Astro 590: next 3 classes

- Dwarf galaxies as probes of evolution
  - Distribution
  - Kinematics
- The star formation history of the universe
  - Star formation indicators
  - Nebular abundances
  - Starburst populations
- The role of AGN
  - AGN - galaxy connections
- High redshift galaxies
  - QSO’s
  - Lyman-break galaxies
  - Extremely red objects

Next Monday: 15 minute presentation of final project proposal
Dwarf ellipticals: dEs

The few dEs in the Local Group are all found around M31
Dwarf irregulars: dIs

- Pegasus
- IC10
- IC1613
- Phoenix
- NGC6822
- NGC3109
- SextansA
- SextansB
- barred
Dwarf spheroidals: dSphs

- dSphs are the most common type of galaxy
- Faintest ones emit less optical light than globular clusters
- Some retain their gas

Half of dwarfs in the Local Group are dSphs

Leo I  Leo II  Fornax  Draco  Ursa Minor
The Virgo Cluster

- Virgo Cluster Catalog (BST85)
- ~2000 objects
- Based on morphological appearance
- Largely confirmed by redshift measurements

Binggeli, Sandage & Tammann 1985, AJ 90, 1681
Structure in the Virgo Cluster

- Extended X-ray emission implies hot ICM
- Redshift distribution implies substructure including main cluster around M87, secondary one around M49, plus infalling spiral groups
**Ram pressure sweeping**

- Spirals in Virgo are HI deficient.
- Hydrodynamical simulations show effectiveness of ram pressure stripping
- Stripping occurs if \( \rho_{ICM} V^2 > 2\pi G \Sigma_{gas} \Sigma_{stars} \)
- Gravitational “restoring” force of stars and gas in galaxy
- \( \Sigma \) is surface density

Vollmer et al. 2001
Harassment

• Supporting evidence:
  - **Intra cluster diffuse light (ICL)**
    • Intergalactic stars, ~10-40% of the cluster stellar population (Feldmeier et al., 2003)
  - **Tidal debris**
    • e.g. Plumes and arc-like structures
    • The amount of tidal debris and ICL depends on local density, which supports the merger scenario (Combes, 2004)
  - **Rings of star formation that are more common than two-armed spirals** (Oemler et al., 1997)
    • Due to bars triggered during tidal interactions?

Calcaneo-Roldan et al. (2000)
HI Deficiency:

HI properties of 324 isolated UGC galaxies: Haynes & Giovanelli, 1984


\[
\text{Def}_{HI} = \log [ M(\text{HI:D})_{\text{pred}} ] - \log [ M(\text{HI:D})_{\text{obs}} ] 
\]

(positive for systems more deficient than isolated galaxies of same type)
Galaxies embedded in the hot X-ray gas are deficient in their HI relative to isolated galaxies of the same size and morphology.
Dwarf galaxies in Virgo

- BST in the VCC identified some 1000 dwarfs in Virgo
- 90% are dE's
- The remainder are dIs and BCDs

dEs: the dominant population in Virgo
Morphological segregation

- Ellipticals prefer highest density regions.
- Spirals are found preferentially in the field.

What about dwarfs?

Dressler 1980

Fig. 4.—The fraction of E, S0, and S+I galaxies as a function of the log of the projected density, in galaxies Mpc$^{-3}$. The data shown are for all cluster galaxies in the sample and for the field. Also shown is an estimated scale of true space density in galaxies Mpc$^{-3}$. The upper histogram shows the number distribution of the galaxies over the bins of projected density.
Morphological subclustering in Virgo

Binggeli, Popescu & Tammann, AApS 1993, 98, 275
Distribution of galaxy types in the Virgo Cluster

Conselice, Gallagher & Wyse (2001)

Number densities vs. distance from cluster center
Substructure in the Local Group

Diagram from Eva Grebel

Galaxies mainly clustered around the two principal galaxies MW & M31

- Giant spirals
- dSph (+dEll)
- dIrr
- dIrr/dSph
Local Group dEs

Keck/DEIMOS observations of Local Group dEs

Surface photometry of NGC 205 consistent with early tidal disruption.

M. Geha
2006 Ringberg conference
Hierarchical Formation Scenario

- Large galaxies (like the Milky Way and M31) form through merger and accretion of smaller systems
- Traces of discrete accretion events and interactions can be identified

Bullock and Johnston
Why study dwarf galaxies in clusters?

Chris Conselice 2006 Ringberg Conf.

1. Most numerous type of galaxy, particularly so in clusters - they are normal galaxies. The ultimate galaxy formation/evolution scenario must account for these objects.

