/s.

- Simulations needed

Stars from different disrupted galaxies along the same line of sight in the Aquarius simulation (Helmi et al 2011)

An alternative scenario is that these sub-structures are multiple wraps of the same disruption event.
Final Remarks

- RR Lyrae stars are great tracers of kinematical groups even if they belong to very low surface brightness features. Since they are rare stars, only a few of them may reveal a group (associated disadvantage: low number statistics!)
- After the Catalina Sky Surveys, a large fraction of the sky has now been searched for RR Lyraes up to distances of ~80-100 kpc. Spectroscopic follow-up is still very limited.
- Distant halo still unknown. Very few surveys reach distances > 100 kpc. This will change soon with DECam and later with LSST


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