The Local Group of Galaxies

- 2 large spirals (Milky Way, M31)
- one small spiral (M33)
- dwarfs: dIrr (e.g. LMC, SMC, NGC 6822)
  dSph (e.g. Leo I)

dIrr tend to be found away from large galaxies
dSph found nearer large galaxies
Dwarf galaxies (smaller than LMC/SMC) have remarkably complex star formation histories, in general, despite the fact that some have similar masses to globular clusters.

Skinner cmhp
Reionization and dwarf galaxies

Before recombination (when CBR emitted) the universe was hot & dense enough to be completely ionized.

Then came the period known as the 'Dark ages' when the universe was optically thin because atoms 're-combined' to become neutral.

Then came the period called 're-ionization' when UV radiation ionized some of the gas again. Evidence from Gunn-Peterson trough

What are possible sources of this ionizing radiation?

-> first stars
-> super-massive 'pop III' metal-free stars
-> AGN

What would make a cloud of gas vulnerable to ionization by this radiation?

(hint: this radiation is still around today)
Q: How might reionization suppress star formation in dwarf galaxies?
Problem with ΛCDM simulations:

*Many* more small halos are predicted than are seen in local group.
DWARF GALAXIES IN THE LOCAL GROUP

Almost all dSphs belong to the Milky Way or M31.

dIrr galaxies have a broader distribution than local Group.

Both dIrr & dE/dSph can have very low central surface brightness.

Irregular galaxy called dIrr at $L < 10^8 L_\odot$

(=LMC has $L_v = 1.7 \times 10^9 L_\odot$

SMC $3.4 \times 10^8 L_\odot$)
NGC 55 is located in the Local Group. Perhaps莫istly in which the NGC 55 have "stretched"
Alternatively, this is where the surface velocity high. NGC55

URAL 9

properties of Local Group diameter to over 40°. The extent of the larger at 1987, Bothun &
low surface brightness galaxies but greatly nevertheless, there have
integrated properties of Vaucouleurs, and its remain the only
Ables 1965, 1968,

es 1 and 2. From top to tively. The directions to top and right edges of the Milky Way, which
large cross represents galaxies (see Table 1 for ms (denoted dIrr/dSph t 250 kpc apart.
stereo pairs; the Local distinct structure in the subgroup; this is best
The set of three singles in the stereo pairs.
and excessive clutter in stereo pair, none of the
rious planes.
a gas, we refer to disks with high values of $V/\sigma$ as 'cold'; 'hot' systems are those in which random motions are relatively more important, so that $V/\sigma$ is low. The stronger the influence of ordered rotation, the more disklike an object must be. Within the solar system, the giant planets Jupiter and Saturn, with a 'day' only ten hours long, are considerably more flattened at the poles than the compact and slow-rotating Earth. We will see in Section 6.2 that not all flattened galaxies rotate fast; but strongly rotating galaxies must always be flattened.

### 4.4.2 Dwarf irregular galaxies

Irregular galaxies are so called because of their messy and asymmetrical appearance on the sky (see Figures 1.13 and 4.19). Starbirth occurs in disorganized patches that occupy a relatively large fraction of the disk, because the size and luminosity of star-forming regions increases only slowly with the size of the parent galaxy. Even quite small irregular galaxies can produce spectacular OB associations.
dIrr galaxies are often irregular in shape & gas-rich; lots of recent star formation.

In all of the dIrrs we have looked carefully at, there is also a more extended, smoother distribution of older stars.

Only 3 local Group dwarfs have nuclei: M32 (has black hole, HSB), NGC 205 (tidally disrupting), Sgr dSph (""")
Figure 4.19 The dwarf irregular galaxy IC 10. Left, H1 contours superposed on an R-band negative image; the box measures 8' vertically, or 19 kpc. Right, negative image showing Hα emission from ionized gas – E. Wilcots, WIYN telescope.

We draw the line between irregular galaxies and the dwarf irregular systems at $L \sim 10^8 L_\odot$. Dwarf irregulars contain gas and recently formed blue stars; but in some other ways, they resemble the dwarf spheroidals. Irregular galaxies are diffuse (see Figure 5.7), and ordered rotational motion is much less important than it is in the Milky Way's disk. The stars and gas clouds have a velocity dispersion of $\sigma \sim 6$–10 km s$^{-1}$, but the peak rotation speed $V$ declines at lower luminosity; so in larger irregulars, $V/\sigma \sim 4$–5, falling to $V/\sigma \lesssim 1$ in the smallest dwarf irregulars. The proportion of metals in dwarf irregular galaxies is very low, $\leq 10\%$ of the solar value; the least luminous are the most metal poor. Gas in the smallest systems, such as Leo A, has only about 1/30 of the solar oxygen abundance, while the more massive galaxy NGC 6822 has about 1/10 of the solar abundance.

