The Galaxy Luminosity Function

Earlier in the course, we discussed the luminosity function of stars. We now apply a similar analysis to galaxies, both in the field & in clusters.

Consider a sample of galaxies *S*. We can define the following quantities:

$n_s(L) \rightarrow$ Number of galaxies in *S* per unit luminosity

$n_s(L)\, dL \rightarrow$ Number of galaxies in *S* with luminosities between L & $L+dL$

$\phi_s(L) \rightarrow$ luminosity function such that

$$\phi_s(L) = \frac{n_s(L)}{V_s(L)}$$

$\phi_s(L)$ is the number of galaxies in *S* per unit luminosity Per unit volume

On small scales, inhomogeneity is important & ϕ depends On *S*. If the universe is homogeneous on large scales,

$$\phi_S(L) \to \phi(L) \quad \text{as} \quad V_s \to \infty.$$

ϕ *(L)* is referred to as the universal luminosity function.

How do n_s & ϕ_s Differ?

AN ANALYTIC EXPRESSION FOR THE LUMINOSITY FUNCTION FOR GALAXIES*

PAUL SCHECHTER

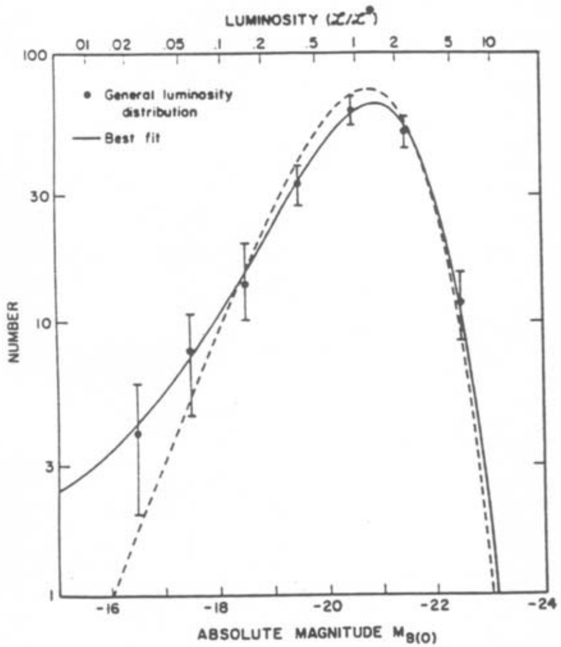

FIG. 1.—Best fit of analytic expression to observed general luminosity distribution. Broken line shows the effect of deleting the Eddington correction.

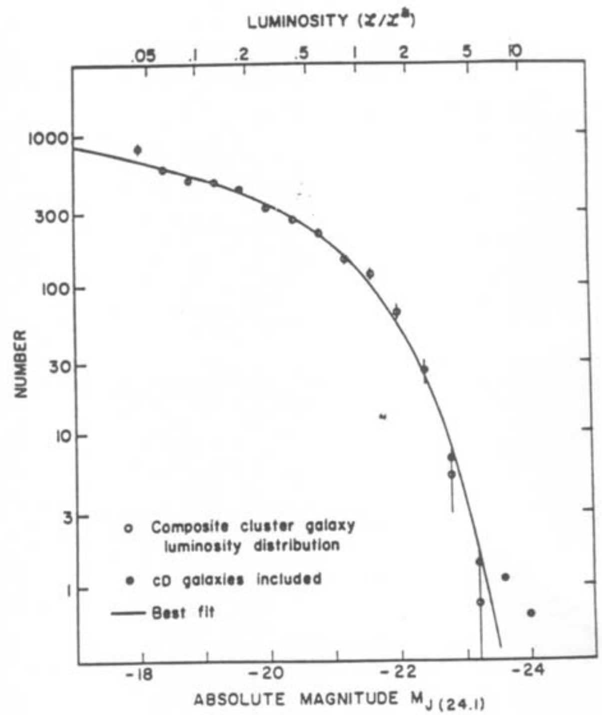

FIG. 2.—Best fit of analytic expression to observed composite cluster galaxy luminosity distribution. Filled circles show the effect of including cD galaxies in composite.

In a cluster, V_s is the same for all L, so n_s & ϕ_s have the same shape. However, if the sample is apparent magnitude limited, then $V_s \downarrow$ as $L \downarrow$.

