Fig. 21. Schematic $d(M)$ distributions for the main types. Closed figures show LF's that go to zero at both the bright and the faint ends. The two open figures for Im/dE and for dE show exponentially increasing LF's.
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LMC & SMC: Visible from the Southern Hemisphere
Star Formation in the LMC

- Dwarf galaxies have low metal abundance
- The shallow potential well = probable gas loss via SN
Magellanic Stream

- HI gas
- Formed by stripping or tidal effects (differential gravity)
- No evidence of star formation (pristine)
Dwarf Galaxies

• Make up faint end of the luminosity function
• Outnumber more massive galaxies
• Some are believed to be comprised mainly of dark matter
• Metal-poor
Properties Discussed thus far

- Dwarf Elliptical Galaxies are the borderline between Galaxies and Globular Clusters
- $M_B \sim -18$ to $-8$
- For dwarf galaxies, $\mu \uparrow$ as $L \uparrow$
- $M/L \sim 5 - 100 \, M_{\odot} / L_{\odot}$, which is strong evidence for dark matter
- Mass $\sim 10^7 - 10^9 \, M_{\odot}$

By Comparison, similar numbers for globular clusters are

- $M_B \sim -10$ to $-5$
- $M/L \sim 1 \, M_{\odot} / L_{\odot}$
- Mass $\sim 10^4 - 10^6 \, M_{\odot}$
Morphologies & Terminology

• The most luminous dwarfs, Dwarf Ellipticals ($M_B < -16$), have nuclei.
  1) dE, N = abbreviation
  2) Luminous nucleus comprising up to 20% of total light
  3) Nuclei may be dynamically separate the rest of galaxy

• Dwarf Spheroidals (dSph) appear to be a cluster of intrinsically luminous stars with no evidence of faint background of less luminous stars, & are not believed to be self gravitating (i.e., have high M/L). They are too faint to be seen at distances much greater than our Local Group.

• Dwarf Irregulars, dIrr have a rich ISM & star-forming knots

• Low Surface Brightness galaxies, LSB, are dwarfs with low surface brightness. There is almost no gradient in their stellar profiles.
Profiles

- **Dwarf ellipticals** have elliptical isophotes, but their profiles can be best fit by an exponential profile

\[ I(r) = I_0 e^{-\left(\frac{r}{r_0}\right)} = I_0 e^{-\alpha r}, \]

where \( I_0 \) is the central intensity, \( r_0 \) is the scale length, and \( \alpha \) is the inverse scale length. In terms of surface brightness

\[ \mu(r) = \mu_0 + 1.086\alpha r, \]

- **Dwarf irregulars** can also be fit well by an exponential profile if the star-forming knots are subtracted first.
HST Images of Dwarf Galaxies in M101 Cluster ($D = 6.5$ Mpc)

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Notes: Columns 5 and 6: 2000.0 epoch coordinates taken from the NED. Column 7: Dwarf type reckoned by B.B. on the system of Sandage & Binggeli (1984). Columns 8 and 9: Diameter at $\mu = 25$ mag/$''$ and total apparent blue magnitude from the present photometry, from Schmidt & Boile (1992a) ($^1$), or from other sources compiled by one of us (B. B.) ($^2$). Column 10: heliocentric velocity from NED.
HST Images of Dwarf Galaxies in M101 Cluster \((D = 6.5 \text{ Mpc})\)


(unless marked otherwise, the galaxies are Im class)
M101 Sample…

\[ \frac{1}{\alpha_B} = 6 - 27'' = 200 - 850 \text{ pc}, \]

\[ \frac{1}{\alpha_R} = 7 - 30'' = 220 - 945 \text{ pc}, \]

Fig. 3. Radial surface brightness profiles of the observed dwarf galaxies in $B$ (lower) and $R$ (upper) except for NGC5204 (only $R$) and DDO181 and MCG 9-23-21 for which only $B$ data are available. The dash-dotted lines represent the exponential fits, as described in Sect. 4.2 and the dashed and dotted lines represent the error envelopes as described in Sect. 4.4. The radii are all equivalent radii ($r = \sqrt{ab}$).
Substructure in Virgo cluster dEs
Dynamics

• Because dwarf galaxies are so faint, the velocities & velocity dispersions are difficult to measure.