Dwarf irregulars tend to be brighter than the dwarf spheroidals, but this is only because of their populations of young stars. They contain relatively large amounts of gas, seen as neutral hydrogen, and the gas layer often extends well beyond the main stellar disk. Figure 4.19 shows the H1 layer of IC 10; as in Figure 4.4, we see large 'holes' blown by the winds of supernovae and hot stars. Ionized gas shines brightly, showing that young stars have formed in the shells of denser gas surrounding the holes. This galaxy has little if any organized rotation.

Figure 4.20 shows the color-magnitude diagram for Sextans A; this gas-rich system has much lower metallicity than the Milky Way.
Gas content:

1-50% \( M_{\text{HII}} / M_{\text{total}} \) dIrr

1-10% transition dIrr/dSph

~0 dSph

CO has been detected in many 2G dBRs including very low luminosity ones.

Q: How might a comparison of CO properties in low-luminosity & high-luminosity galaxies be interesting?
STAR formation history in local Group dwarfs

What might you use to trace the star formation history in a dIrr? a dSph?

• compare galaxy's color-magnitude diagram with predictions of stellar models (as good as the models are)

• Wolf-Rayet stars
  - very high mass
  - lots of mass loss
  → vigorous star formation in past $10^7$ yr
(Gallagher & Hunter 1984, and references therein). We also find that our data indicate that this additional extinction is not limited to these OB associations themselves; typically the “field stars” within each of these regions show much the same reddening as the OB association stars.

What about M33? No such clear picture of systematic spatial variations in the color excesses emerges for this galaxy. In Table 6(B) we see that the typical color excess is \( E(B-V) \sim 0.16 \). The fact that the reddening is lower than the average for Fields I and III is perhaps not too surprising, although it is curious that Field V also has a low value, given its location. The highest value, 0.33, is found in Field II, which is again not what we would expect. However, Fig. 25 of Humphreys & Sandage (1980) does show a dust silhouette extending on either side of M33—OB127. We conclude that the reddening in M33 is patchy, and in this way resembles the variation we see from OB association to OB association in the other spiral in our sample, M31.

The foreground reddening towards M31 and M33 have been measured by McClure & Racine (1969) using a very clever method of photometry of late-type field stars. They conclude that the foreground color excess is \( 0.11 \pm 0.02 \) for M31, and \( 0.05 \pm 0.02 \) for M33. Our values are consistent with these numbers (and with other reddening determinations by Humphreys 1979 and Humphreys et al. 1990 for M31, and Sandage & Johnson 1974, Humphreys 1980b, and Johnson & Joner 1987 for M33), and suggest that the additional extinction seen is intrinsic to these galaxies themselves. This clearly has implications for interpretation of data on standard candles, such as Cepheids observed in the visible or on the \( \lambda 5007 \) fluxes of planetary nebulae (Jacoby et al. 1992).


We next proceed to address the issues raised in the introduction: how do the massive star content of these galaxies compare to each other and to that of the Milky Way and Magellanic Clouds? To make this comparison, we must construct H–R diagrams using our results from the previous sections.

4.1 The Color–Magnitude Diagrams and the Question of Foreground Contamination

First let us ask what selection effects are in play in our sample, and to what extent Galactic foreground contamination is a problem. We show in Fig. 16 the color–magnitude diagrams for NGC 6822, M31, and M33. We show in this diagram our complete photometry sample, i.e., not just the blue stars selected for Table I for NGC 6822 and M33. (We have similarly used Tables IV–VI in Massey et al. 1986 for M31.) We denote by open circles the sample of bright and blue stars (i.e., Table 1 of this paper for NGC 6822 and M33 and a slightly modified version of Tables VIII–X of Massey et al. 1986 for M31) and by filled circles those stars for which we have spectral types listed in the preceding section.

Using the Ratnatunga & Bahcall (1985) model, we have also estimated the number of foreground stars as a function of magnitude and color. These numbers are shown in Fig. 16. We see that nearly all of our “bright and blue” samples are...
Fig. 10. The spectra of a representative sample of NGC 6822 stars are shown, with the primary spectral lines identified.

for supergiants, and

$$(B - V)_0 = -0.013 + 0.325 \times Q$$

denoted stars were observed spectroscopically), as the same disparity is apparent when we restrict this comparison purely to the spectroscopic sample. Either there is something wrong with the M31 $UBV$ photometry of Massey et al. (1986), or there is something peculiar about the intrinsic colors or the reddening in M31.