(Schechter 1976)

The Schechter Function

is typically used to characterize galaxy luminosity functions, & it has the form

$$\phi(L) = \left(\frac{\phi^*}{L^*}\right)\left(\frac{L}{L^*}\right)^{\alpha} e^{-(L/L^*)},$$

where ϕ^* is the normalization density, L^* is a characteristic luminosity corresponding to $M_B = -20.6$, & α is the power law slope at low L.

This function can also be expressed in terms of magnitudes by making the substitutions

$$\phi(M)dM = \phi(L)d(-L);$$

$$M - M^* = -2.5 \log \left(\frac{L}{L^*} \right).$$

This yields

$$\phi(M) = \frac{\ln 10}{2.5} \phi^* 10^{0.4(\alpha+1)(M-M^*)} exp \left[-10^{0.4(M-M^*)} \right].$$

Typical values derived from *B*-band measurements are

$$\phi^* = (1.6 \pm 0.3) \times 10^{-2} h^{-3} \mathrm{Mpc}^{-3},$$

$$M_B^* = -19.7 \pm 0.1 + 5 \log 5,$$

$$\alpha = -1.07 \pm 0.07, \text{ and}$$

$$L_B^* = (1.2 \pm 0.1) h^{-2} \times 10^{10} \mathrm{L}_\odot.$$

The Schechter function at *K*-band avoids the affects of extinction & potential irregularities caused by star formation

$$\phi^* = (1.6 \pm 0.2) \times 10^{-2} h^{-3} \mathrm{Mpc}^{-3},$$

$$M_K^* = -23.1 \pm 0.2 + 5 \log 5, \text{ and}$$

$$\alpha = -0.9 \pm 0.2.$$

Note the similarities in ϕ^* & α as measured in both bands.

Properties

- The number density of galaxies whose luminosities exceed *L* is,

$$= \int_L^\infty \phi(L) dL = \phi^* \int_{(L/L^*)}^\infty \left(\frac{L}{L^*}\right)^\alpha e^{-L/L^*} d\left(\frac{L}{L^*}\right) = \phi^* \Gamma(\alpha + 1, L/L^*),$$

diverges for $\alpha < -1$ as $L/L^* \to 0$.

- The luminosity density of galaxies whose luminosities exceed *L* is,

$$= \int_L^\infty L\phi(L) dL = \phi^* L^* \int_{(L/L^*)}^\infty \left(\frac{L}{L^*}\right)^{\alpha+1} e^{-L/L^*} d\left(\frac{L}{L^*}\right) = \phi^* L^* \Gamma(\alpha + 2, L/L^*),$$

which converges for $\alpha > -2$. In other words, the Schechter function diverges by number density, but not by luminosity density.

For α = -1, the total luminosity density is,

$$= \phi^* L^* \Gamma(2+\alpha) = \phi^* L^* = 1 \times 10^8 h \mathrm{L}_B(\odot) \mathrm{Mpc}^{-3}.$$

Half of the luminosity density is contributed by galaxies with $L/L^* > \frac{1}{2}$.

Though the number density diverges, we can determine the number density of galaxies in units of Milky Ways,

$$N_{\mathrm{gal}} = \frac{1 \times 10^8 \mathrm{L}_\odot \mathrm{Mpc}^{-3}}{1.7 \times 10^{10} \mathrm{L}_\odot} = 0.006 \mathrm{Mpc}^{-3}.$$

I.e., if the universe were comprised only of Milky Ways & the luminosity density was 1×10^8 L_{sun} Mpc^{-3}, there would be 0.006 galaxies per Mpc^3.

For an apparent magnitude limited sample,

$$r \text{ to which an } L \text{ galaxy can be seen} \propto L^{1/2}.$$

$$V \text{ to which an } L \text{ galaxy can be seen} \propto L^{3/2}.$$

Thus,

$$n(L) \propto \phi(L) L^{3/2} \propto \left(\frac{L}{L^*}\right)^{\alpha+3/2} e^{-L/L^*}.$$

For an α = -1.25, which is the value for rich clusters, the above function peaks at ~ 0.25 L^*, & the median galaxy has $L \sim L^*$.

Three more points to note:

1) ϕ *(L)* is best determined near L^*.

→ Few galaxies have $L \gg L^*$ because they are rare
→ Few galaxies have $L \ll L^*$ because they are too faint to see

2) M31 (M_B = -20.3) is a 0.5L^* galaxy, & the combined Local Group ~ 1 L^*.
3) cD galaxies, which are 5 – 10 L^*, do not fit into the Schechter function scheme.