• High resolution spectroscopy is also required such that dispersions as low as 15 km / s can be measured

• dS0s are supported by rotation

• dEs are generally not supported by rotation, with $v / \sigma^* < 0.4$. Recall that,

$$\frac{v}{\sigma^*} = \frac{(v/\sigma)_{\text{observed}}}{(v/\sigma)_{\text{ISO}}}$$
Keck Spectroscopy of dEs in Virgo Cluster

Figure 1: Mean velocity and velocity dispersion profiles for four Virgo dEs. The bar at the lower left of each panel indicates the seeing FWHM during each observation. At the distance of the Virgo Cluster, 1" = 100 pc.

(Geha et al. 2002, AJ, 124, 3073)

Figure 2: The ratio of the upper limit on the rotation velocity $v_{\text{max}}$ to observed velocity dispersion $\sigma$ plotted versus mean ellipticity for four Virgo dwarf ellipticals. The solid line is the expected relation for an oblate, isotropic galaxy flattened by rotation.
Keck Spectroscopy of dEs in Virgo Cluster

(Geha et al. 2003, AJ, 126,1794)

Fig. 4.— The ratio of the rotation velocity $v_{rot}$ to velocity dispersion $\sigma$ plotted versus mean isophotal ellipticity (left panel) and absolute magnitude (right panel). The solid line in the left panel is the expected relation for an oblate, isotropic galaxy flattened by rotation. Solid symbols indicate Virgo Cluster dEs from the sample in this paper, while open symbols are two dEs taken from Simien & Prugniel (2002); dEs are plotted as circles if $v_{rot}/\sigma \leq 0.1$ (most of these represent upper limits), and as squares otherwise. Lower limits are indicated for rotating galaxies for which we do not observe a turnover in the rotation curve due to insufficient radial coverage.
M / L and Anisotropies

- A possible worry is that $M / L$ determinations for dwarf galaxies are being affected by anisotropies.
- However, reasonable models of anisotropies yield values in a few well-studied cases greater than 30 $M_{\text{sun}} / L_{\text{sun}}$. 

![Graph showing M/L vs. L/L_☉ for Local Group galaxies]
How does $M/L$ of dwarf galaxies compare with Es and GCs? Is There Continuity?

Fig. 8. - Core mass-to-light ratios for bulges, elliptical galaxies and globular clusters (Kormendy 1987b). The line is a least-squares fit to the ellipticals. The plus sign is the mean $M/L_V$ for old disks; the error bar is the dispersion of values seen (Kormendy 1987a).
Discontinuity of Fundamental Plane – Es vs. dwarf galaxies

Local Group dEs & dSphs: 
$M/L \sim L^{0.4}$

Ellipticals 
$M/L \sim L^{0.2}$

Problems
- Measuring $\sigma$
- Dynamically detached nucleus in dE, N

(Ferguson & Binggeli 1994)
Virgo & Local Group Data: dSph show a wide range in M/L Relative to dE

Globular Clusters
Elliptical Galaxies
dEs (nonrotating - solid, rotating - grey, local group - unfilled)
dSph

“…rotation velocity is not correlated with a dE’s position in the FP, the presence or absence of underlying disks or substructures, absorption line indices, or local environment.”

(Geha et al. 2003)

Fig. 5.— Face-on and edge-on projections of the Fundamental Plane for dynamically hot stellar systems (upper and lower panels, respectively), where $\kappa_1$, $\kappa_2$, and $\kappa_3$ are related to galaxy mass, surface brightness, and mass-to-light ratio, respectively. Note that the vertical scale is greatly expanded in the lower panel relative to the upper panel. Our sample of dEs is shown as solid diamonds for non-rotating dEs, and solid grey diamonds for rotating dEs. Data for other systems from Burstein et al. (1997) are: classical ellipticals and spiral bulges (open triangles), Local Group dEs (open diamonds), Local Group dwarf spheroidals (open circles), and Galactic globular clusters (crosses). Note the change in vertical scale between the two panels.
Unprojected FP: dwarfs Form a Distinct Family

- E + Bulges (M32 is the faint end)
- Dwarf galaxies
- Globular Clusters
M32 is an Extension of the E + Bulge Family

\[ L(dE) \sim L(M32) \]

\[ r_c(dE) > 500r_c(M32) \]

\[ I(dE) < 5000I(M32) \]
\( \mu \) vs. \( M_B \): Evolutionary Connection Between Late-Type Spirals, dIrrs and dEs?