We give in Table 5 the ratio of $E(U-B)/E(B-V)$ for the spectroscopic sample. We see that both NGC 6822 and M33 yield values close to the canonical 0.72. Real variations are seen in Milky Way associations, with values 0.65–0.80 being the norm (cf. Massey et al. 1995a). However, we derive a substantially different value, 0.4–0.5, for the three M31 fields.

We believe that the agreement in $E(U-B)/E(B-V)$ between the three M31 fields argues that the effect is real and reflects either a real difference in the intrinsic colors of the M31 stars or that the reddening law itself has a slope which is substantially different than Galactic. Searle (1983) has found that the optical reddening law in M31 is anomalous from globular cluster observations. The UV-extinction curve...
4.3 The Most Massive Stars

We list in Table 7 the most luminous and massive (>40 $\text{M}_\odot$) stars in these fields. Masses have been estimated using the evolutionary tracks, and refer to the initial (ZAMS) mass. In interpreting these, one should keep the error bars in Fig. 17 in mind; i.e., a star listed with 60 $\text{M}_\odot$ might well have a mass of anywhere from 40 to 85 $\text{M}_\odot$ based only upon random errors in the photometry at the 0.02 mag level. (For this reason, we have rounded the masses to the nearest 5; i.e., we have really included stars of mass 35 $\text{M}_\odot$ in this and all subsequent discussions of “the most massive stars.”) Indeed, in interpreting the number of stars in a given mass range in Table 7 it would be well to keep in mind the demonstration by Massey et al. (1995b) and Massey et al. (1989b) that had photometry alone been available that the number of massive stars in LH 58 and NGC 346 (well-populated OB associations in the LMC and the SMC) would have been underestimated by a factor of 2–3. (Compare, for example, Figs. 17 and 20 in Massey et al. 1989b, or Figs. 12(a) and 12(c) in...
Figure 1 The evolutionary paths in the HRD of model stars of composition $Y = 0.25$ and $Z = 0.008$ and of initial mass $0.8M_\odot$, $5M_\odot$, $20M_\odot$, and $100M_\odot$. The models are calculated with the overshoot scheme for central convection. $M_{\text{HeF}}$ and $M_{\text{up}}$ are the masses separating low-mass stars from intermediate-mass stars, and the latter from the massive ones, respectively. For low- and intermediate-mass stars the tracks go from the zero-age main sequence (ZAMS) to the end of the asymptotic giant branch (AGB) phase, whereas for the massive stars they reach the stage of C-ignition in the core. Massive stars include the effect of mass loss by stellar wind. H-b and He-b stand for core H- and He-burning, respectively. He-flash indicates the stage of violent ignition of central He-burning in low-mass stars at the tip of the red giant branch (RGB). The main episodes of external mixing ($1^{\text{st}}$ and $2^{\text{nd}}$ dredge-up) are indicated by $1^{\text{st}}$ D-up and $2^{\text{nd}}$ D-up, respectively. The AGB phase is separated into the early stages (EAGB) and thermally pulsing regime (TPAGB) of the He-burning shell. For low- and intermediate-mass stars we show the stage of planetary nebula (PN) ejection, the region where PN stars are observed, and the white dwarf (WD) cooling sequence. A horizontal line indicates the locus of the zero-age horizontal branch (ZAHB)—core He-burning models—of low-mass stars with composition typical of globular clusters. The shaded vertical band shows the instability strip of Cepheid and RR Lyrae stars. In the region of massive stars, we show the de Jager limit, the location of the blue luminous variables (LBVs) and Wolf-Rayet stars (WRs). Finally, the thick portions of the tracks indicate the stages of slow evolution, where the majority of stars are observed.
Figure 4.20 Color-magnitude diagram for the dwarf irregular galaxy Sextans A: its luminosity $L_V \approx 4 \times 10^7 L_\odot$ at a distance $d = 1400$ kpc. The bluest near-vertical ‘plume’ of stars, rising from $V - I, m_V \approx (-0.3, 25)$, is the main sequence. Stars in the slightly redder plume beside it, at $V - I \sim 0$, are blue supergiants: massive stars with $M \gtrsim 2 M_\odot$, burning helium in their cores. The red giant branch rises from the red clump, at $V - I, m_V \approx (0.8, 26)$; the stars with $L \gtrsim 1000 L_\odot$ and $V - I \sim 1$ are red supergiants – R. Dohm-Palmer et al.

supergiants on the parallel plume at $V - I \sim 0$. The mass of stars at $V - I \sim 0.8$ at the base of the figure is the red clump; the red giant branch rises from it. Star formation has gone on for $\gtrsim 1$ Gyr; lately, it has been especially vigorous, increasing at least threefold over the past 50–100 Myr.