Luminosity Function as a Function of Hubble Type

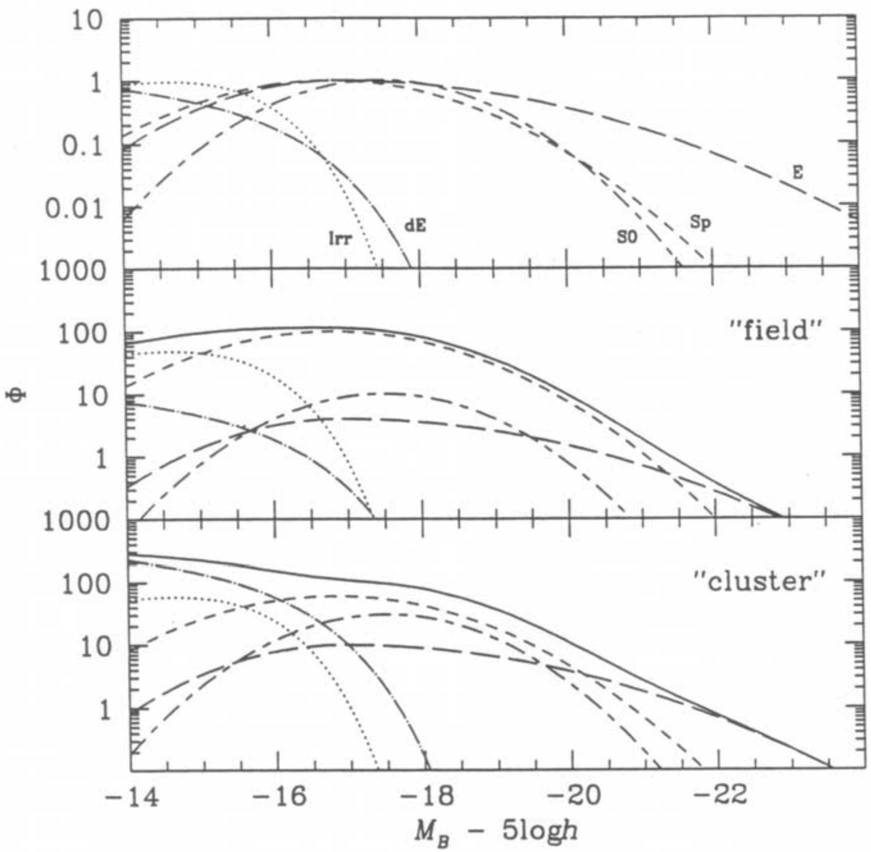

Figure 4.14 Luminosity functions for galaxies of various morphological types. The top panel shows The separate functions at arbitrary normalization, while the lower panels show approximately how these components combine to produce the total luminosity function in the field and in clusters.

Schechter Function
- Total LF
- dE/Irr LF

Gaussian
- Sa – Sc
- S0
- ~ Es

For dwarf galaxies & Irr's,

$$M_B^*(\mathrm{Irr}) = -15 + 5\log h \quad \text{and} \quad \alpha(\mathrm{Irr}) = -0.3,$$

$$M_B^*(\mathrm{dE}) = -16 + 5\log h \quad \text{and} \quad \alpha(\mathrm{dE}) = -1.3.$$

For all other Hubble Types, the LF is a gaussian with the parameters,

$$\overline{M_B}(\mathrm{Sa - Sc}) = -16.8 \quad \text{and} \quad \sigma_B = -0.3;$$

$$\overline{M_B}(\mathrm{SO}) = -17.5 \quad \text{and} \quad \sigma_B = 1.1.$$

The elliptical galaxy function is a little more complex,

$$\Phi_E(M_B) \propto exp\left(-\frac{[M_B^E - M_B]^2}{2\{\sigma_B^E(M_B)\}^2}\right);$$

where

$$M_B^E = -16.9 + 5\log h \text{ and}$$

$$\sigma_B^E = 2.2 \text{ for } M_B < M_B^E \text{ and } 1.3 \text{ for } M_B > M_B^E.$$

X-ray Emitting Gas in Clusters

- Rich clusters have strong X-ray emission associated with them. This emission makes it possible to ID distant rich clusters
- The mass of X-ray gas in rich cluster is in many cases equivalent to the mass of stars in the cluster galaxies
- The X-ray gas has temperatures on the order of $10^{7\text{-}8}$ K, & thus velocity dispersions of

$$\sigma \sim \left(\frac{kT}{\mu m_H}\right)^{1/2} \sim 1000 - 3000\text{km s}^{-1}.$$