2. In hierarchical galaxy formation, low mass systems are the first to form.

Low-mass galaxies may be the oldest galaxies in the universe and we can learn how large galaxies formed through merging by studying the properties of these systems. Alternatively, they may have formed their stars most recently ("downsizing").
Hubble Space Telescope Survey of the Perseus Cluster core

12 Orbits centered around the core of Perseus
(Conselice (PI), Held, DeRijke)
Dwarf ellipticals exist in clusters and morphologically appear similar to Local Group dwarf ellipticals.

Discovered in 1950s by G. Reaves through a Virgo cluster imaging survey.

There are however 5 - 10 as many low-mass cluster galaxies per giant galaxy as there are in groups.

Low-Mass Galaxies in the Perseus Cluster.
Background Spirals?

Perseus Cluster HST survey
(Conselice, Gallagher & Wyse '03 sample)

Real Dwarfs

Compact dwarfs

Background Spirals?

Ambiguous cases
Cluster dEs deviate from the color-magnitude relation

Clues for this deviation are old (e.g., Held & Mould 1994)

Low L galaxies in clusters are a heterogenous population

Color-Magnitude diagram for Perseus galaxies with Local Group dEs plotted.

Both 'blue' and 'red' dEs

Other studies have found similar trends

In the Fornax cluster (Rakos et al. 2001)

and Coma cluster (Poggianti et al. 2001)

Others (e.g., Adami et al. 2000) find similar results

Low mass galaxies in clusters are not a homogenous population, especially at $M > -15$
Cluster dEs likely have a mix of stellar populations – some might be metal rich.

Three stellar synthesis-modeled age tracts at constant metallicity (3 different ones) for different age populations.

Conselice et al. (2003)
Cluster dEs appear to have properties fundamentally different from low-mass galaxies in groups

**Question**: What part of the cluster environment produced this difference? Perhaps cluster dEs do not form by the standard supernova feedback mechanism (Dekel & Silk 1986).

**Some Possibilities** (all with interesting implications)

1. Delayed formation – dEs are not old
2. Containment by the intracluster medium
3. Removal of mass from accreted galaxies
4. Very massive dark halos
Conselice 2006 (Ringberg conference)

I. Cluster dwarf elliptical galaxies have properties that are fundamentally different from low-mass galaxies in groups, including:
   - spatial extent
   - relative density compared with giants
   - types of stellar populations

II. Some dEs in clusters have kinematic and stellar populations which appear fundamentally different from giant cluster galaxies suggests a different formation scenario.

III. Dwarf ellipticals in clusters have stellar populations with a mix of ages and metallicities at a given luminosity.

IV. These properties can be explained if some low-mass cluster galaxies formed both with the cluster, while others are the remnants of stripped galaxies accreted after the cluster was in place and/or delayed formation.
dEs in Virgo

- dEs are widely distributed in Virgo.
  - Do not cluster around giants
  - Different dynamics from Es
- dEs versus dE,Ns
  - At the faint end, $M_B \sim -12$, only 10% of dEs are nucleated.
  - At the bright end, $M_B \leq -16$, almost 100% are.
- A significant fraction of dEs in Virgo are rotation dominated.

van Zee et al. 2004, AJ
Velocity distribution of dEs is large, with more substructure than giant cluster galaxies.

Conselice et al. (2001)

**TABLE 4**

<table>
<thead>
<tr>
<th>Class</th>
<th>Mean (km s(^{-1}))</th>
<th>(\sigma) (km s(^{-1}))</th>
<th>Median (km s(^{-1}))</th>
<th>(N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>1090 ± 73</td>
<td>462</td>
<td>1095</td>
<td>40</td>
</tr>
<tr>
<td>S0</td>
<td>1164 ± 86</td>
<td>647</td>
<td>1115</td>
<td>56</td>
</tr>
<tr>
<td>dE</td>
<td>1146 ± 150</td>
<td>636</td>
<td>1220</td>
<td>18</td>
</tr>
<tr>
<td>dE,N</td>
<td>1033 ± 84</td>
<td>747</td>
<td>1159</td>
<td>79</td>
</tr>
<tr>
<td>dET</td>
<td>1054 ± 73</td>
<td>726</td>
<td>1159</td>
<td>97</td>
</tr>
<tr>
<td>dSO</td>
<td>960 ± 116</td>
<td>612</td>
<td>895</td>
<td>28</td>
</tr>
<tr>
<td>Irr</td>
<td>1054 ± 81</td>
<td>727</td>
<td>1100</td>
<td>81</td>
</tr>
<tr>
<td>S</td>
<td>1056 ± 71</td>
<td>776</td>
<td>1037</td>
<td>119</td>
</tr>
<tr>
<td>Virgo</td>
<td>1064 ± 34</td>
<td>705</td>
<td>1100</td>
<td>429</td>
</tr>
</tbody>
</table>

A sign of their formation mechanism?
Debattista et al. 2006 ApJL 651, L000 (rapid release)
WFPC2 images => double nucleus?
• Separated by ~32 pc
• Components have same magnitude and color
The case of VCC 128

Debattista et al.