Some dwarf galaxies, such as Phoenix and LGS3, are classified as intermediate between dwarf irregulars and dwarf spheroidals. Almost all their stars are more than a few gigayears old, but they contain a little gas and a few young stars. A few stars as young as 500 Myr have been found in Fornax, so this dwarf spheroidal galaxy must have had some gas until quite recently. The Carina dwarf spheroidal made most of its stars in a few discrete episodes (see Figure 4.9); at times of peak starbirth, it may have been a miniature version of Sextans A. Because of their similar structures, small irregulars like the Pegasus dwarf may be at an early stage, while dwarf spheroidals represent the late stages, in the life of a similar type of galaxy. In the dwarf spheroidals, which orbit close to the Galaxy or M31,
which differs greatly from the Cepheids estimate for this galaxy, suggesting that unsolved problems could exist for that Cepheids' estimate. Lee et al. (1993) have given more strength to the validity of using TRGB as a distance indicator. The data we present in this paper offer a very good opportunity to check the agreement between the values for the distance modulus determined using both methods, since a new Cepheid value for the distance using homogeneous data has been given, and the TRGB is very well defined in our data.

We use the method described in Lee et al. (1993) to derive an alternative distance modulus to the galaxy. Figure 14 shows (solid line) the $I$ luminosity function for red ($(V-I)>1$) stars in NGC 6822. No correction for crowding effects has been performed. The dotted line represents the convolution of the luminosity function with an edge-detector, a Sobel filter of kernel $[-1,0,1]$ in particular, as described in Madore & Freedman (1995, and references therein). According to Fig. 14, the TRGB is situated at $I=19.8\pm0.1$, in good agreement with a rough estimate of the tip position in the $[(V-I),I]$ CM diagram. Also from this diagram (Fig. 17), the mean color of the tip is $(V-I)=2.0$. Adopting the value for the reddening obtained from the multiwavelength fit of the Cepheids, and using the extinction law of Cardelli et al. (1989), the TRGB moves to $I_0=19.35$ and $(V-I)_0=1.65$.

Following Lee et al. (1993, and reference therein) we obtain the distance modulus using the equation:

$$ (m-M)_0 = I_{0,\text{TRGB}} + B C_I - M_{\text{bol,TRGB}}. \quad (18) $$

As given by Da Costa & Armandroff (1990), the value for the bolometric correction can be written as:

$$ B C_I = 0.881 - 0.243(V-I)_{\text{TRGB}} \quad (19) $$

and the bolometric magnitude of the TRGB as:

$$ M_{\text{bol,TRGB}} = -0.19[\text{Fe/H}] - 3.81. \quad (20) $$

Using this expression in Eq. (18), and replacing the values of $I_{0,\text{TRGB}}$ and $(V-I)_{\text{TRGB}}$, we obtain the relation:

$$ (m-M)_0 = 23.64 + 0.19[\text{Fe/H}]. \quad (21) $$

The $[\text{Fe/H}]$ value can be estimated from the expression (Lee et al. 1993):

$$ [\text{Fe/H}] = -12.64 + 12.6(V-I)_{-3.5} - 3.3(V-I)^2_{-3.5}, \quad (22) $$

where $(V-I)_{-3.5}$ is the $(V-I)$ color index of the RGB measured at $M(I)=-3.5$. From the $[(V-I),I]$ CM diagram $(V-I)_{-3.5}=1.4\pm0.2$, (measured at the $I$ magnitude $0.4-0.5$ mag below the TRGB). This leads to a value of $[\text{Fe/H}]=-1.5\pm0.3$, which yields $(m-M)_0=23.4\pm0.1$, where the quoted error was estimated taking into account the uncertainties in the different values involved. Note that we adopted a value of $12+\log(O/H)=8.25$ for the current metallicity of the gas in NGC 6822 (see Sec. 1), which corresponds to $[\text{Fe/H}]=-1.0$.

Within errors, the value obtained using TRGB is in good agreement with that obtained with the Cepheid-based estimate. In what follows, we definitively adopt the Cepheid value, $(m-M)_0=23.49\pm0.08$, as the best estimate of the distance modulus.