- The luminosity of X-ray gas is given by,

$$L_X \propto n_e^2 T^{1/2} R^3,$$

where n_e is the e- number density & R is the radius of the spherical distribution of X-ray gas. Note: Only massive clusters have deep enough potential well to retain X-ray gas

Clusters vs. Field

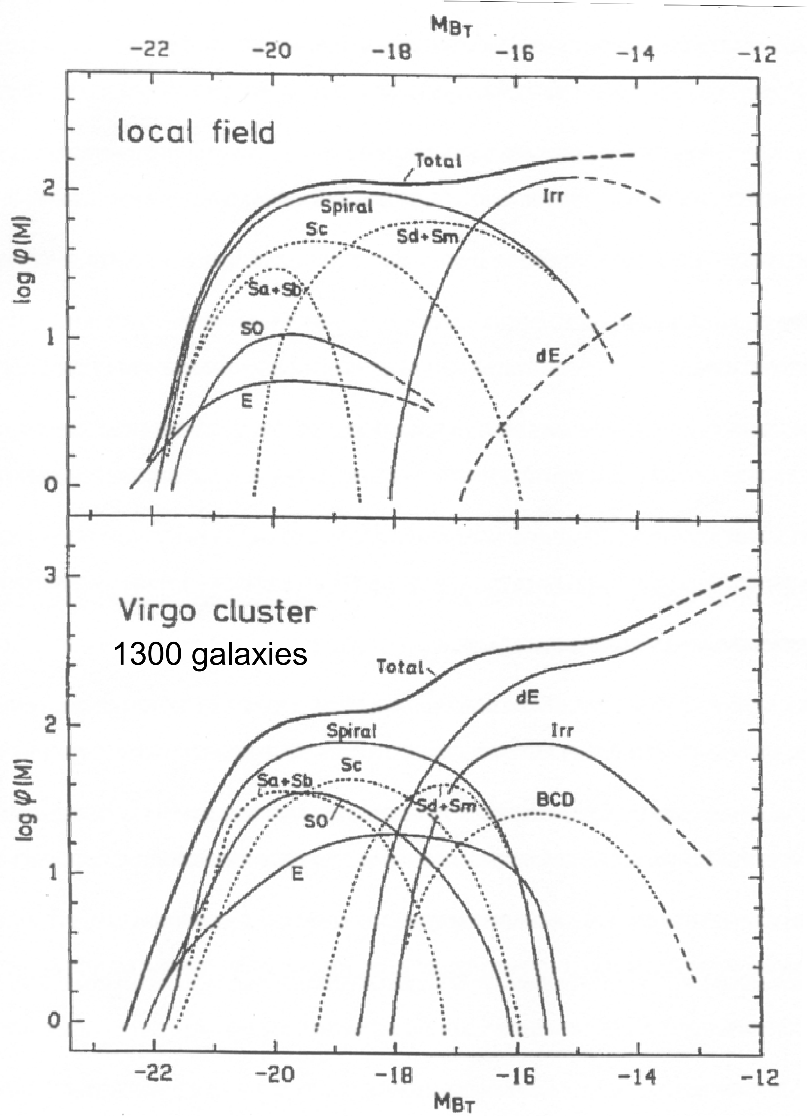

Figure 1 The LF of field galaxies (top) and Virgo cluster members (bottom). The zero point of log $\varphi(M)$ is arbitrary. The LFs for individual galaxy types are shown. Extrapolations are marked by dashed lines. In addition to the LF of all spirals, the LFs of the subtypes Sa + Sb, Sc, and Sd + Sm 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).

- The fraction of Ellipticals & S0s increases with increasing clustering
- The fraction of dE increases with increasing clustering
- The merger fraction is effectively zero in dense clusters. This is because the velocity dispersions of clusters are extremely high (≥ 1000 km/s), which is higher than the escape velocity of galaxy flybys.