Comparison of the galaxy (left) and the nucleus (right) with best-fitting SED (black line).

Below: corresponding mean properties off the best-fit stellar populations. For the nucleus, the mass shown is for the two components combined.

Best fit "foreground star" would be a G8V at 25 kpc but with $V=1190 \pm 289/-190$ km/s
The case of VCC 128

Debattista et al.
Analysis of the nuclear spectrum assuming it is stellar.

Open star = VCC 128
Open circle = NGC4486b (Kormendy & Gebhardt 2001)
Others: Tremaine et al 2002
Internal Dynamics of NGC 205

CFHT12K mosaic images (Demers et al. 2003)

Keck/ DEIMOS slitmasks chosen to lie along tidal extensions.

Spectroscopic targets chosen to be likely RGB stars in NGC 205.
NGC 205

Inner rotation = 15 km s$^{-1}$

Local Group rotation curves

- **NGC 205**
  - Geha et al. (2006)

- **NGC 147**
  - Geha et al. in prep

- **NGC 185**
  - Bender et al (1991)

$v_{\text{rot}} = 17 \text{ km/s}$
Unlike dEs in the Local Group, some dEs in Virgo are rotation-dominated.

Long slit stellar absorption line spectroscopy from Palomar 5m

Rotation curve
Velocity dispersion

van Zee et al 2004
dE’s as stripped dI’s?

- Rotation-dominated dEs appear to avoid the cluster center.
- Non-rotating dEs are found in the core.

*van Zee et al 2004*
Do dwarfs in clusters form after giants?

Their globular clusters may tell us

Keck spectroscopic study of globular clusters surrounding the dE VCC 1386 in the Virgo cluster

Numbered objects are the GCs with spectroscopy

VCC 1386 in the Virgo Cluster

Similar comparison with (V-I) colors shows that ages are > 5 Gyr for these globular clusters.
Can find dEs which are HI emitters - usually in outer parts

Arecibo observations of dEs in Virgo, with HI emitters as solid circles

Upper limits ~ $5 \times 10^5 \text{ M(solar)}$ in HI

Most emitters are in the outer part of the Virgo cluster - evidence of infall and future stripping of material? or gas for a future generation of star formation?

Conselice, O’Neil, Gallagher & Wyse 2003
The optical luminosity function

\[ \phi(L)dL \sim L^\alpha \exp\left(\frac{L}{L^*}\right) dL \]
\[ \phi(M)dM \sim 10^{-0.4(\alpha+1)M} \exp\left(-10^{0.4(M-M^*)}\right) dL \]

Press-Schechter (1974) formalism plus CDM fluctuation spectrum predicts faint end slope \( \alpha = -1.8 \)

- The LF has been well-determined down to \( M_R \sim -16 \) in a wide variety of environments, ranging from rich clusters to the field.
- The faint end (down to \( M_R \sim -10 \)) has been explored only in a few local regions.
  - Low L galaxies can only be seen nearby
  - Hard to measure redshifts for very faint, LSB objects
  - Small number statistics render local LFs uncertain

What do we know about dwarf galaxies in the Local Group and the Local Supercluster?
VCC Luminosity Function

- The LF is different among the different morphological classes
- The overall LF has a faint end slope of \( \alpha = -1.3 \)

But still large uncertainties
- Virgo is special place
- Small numbers at faint end

VCC: Virgo Cluster Catalog
Sandage, Binggeli & Tammann
1985AJ 90, 1759

Figure 1  The LF of field galaxies (top) and Virgo cluster members (bottom). The zero point of \( \log \phi(M) \) is arbitrary. The LFs for individual galaxy types are shown. Extrapolations are marked by dashed lines. In addition to the LF of all spirals, the LFs of the subtypes Sa+Sh, Sc, and Sd+Sm are also shown as dotted curves. The LF of Irr galaxies comprises the Im and BCD galaxies; in the case of the Virgo cluster, the BCDs are also shown separately. The classes dS0 and “dE or Im” are not illustrated. They are, however, included in the total LF over all types (heavy line).
Hunting for more dwarfs in Virgo

- CCD survey of 14 deg$^{-2}$ part of INT WFC survey
- New technique for identifying dwarfs in Virgo
- Faint end slope of LF:
  - $-1.4 \pm 0.2$ inner
  - $-1.8 \pm 0.2$ outer

Steeper value for the faint end slope in the outer region than the Inner core.