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• Blue-loop stars (e.g. Cepheids)
  Intermediate mass stars, the core burning
  ages $10^8 \rightarrow 5 \times 10^8$ yrs

• AGB stars — extending redward
  from red giant branch
  ages $\geq 1$ Gyr

• Red giant branch — crude
  indicator for ages $\geq 1$ Gyr

• Clump and horizontal-branch
  stars (RR Lyrae, RHB, BHB)
  Clump: $\approx 1$–10 Gyr
  HB stars: $\geq 10$ Gyr
- main-sequence stars: present in populations of all ages.

**Q** Why is this less useful for older populations in local group galaxies?
b) Intermediate Age Regions

a) Selection Population?

20

22

24

BHB

Spur

SGB

Old

B-S

c) Foreground Object?

d) Model with Binaries
Star formation history of dSph galaxies can be complex.

What do you think the Carina dSph’s color-magnitude diagram implies about its star formation history?

Do bursts of star formation make sense in a system of low mass with no current gas content?
Figure 4.9 Left, color-magnitude diagram for the Carina dwarf spheroidal galaxy. Right, superposed isochrones give the locus of metal-poor stars ($Z = Z_{\odot}/50$) at ages of 3 Gyr (solid), 7 Gyr (dotted), and 15 Gyr (dashed); we see young red clump stars close to $B - R$, $m_R = (1, 20)$, and old stars on the horizontal branch. Carina's distance modulus is taken as $(m - M)_0 = 20.09$; dust reddening is assumed to dim stars by 0.108 magnitudes in $B$ and 0.067 magnitudes in $R$ – T. Smecker-Hane; A. Cole, Padova stellar tracks.
Figure 8 (Continued)
Figure 8  Schematic plots of the star-formation histories of all Local Group dwarfs with sufficient data. The labels within the individual panels specify the nature of the stellar indicators used to infer the presence of a given age component: MS = main-sequence stars; AGB = asymptotic giant branch stars; RG = red giants; RR = RR Lyr variables; AC = anomalous Cepheids; SG = blue and red supergiants; W = Wolf-Rayet stars; PN = planetary nebulae. “2P” means that the galaxy has an anomalously red horizontal-branch (HB) population for its (low) metallicity—that is, the galaxy exhibits
Summary of dwarf star formation

- No two local group dwarfs have the same star formation history.

- No galaxy (except UMi) has only stars older than 10 Gyr.

- Some (like M32) may have no stars older than 10 Gyr.
THE LOCAL GROUP

Size $\sim 1$ Mpc

2 big spirals

most of the rest are dwarfs:

dIrr (eg SMC)
dSph (eg Fornax)
Table 4.1 Galaxies of the Local Group within 1 Mpc of the Sun: the Milky Way and its satellites are listed in **boldface**; M31 and its companions are listed in *italics*