(Binggeli, Sandage, Tammann 1988)

Astron. Astrophys. 228, 42–60 (1990)

The abundance and morphological segregation of dwarf galaxies in the field

B. Binggeli[1,2], M. Tarenghi[3], and A. Sandage[4]

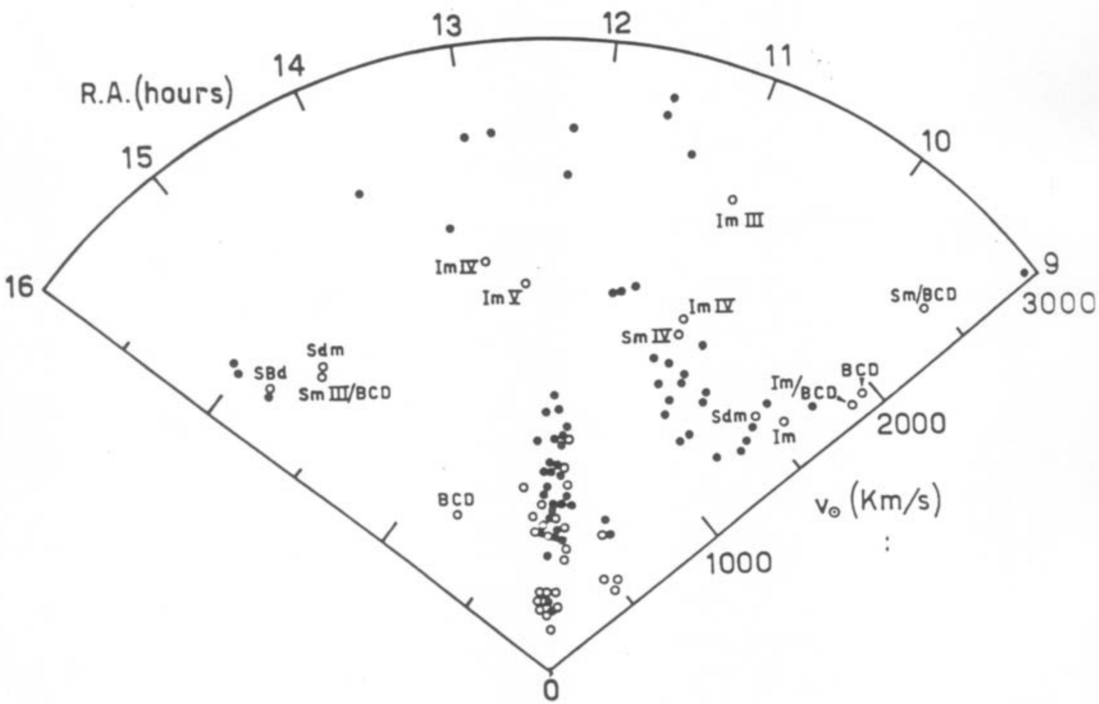

Fig. 6. Wedge diagram for all Zwicky giants (closed circles) and dwarfs (open circles) in the southern survey strip (+30°, +36°), from 9ʰ to 16ʰ, out to a heliocentric velocity of 3000 km s⁻¹. Some dwarfs are indicated with their type

Dwarfs are associated
With large galaxies.

I.e., is it not the case that bright galaxies form in dense environments & faint galaxies formed in less dense environments.

(Binggeli, Tarenghi & Sandage 1990)

- Fraction of S & Irr increases with increasing *R*
- Fraction of S increases with decreasing galaxy density