Sabatini et al. 2003
Ap Sp Sci 28, 97

Still small numbers of the faintest galaxies
The faint end slope of the LF

- Over the years, studies of the LF in Virgo have produced widely varying results for the faint end slope $\alpha$ of the optical LF.

-1.3  Sandage, Binggeli & Tamman 1985
-2.   Phillips et al. 1998
-1.2  Trentham & Tully 2002
-1.6  Sabatini et al. 2003

CDM + Press-Schechter predicts $\alpha = -1.8$
Dwarf galaxies in the Local Group

- dEs/dSphs found around giant galaxies
- dIs found at larger distances; some “isolated”
- Where/what are the compact high velocity clouds (HVCs)?

Here, we lump dEs and dSphs into the dE class.

- dEs span a wide range in surface brightness
- Right: simulation of LG dEs if located at 10 Mpc

Katy Flint’s homepage
http://www.ciw.edu/flint
Dwarfs are hard to find

**Green:** lines of constant exponential scale length

**Blue:** lines of constant isophotal size for an exponential profile with limiting $\mu$ of 26.7 $R$ mag arcsec$^{-2}$

Katy Flint's homepage: [http://www.ciw.edu/flint](http://www.ciw.edu/flint)
TABLE 1. Properties of three nearby clusters.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Virgo</th>
<th>Fornax</th>
<th>Ursa Major</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. E/S0</td>
<td>66</td>
<td>19</td>
<td>9</td>
</tr>
<tr>
<td>No. S/Ir</td>
<td>91</td>
<td>16</td>
<td>53</td>
</tr>
<tr>
<td>Distance</td>
<td>15.6 Mpc</td>
<td>14.5 Mpc</td>
<td>15.5 Mpc</td>
</tr>
<tr>
<td>Vel. dispersion</td>
<td>715 km s(^{-1})</td>
<td>434 km s(^{-1})</td>
<td>148 km s(^{-1})</td>
</tr>
<tr>
<td>Virial radius</td>
<td>0.73 Mpc</td>
<td>0.27 Mpc</td>
<td>0.88 Mpc</td>
</tr>
<tr>
<td>Crossing time</td>
<td>0.08 H(_0)^{-1}</td>
<td>0.07 H(_0)^{-1}</td>
<td>0.5 H(_0)^{-1}</td>
</tr>
<tr>
<td>Log luminosity</td>
<td>12.15</td>
<td>11.40</td>
<td>11.62</td>
</tr>
<tr>
<td>Log mass</td>
<td>14.94</td>
<td>14.10</td>
<td>13.64</td>
</tr>
</tbody>
</table>
Virgo vs Ursa Major

Ursa Major
Spiral-rich cluster
D ~ 18.6 Mpc

- Fewer dwarfs than predicted
- $\frac{1}{2}$ of dwarfs are blue irregulars
- $\alpha = -1.1$ for $-17 < M_R < -11$

Trentham & Tully
2002 MNRAS 335, 712

Trentham et al
2001 MNRAS 325, 385
Leo I: An interesting region

- Quite nearby D=10Mpc
- Leo I is dominated by early types
- Velocity dispersion is very small ~112 km/s
- Leo I contains the “Leo ring” of HI
Missing dwarfs in Leo I?

Katy Flint’s page: http://www.ciw.edu/flint
Leo I LF by TT02

- Faint end slope is very flat
- $d/g = 1.6 +/- 0.9$

Small number statistics!

Trentham & Tully
2002 MNRAS 335, 712
Fraction of dwarfs that are dEs

- The fraction of the dwarf population that are dEs is much higher in Virgo than in Leo.

Virgo $f(\text{dE}) \sim 83\%$
Leo $40\%$

Trentham & Tully 2002 MNRAS 335, 712
• Far fewer dwarfs than predicted by CDM simulations

• Mean logarithmic slope for \((-10 < M_R < -18)\) is \(-1.2\).

• Hint of difference in slope

• Clear difference in dwarf-to-giant ratio (fewer dwarfs per giant in Ursa Major)

Trentham & Tully
2002 MNRAS 335, 712
Comparison of 6 nearby groups

Trentham & Tully (2002 MNRAS 335, 712) used the Suprime-Cam mosaic camera on the Subaru 8m telescope to image 6 nearby groups including Virgo to identify low surface brightness galaxies as faint as R ~ 22.