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Type</th>
<th>$d$ (kpc)</th>
<th>$L_V$ ($10^7L_\odot$)</th>
<th>$V_r(\odot)$ (km s$^{-1}$)</th>
<th>$l$ (deg)</th>
<th>$b$ (deg)</th>
<th>$M$(HI) ($10^6M_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M31 (NGC 224)</td>
<td>Sb</td>
<td>770</td>
<td>2700</td>
<td>-299</td>
<td>121</td>
<td>-22</td>
<td>5700</td>
</tr>
<tr>
<td>Milky Way</td>
<td>Sbc</td>
<td>8</td>
<td>1500</td>
<td>-10</td>
<td>0</td>
<td>0</td>
<td>4000</td>
</tr>
<tr>
<td>M33 (NGC 598)</td>
<td>Sc</td>
<td>850</td>
<td>550</td>
<td>-183</td>
<td>134</td>
<td>-31</td>
<td>1500</td>
</tr>
<tr>
<td>Large MC</td>
<td>SBm</td>
<td>49</td>
<td>170</td>
<td>274</td>
<td>280</td>
<td>-33</td>
<td>700</td>
</tr>
<tr>
<td>NGC 205</td>
<td>dE</td>
<td>850</td>
<td>40</td>
<td>-241</td>
<td>121</td>
<td>-21</td>
<td>0.4</td>
</tr>
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<td>Small MC</td>
<td>dIrr</td>
<td>58</td>
<td>34</td>
<td>148</td>
<td>303</td>
<td>-44</td>
<td>650</td>
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<tr>
<td>M32 (NGC 221)</td>
<td>dIrr</td>
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<td>-203</td>
<td>121</td>
<td>-22</td>
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<td>30</td>
<td>-56</td>
<td>25</td>
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<td>dIrr</td>
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<td>-344</td>
<td>119</td>
<td>-3</td>
<td>150</td>
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<td>dE</td>
<td>760</td>
<td>12</td>
<td>-193</td>
<td>120</td>
<td>-14</td>
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<tr>
<td>NGC 185</td>
<td>dE</td>
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<td>10</td>
<td>-202</td>
<td>121</td>
<td>-15</td>
<td>0.1</td>
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<tr>
<td>IC 1613 (DDO 8)</td>
<td>dIrr</td>
<td>715</td>
<td>10</td>
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<td>130</td>
<td>-61</td>
<td>60</td>
</tr>
<tr>
<td>Pegasus (DDO 216)</td>
<td>dIrr</td>
<td>760</td>
<td>8</td>
<td>-183</td>
<td>95</td>
<td>-44</td>
<td>3</td>
</tr>
<tr>
<td>WLM (DDO 221)</td>
<td>dIrr</td>
<td>970</td>
<td>4</td>
<td>-120</td>
<td>76</td>
<td>-74</td>
<td>80</td>
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<tr>
<td>Leo A (DDO 69)</td>
<td>dIrr</td>
<td>690</td>
<td>2</td>
<td>20</td>
<td>197</td>
<td>52</td>
<td>20</td>
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<td>Fornax</td>
<td>dSph</td>
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<td>1.4</td>
<td>53</td>
<td>237</td>
<td>-66</td>
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<td>dSph</td>
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<td>1</td>
<td>170</td>
<td>6</td>
<td>-14</td>
<td>none</td>
</tr>
<tr>
<td>And I</td>
<td>dSph</td>
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<td>0.5</td>
<td>-370</td>
<td>122</td>
<td>-25</td>
<td>none</td>
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<td>285</td>
<td>226</td>
<td>49</td>
<td>none</td>
</tr>
<tr>
<td>And VII/Cas dSph</td>
<td>dSph</td>
<td>760</td>
<td>0.5</td>
<td>-307</td>
<td>110</td>
<td>-10</td>
<td>none</td>
</tr>
<tr>
<td>And II</td>
<td>dSph</td>
<td>590</td>
<td>0.3</td>
<td>-188</td>
<td>129</td>
<td>-29</td>
<td>none</td>
</tr>
<tr>
<td>And VII/Peg dSph</td>
<td>dSph</td>
<td>830</td>
<td>0.3</td>
<td>-341</td>
<td>106</td>
<td>-36</td>
<td>none</td>
</tr>
<tr>
<td>Aquarius (DDO 210)</td>
<td>dIrr</td>
<td>950</td>
<td>0.2</td>
<td>-137</td>
<td>34</td>
<td>-31</td>
<td>3</td>
</tr>
<tr>
<td>Sculptor</td>
<td>dSph</td>
<td>72</td>
<td>0.14</td>
<td>107</td>
<td>288</td>
<td>-83</td>
<td>$\lesssim$0.1c</td>
</tr>
<tr>
<td>Sagittarius DIG</td>
<td>dIrr</td>
<td>800</td>
<td>0.1</td>
<td>-78</td>
<td>21</td>
<td>-16</td>
<td>4</td>
</tr>
<tr>
<td>And III</td>
<td>dSph</td>
<td>770</td>
<td>0.1</td>
<td>-352</td>
<td>119</td>
<td>-26</td>
<td>$&lt;$0.1</td>
</tr>
<tr>
<td>Phoenix</td>
<td>dIrr/dSph</td>
<td>420</td>
<td>0.08</td>
<td>56</td>
<td>272</td>
<td>-69</td>
<td>none</td>
</tr>
<tr>
<td>Cetus</td>
<td>dSph</td>
<td>775</td>
<td>0.08</td>
<td>—</td>
<td>101</td>
<td>-73</td>
<td>none</td>
</tr>
<tr>
<td>LGS3 (Pisces)</td>
<td>dIrr/dSph</td>
<td>810</td>
<td>0.06</td>
<td>-281</td>
<td>127</td>
<td>-41</td>
<td>0.2</td>
</tr>
<tr>
<td>Leo II (DDO 93)</td>
<td>dSph</td>
<td>207</td>
<td>0.06</td>
<td>76</td>
<td>220</td>
<td>67</td>
<td>none</td>
</tr>
<tr>
<td>Tucana</td>
<td>dSph</td>
<td>870</td>
<td>0.05</td>
<td>—</td>
<td>323</td>
<td>-47</td>
<td>none</td>
</tr>
<tr>
<td>Sextans</td>
<td>dSph</td>
<td>83</td>
<td>0.04</td>
<td>225</td>
<td>244</td>
<td>42</td>
<td>none</td>
</tr>
<tr>
<td>Carina</td>
<td>dSph</td>
<td>100</td>
<td>0.03</td>
<td>223</td>
<td>260</td>
<td>-22</td>
<td>none</td>
</tr>
<tr>
<td>And V</td>
<td>dSph</td>
<td>810</td>
<td>0.03</td>
<td>-387</td>
<td>126</td>
<td>-15</td>
<td>none</td>
</tr>
<tr>
<td>Ursa Minor</td>
<td>dSph</td>
<td>64</td>
<td>0.02</td>
<td>-247</td>
<td>105</td>
<td>45</td>
<td>none</td>
</tr>
<tr>
<td>Draco (DDO 216)</td>
<td>dSph</td>
<td>72</td>
<td>0.02</td>
<td>-293</td>
<td>86</td>
<td>35</td>
<td>none</td>
</tr>
</tbody>
</table>