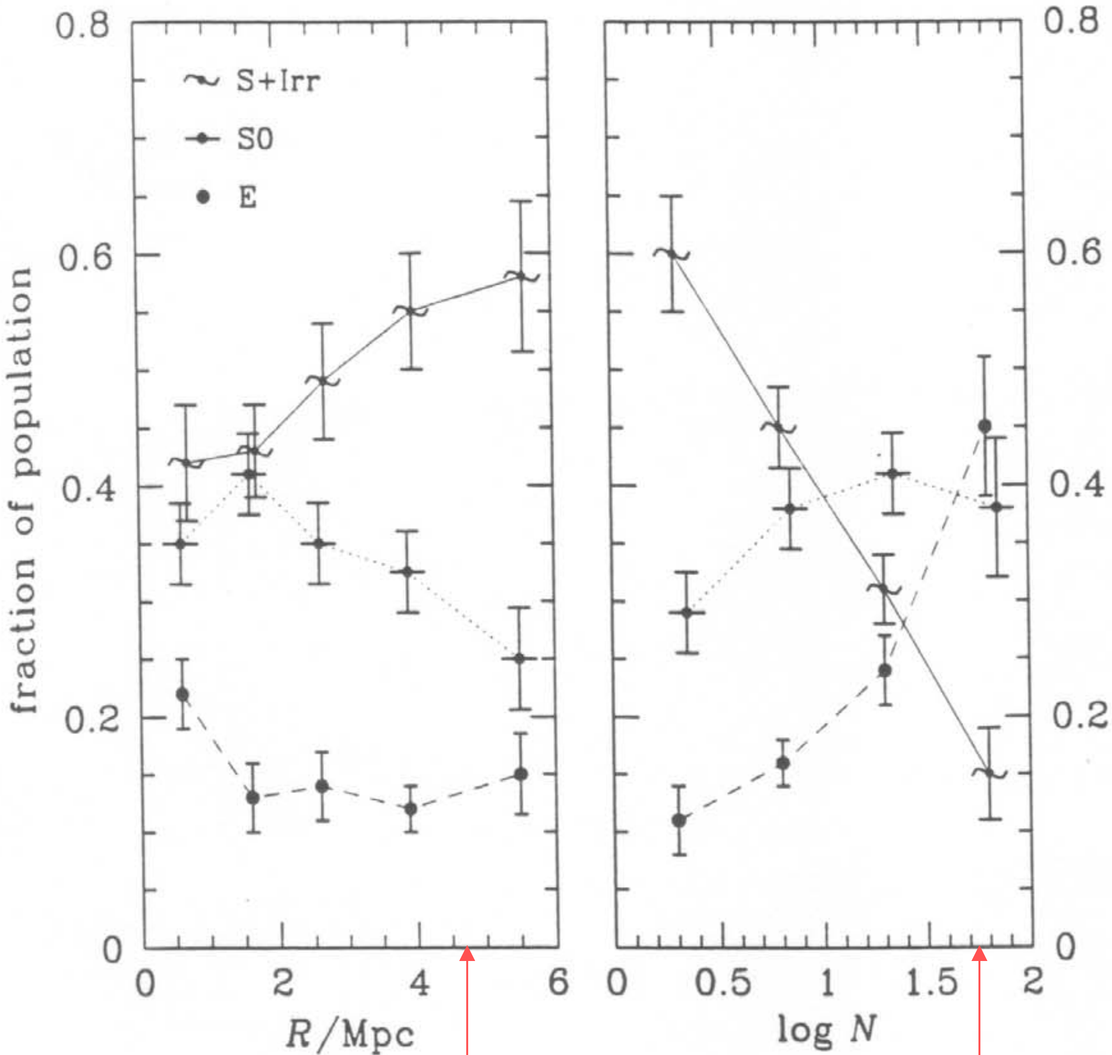

Figure 4.10 The fraction of galaxies of different types in a sample of 6 clusters plotted both as a function of radius and as a function of local projected galaxy density. [From data published in Dressler (1980)]

(B&M, pg 159)

Morphology-Radius Relation

Morphology-Density Relation

- Cold disk component disrupted by intercluster medium & interactions?

Are we missing any Galaxies?

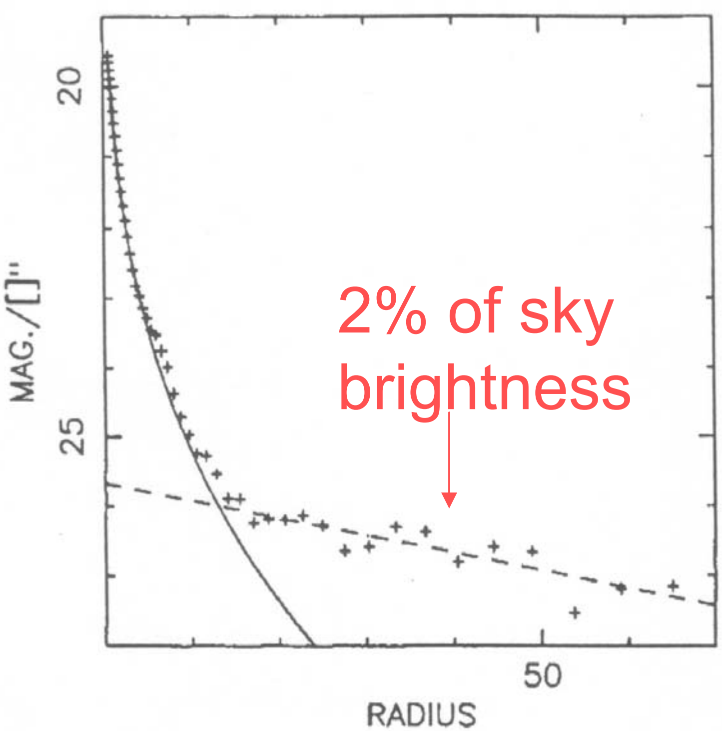

FIG. 3. V band luminosity profile. The solid line indicates the best-fitting $r^{1/4}$ component while the dashed line corresponds to the exponential disk. The fits are schematic only, as the total luminosity profile does not readily deconvolve into distinct components. Radius is in arcsec.