<table>
<thead>
<tr>
<th>Property</th>
<th>N1407</th>
<th>Coma I</th>
<th>Leo I</th>
<th>N1023</th>
<th>UMa</th>
<th>Virgo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dist (Mpc)</td>
<td>25.0</td>
<td>16.4</td>
<td>11.1</td>
<td>10.0</td>
<td>18.6</td>
<td>17.0</td>
</tr>
<tr>
<td>E-Sab/Sb-Irr</td>
<td>15.</td>
<td>1.1</td>
<td>7.</td>
<td>0.1</td>
<td>0.3</td>
<td>1.6</td>
</tr>
<tr>
<td>Vel disp (km/s)</td>
<td>385</td>
<td>291</td>
<td>112</td>
<td>57</td>
<td>148</td>
<td>715</td>
</tr>
<tr>
<td>Area surveyed (Mpc⁻²)</td>
<td>0.087</td>
<td>0.112</td>
<td>0.067</td>
<td>0.061</td>
<td>1.43</td>
<td>0.067</td>
</tr>
<tr>
<td>No. dw/Mpc²</td>
<td>471</td>
<td>143</td>
<td>151</td>
<td>147</td>
<td>29</td>
<td>894</td>
</tr>
<tr>
<td>Dwarfs/giants</td>
<td>5.1±1.4</td>
<td>2.2 ± 0.7</td>
<td>1.6±0.9</td>
<td>3.7 ± 1.7</td>
<td>2.7 ± 0.8</td>
<td>3.6±0.8</td>
</tr>
<tr>
<td>Faint end slope $\alpha$</td>
<td>0.8</td>
<td>1.7</td>
<td>1.2</td>
<td>1.3</td>
<td>1.4</td>
<td>1.2</td>
</tr>
</tbody>
</table>
Average LF of groups

- Average LF for the 6 groups normalized by $N_d$ as derived for each group
- Line has a slope $-1.19 \pm 0.03$

Trentham & Tully
2002 MNRAS 335, 712
Optical LF: Summary

- Low mass, faint, low surface brightness galaxies are hard to find.

- Both structurally and kinematically, dEs bear closer resemblance to dIs than they do to normal Es.
- dEs and dIs do not occupy the same volumes.
  - Environment affect the morphological mix of the low mass population as well as its local number density

- Most studies of the optical LF suggest that environment plays a role in determining the faint end slope

- The discrepancies in counts of the faintest galaxies in different samples arise at least in part from the inherent difficulty in obtaining a reliable census of the faintest populations.

- We really don’t know much about dwarf galaxies...
Substructure in the Local Group

Diagram from Eva Grebel

Galaxies mainly clustered around the two principal galaxies MW & M31

- Giant spirals
- dSph (+dEll)
- dIrr
- dIrr/dSph

Diagnosis

MW

M31
Stellar Streams around M31

Ibata et al. 2001

McConnachie et al. 2004
Anatomy of M31’s Halo

- Giant Stream Progenitor:
  - M32?
  - NGC 205?
  - PNe?
  - Northern Spur?
  - ...

- Eastern Shelf
- Northern Spur
- Giant (Southern) Stream
- Andromeda NE (a.k.a. NE Blob)
- GI Clump
M31 RGB Stars by Color (SDSS)

Spatial Density of Probable M31 RGB Stars by Color (2’ x 2’)

And NE

And V

And IX

20 kpc
Andromeda IX Properties

- And IX: the lowest surface brightness ($\mu_{V,0} \sim 26.8$ mag arcsec$^{-2}$), lowest luminosity ($M_V = -8.3$) galaxy found up to that point
- Low metallicity ($[Fe/H] \sim -2$)
- $\sigma_v \sim 6$ km s$^{-1}$ ($\pm 3$)

Zucker et al. 2004,
Chapman et al. 2005
Andromeda IX Properties

Subaru g'r'i'

Zucker et al. 2004,
Chapman et al. 2005
Still Fainter -- Ursa Major

- $M_V = -7$ (?)
- $\sigma_v > 6.5 \text{ km s}^{-1}$

Willman et al. 2005, Kleyna et al. 2005
More M31 Satellites?

Andromeda V

Andromeda X

Andromeda IX
Andromeda X: Observations
Andromeda X Properties

- $\mu_{V,0} \sim 26.7$ mag arcsec$^{-2}$
- $M_V = -8.1$
- $[\text{Fe/H}] < -2$
- $\sigma_v$: TBD...

Zucker et al. 2006, Guhathakurta et al. 2006
LGS 3

• Stellar population dominated by old, metal poor stars but....
• Handful of young blue stars + HI gas
• Transition object between dSph and dI?