Note: $d$ is measured from the Sun; $V_r(\odot)$ is the radial velocity with respect to the Sun.

* HI is confused with Galactic emission (NGC 6822) or gas of the Magellanic Stream (Sculptor).

In ‘late type’ galaxies, spirals, and irregulars, and poor in the ‘early type’ giant ellipticals and S0 galaxies.

In the Local Group, mutual gravitational attraction is strong enough to have overcome the general expansion of the Universe. Allowing for the Sun’s motion around the Galaxy, we find that the Milky Way and the Andromeda Galaxy are approaching each other instead of receding, closing at about 120 km s$^{-1}$. We can measure proper motions only for the Milky Way’s immediate satellite galaxies.
4 Our backyard: the Local Group

Figure 4.2  The Local Group: our Milky Way is at the origin. Spirals designated S; asterisks show the Magellanic Clouds; filled stars mark irregular galaxies; circles are ellipticals or dwarf ellipticals (filled) and dwarf spheroidals (open). Left, positions projected onto the Galactic plane; axis $x$ points to Galactic center, $y$ in the direction of the Sun’s orbital motion. Arrow shows the direction of view in the right panel. Right, view perpendicular to the plane containing M31 and axis $z$ toward the north Galactic pole; the dotted line marks the Galactic midplane. Many of the Milky Way’s satellites, including the Magellanic Clouds, lie near a single plane.
What might you speculate to be the origin of the coplanarity of many Milky Way satellites?
Dwarf galaxies in Local Group

Reference: Mateo ARAA 1998

Still more to be discovered
(see plot vs. galactic latitude b)

Metallicity - luminosity relation

Most luminous galaxies are most metal-rich

Q Why?

Why do dIrr and dSph galaxies occupy different regions of the plot?
Figure 2  Plots of the cumulative distribution of all Local Group galaxies (upper plot) and of the galaxies in the MW subgroup (lower plot) as a function of $(1 - \sin |b|)$, where $b$ is Galactic latitude. The dotted lines show the expected distribution of a uniform sample of 40 and 12 objects. The vertical lines show where 50% (left) and 67% (right) of a uniform cumulative distribution would be found. For example, based on the fiftieth percentile value of $N_c = 10$ in the lower panel, a total of 20 MW satellites would be expected if they were uniformly distributed and if there was no gradient in Galactic extinction as a function of latitude.
abundance has been derived by Jones et al (1996) for NGC 205 ([Fe/H] \sim -1.4) from UV spectra.

5.2 The Metallicity-Luminosity Relation and the dIrr/dSph Connection

The fact that the more luminous dwarf galaxies are also on average the most metal rich has been known for some time for both dIrr (Lequeux et al 1979, Talent 1980, Skillman et al 1989a) and dSph galaxies (Aaronson 1986, Caldwell et al 1992). Aaronson (1986) and Skillman et al (1989a) merged the abundance data for both types into a a single luminosity-abundance (L-Z) relation spanning 12 mag in \( M_B \) and about 1.6 dex in oxygen/iron abundance. A recent determination of [Fe/H] of a low-surface brightness but relatively luminous dSph galaxy in the M81 group (Caldwell et al 1998) demonstrates clearly that luminosity, not surface brightness, is the principal parameter correlated with metallicity in dSph and, presumably, dIrr galaxies.