- dSpiral + Irr \( \rightarrow \) dE
  (Gas Rich) \( \rightarrow \) (Gas Poor)
  (Ferguson & Binggeli 1994)

ISM Blown out by Supernova Winds?
dSph vs. Spirals

- dE have higher central mass densities
- lower core radii
- lower velocity dispersion

(Kormendy 1990)
Origin

- Collapse from dark matter halos
- Ram pressure stripping of galaxies in clusters
- Tidal debris from interactions
Tidal Debris

Fig. 1. V-band image of the NGC 7352 “Atoms For Peace” system with two tidal dwarfs, NGC7252W and NGC7252E, the latter of which was not observed in CO. The image is saturated to show the stars in the tidal tails. The green contours represent H\textsc{i} column densities (Hibbard & van Gorkom 1996) of \(2, 3, 4, 5 \times 10^{20} \text{cm}^{-2}\) at 27\arcsec \times 16\arcsec resolution. Circles show the positions observed in CO; the size of the circle is that of the CO(1–0) beam. Above the image the spectra of the Western TDI, NGC7252W, and the center of the merger are shown and color coded as follows: HI as thick dotted green, CO(1–0) as black and CO(2–1) as dashed red. The velocities are in km s\(^{-1}\) and the left vertical scale gives the intensity in mJy per beam for the HI and mK for the CO(1–0). The right vertical scale indicates the CO(2–1) line strength in mK. CO observations are presented on the main beam temperature scale.

Fig. 3. The Arp 245 (NGC 2992/3) system: V-band image with HI contours (Ibar et al. 2000) superimposed in green. HI contours are 2, 4 (dashed), 12 (dotted), 16 (black), and 20 (black dashed) \(10^{19} \text{cm}^{-2}\). The blue circle show the CO(1–0) beamwidth, small for IRAM and large for SRT, and mark the positions observed in CO. The top six spectra are of the TDI at the position of the circle from North to South and below are the spectra of the centers of NGC 2993 and 2994 (bottom), where the scale indicates CO(1–0) intensity in mK; HI spectra are in arbitrary units. The new CO spectra have been added to the data presented in Paper I.
ISM: $M_{\text{mol}}/M_{\text{HI+He}}$ vs. Compactness

Evolution

- compact, detached
- tidal tail

A105S
N5291S
A245N
N5291N
N7252W
N4676N
N4038S

order
ISM: $\alpha$ vs. metallicity. Recall that,

$$\frac{\rho^{0.5}}{T_{CO}} \sim \text{constant}$$

$$M_{\text{cloud}} \propto L_{CO}$$

Figure 2. The CO luminosity is closely correlated with the virial masses of the clouds both with and without massive OB star formation (Scoville et al. 1986). This linear proportionality justifies the use of CO as a tracer of the galactic H$_2$ mass. The best fit is equivalent to a constant of proportionality of 3.6x10$^{20}$ H$_2$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$. 
ISM: CO-to-$\text{H}_2$ conversion factor is independent of Metallicity

(Bolatto et al. 2003)

Fig. 1. Virial CO-to-$\text{H}_2$ conversion factor as a function of metallicity, normalized to the Galactic value. Each point represents the average of the ratio of virial to molecular mass for all the GMCs analyzed in one galaxy, with the molecular mass computed using the integrated CO intensity and the Galactic $X_{\text{CO}}$ factor. Symbol color identifies the telescopes used for the measurements, while size is proportional to the spatial resolution attained in the observations. The data include clouds in M 33, the SMC (N83/N84), the LMC (N159/N160), IC 10, NGC 2976, NGC 3077, NGC 4214, NGC 4449, and NGC 4605.

SFR via radio similar to SFR via CO.
Dwarf Galaxies Metallicities - no difference between rotating and non-rotating dEs

Fig. 9.— Determination of [α/Fe] ratios from a Mgb versus (Fe) diagram. The dEs in our sample are plotted as 1σ error crosses; dEs with significant rotation velocities are shown with solid squares. The classical elliptical galaxy sample of Trager et al. (2000) is plotted as open triangles. Model predictions by Thomas et al. (2002) are plotted for the abundance ratios [α/Fe] = −0.3, 0.0, and +0.3 (light to dark grey lines), age = 1−15 Gyr in increments of 1 Gyr, and [Fe/H] = −2.25, −1.35, −0.33, 0.0, +0.35, and +0.67 dex. Rotating and non-rotating dEs cannot be distinguished in this plot. The majority of these dEs are consistent with solar abundance ratios, in contrast with the majority of classical elliptical galaxies which have enhanced [α/Fe] abundance ratios.

Fig. 11.— Line-strength indices plotted as a function of the logarithm of the average velocity dispersion σ. Symbols in each panel are the same as in Figures 9 and 10. Dotted lines are fits to the classical ellipticals (open triangles) of Trager et al. (2000). The extrapolation of these fits are consistent with our measured dE line-strengths.

Timescale for E star formation is rapid