TABLE I. Observed properties of Malin 1. Assumed distance = 250 Mpc.

Photometric properties at V:	
Disk scale length:	$45 \pm 5''$ (~55 kpc)
Central surface brightness:	25.7 ± 0.1
Bulge effective radius:	$2.9 \pm 0.5''$ (~4 kpc)
Surface brightness at effective radius:	22.2 ± 0.2
Bulge-to-disk luminosity ratio:	0.4 ± 0.05
$(B - V)$ aperture diameter = 4'':	0.95 ± 0.02
Apparent V mag:	17.5
$(B - V)$ aperture diameter = 20'':	0.90 ± 0.02
Apparent V mag:	16.9
Diameter at $V = 27.0$:	$120 \pm 10''$ (~150 kpc)
H I properties:	
Systemic velocity:	$24\,750 \pm 10$ km/s
Flux integral:	3.5 ± 0.5 Jy km/s
20% linewidth:	341 ± 20 km/s
[a]Log H I mass:	11.02 $\mathscr{M}_{\odot}$

[a]Includes factor of 2 correction for partial resolution and mispointing.

Example: The Low Surface Brightness Galaxy Malin 1.

(Bothun et al. 1987)

The LSB Malin 1

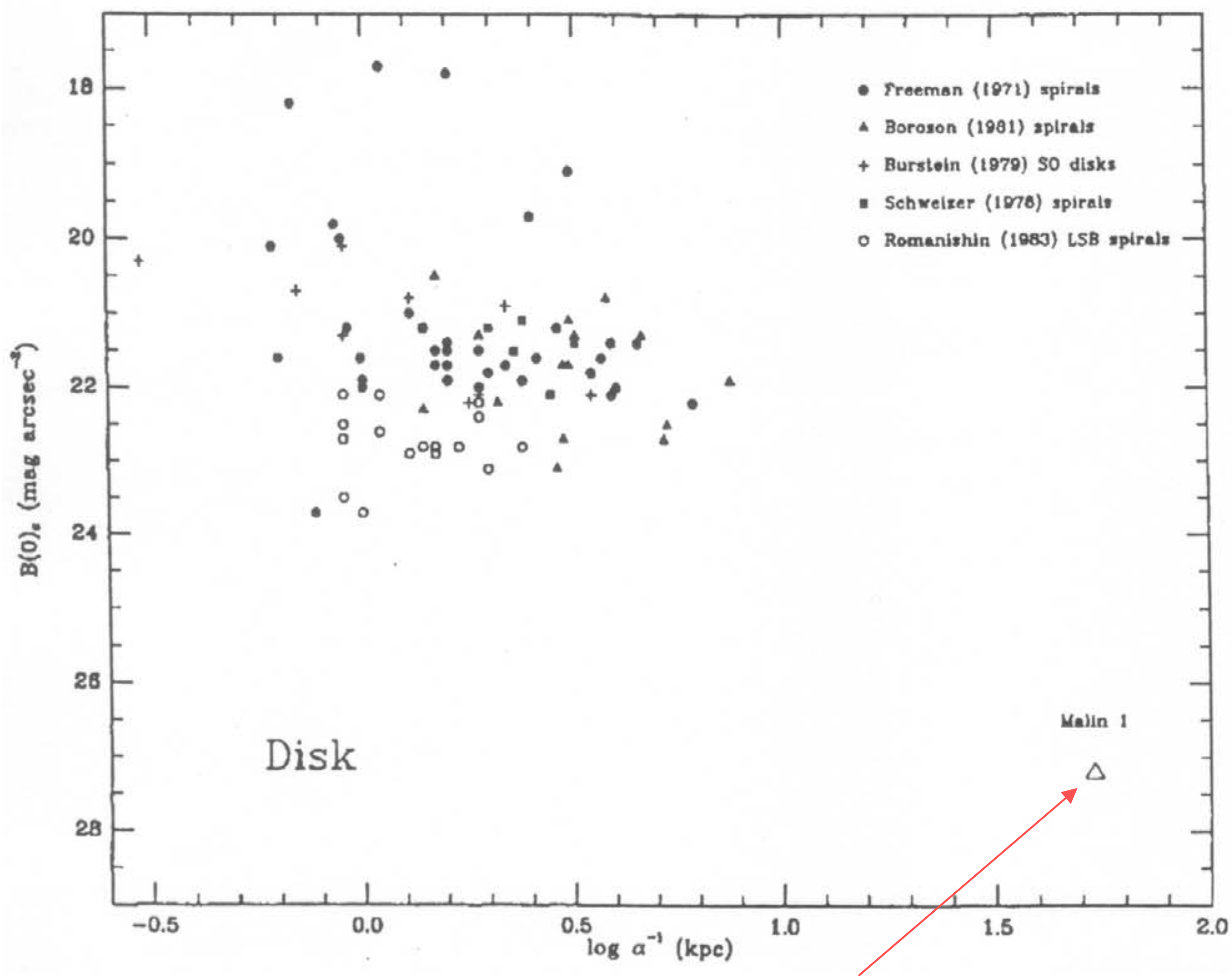

FIG. 7. Location of Malin 1 in the scale length versus central surface-brightness relation compared to spirals in other samples.

Low Central Surface Brightness
Large Disk

(Bothun et al. 1987)

Malin 1 (cont)

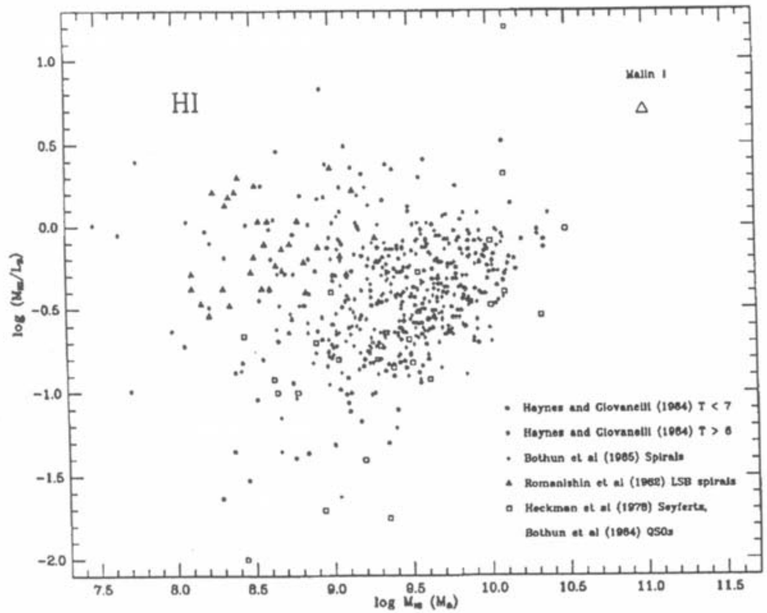

FIG. 9. Comparison of the H I mass of Malin 1 with previously studied spirals.

- Very gas rich. But the gas surface density is too low to have star formation initiated by disk instabilities

- The only obvious activity is the Seyfert nucleus

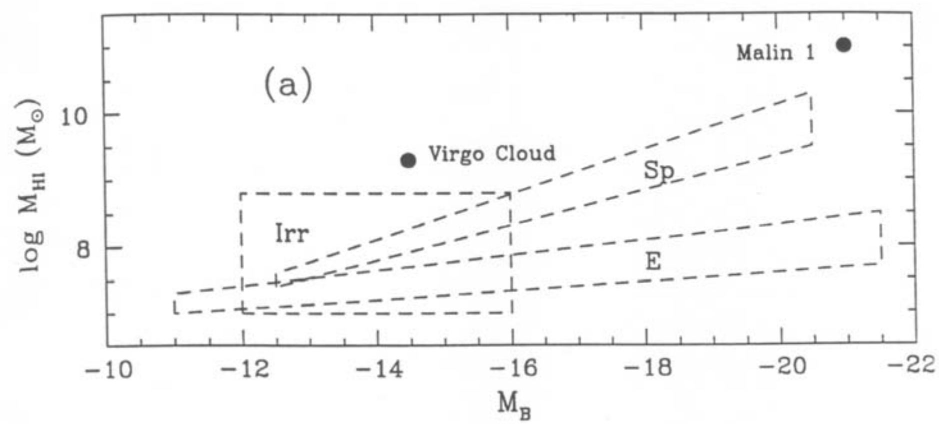

Figure 7 (*a*) Schematic plot of stellar luminosity against gas mass for different galaxy types. LSB galaxies of various types lie not far off the relationship defined by most galaxies. (From Giovanelli & Haynes 1989, Bothun et al 1987.)

(Impey & Bothun 1997)