Figure 7 is a plot of the mean abundances for all of the galaxies in Table 6 (except DDO 210 for which [Fe/H] is uncertain; Greggio et al 1993) vs their

![Figure 7](image_url)

*Figure 7* A plot of [Fe/H] (filled squares) or [O/H] \sim -0.37 [I assume 12 + log(O/H)\odot = 8.93 after Anders & Grevesse (1989)] vs absolute V-band magnitude. The dotted line is a rough fit to the [Fe/H]-\( M_V \) relation for the dSph and transition objects. Sagittarius corresponds to the points near (\( M_V, [Fe/H] \)) \sim (-13.4,-1.0). Square symbols refer to dSph or dE galaxies; triangles refer to transition galaxies (denoted dIrr/dSph in Table 1); circles refer to dIrr systems. Filled symbols correspond to [Fe/H] abundances determined from stars, while open symbols denote oxygen abundance estimates from analyses of HII regions and planetary nebulae. See Table 6 for details.
### Table 4.2 Dwarf galaxies, compared with the nuclear star cluster of M33, and three Milky Way globular clusters

<table>
<thead>
<tr>
<th>System</th>
<th>( L_V ) ((10^7 L_\odot))</th>
<th>( \sigma_r ) (km s(^{-1}))</th>
<th>( r_c ) (pc)</th>
<th>( r_t ) (pc)</th>
<th>( t_{sf} ) (Gyr)</th>
<th>( M/L_V ) ((M_\odot/L_\odot))</th>
<th>([\text{Fe/H}]) (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 147 dE</td>
<td>12</td>
<td>20–30</td>
<td>260</td>
<td>1000</td>
<td>3–5</td>
<td>7 ± 3</td>
<td>−1.5 to −0.5</td>
</tr>
<tr>
<td>NGC 185 dE</td>
<td>10</td>
<td>20–30</td>
<td>170</td>
<td>2000</td>
<td>&lt;0.1</td>
<td>5 ± 2</td>
<td>−1.3 to −0.8</td>
</tr>
<tr>
<td>Pegasus dIrr</td>
<td>2</td>
<td>9(Hi)</td>
<td>—</td>
<td>500(Hi)</td>
<td>&lt;0.1</td>
<td>1.6 ± 1</td>
<td>−1.3 to −0.7</td>
</tr>
<tr>
<td>Fornax dSph</td>
<td>1</td>
<td>11</td>
<td>400</td>
<td>2080</td>
<td>&lt;2</td>
<td>7 ± 3</td>
<td>−2.2 to −0.7</td>
</tr>
<tr>
<td>M33 nucleus</td>
<td>0.25</td>
<td>20–25</td>
<td>&lt;0.4</td>
<td>—</td>
<td>&lt;1:</td>
<td>0.4</td>
<td>−1 to 0</td>
</tr>
<tr>
<td>Sculptor dSph</td>
<td>0.1</td>
<td>7</td>
<td>100</td>
<td>1330</td>
<td>&gt;10</td>
<td>11 ± 8</td>
<td>−1.9 to −1.3</td>
</tr>
<tr>
<td>( \omega \text{ Cen gc} )</td>
<td>0.1</td>
<td>10–22</td>
<td>4</td>
<td>66</td>
<td>&gt;10</td>
<td>4</td>
<td>−1.6</td>
</tr>
<tr>
<td>Carina dSph</td>
<td>0.02</td>
<td>7</td>
<td>180</td>
<td>580</td>
<td>2–10</td>
<td>74 ± 50</td>
<td>−1.8 to −1.6</td>
</tr>
<tr>
<td>( M92 \text{ gc} )</td>
<td>0.02</td>
<td>8</td>
<td>0.5</td>
<td>35</td>
<td>&gt;10</td>
<td>2</td>
<td>−2.3</td>
</tr>
<tr>
<td>( M30 \text{ gc} )</td>
<td>0.01</td>
<td>5</td>
<td>&lt;0.1</td>
<td>45</td>
<td>&gt;10</td>
<td>2</td>
<td>−2.3</td>
</tr>
</tbody>
</table>

Note: higher values of dispersion \( \sigma_r \) in measured radial velocity refer to central regions; at core radius \( r_c \), surface brightness falls to half its central value, dropping near zero at truncation radius \( r_t \); \( t_{sf} \) is time since last significant star formation, with : indicating an uncertain value; 
\([\text{Fe/H}] = \log_{10} Z/Z_\odot \) is the logarithm of abundance of iron to hydrogen, compared to solar value. 
\( \text{HI} \) denotes a measurement from \( \text{HI} \) gas, not stars; globular clusters are labelled gc.