STRUCTURE OF GALAXIES

Lecture 1. Stellar Populations, classification, surface photometry.

Stellar Populations.

History

Lindblad* in 1925 argued that the Galaxy is made up of a set of components with a continuous range of flattening.

Baade† in 1944 resolved red stars in the central regions of M32 and the elliptical companions and introduces the concept of two stellar populations, mainly based on the characteristics of their H-R diagrams.

Population I is in the disk and has blue stars and Population II in the halo with globular cluster type H-R diagrams with red stars the brightest.

*Arkiv. Mat. Astron. Fysik 19A, No. 21

†Ap.J. 100, 137 and 147

THE RESOLUTION OF MESSIER 32, NGC 205, AND THE CENTRAL REGION OF THE ANDROMEDA NEBULA*

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ABSTRACT

Recent photographs on red-sensitive plates, taken with the 100-inch telescope, have for the first time resolved into stars the two companions of the Andromeda nebula—Messier 32 and NGC 205—and the central region of the Andromeda nebula itself. The brightest stars in all three systems have the photographic magnitude 21.3 and the mean color index +1.3 mag. Since the revised distance-modulus of the group is $m - M = 22.4$, the absolute photographic magnitude of the brightest stars in these systems is $M_{pg} = -1.1$.

The Hertzsprung-Russell diagram of the stars in the early-type nebulae is shown to be closely related to, if not identical with, that of the globular clusters. This leads to the further conclusion that the stellar populations of the galaxies fall into two distinct groups, one represented by the well-known H-R diagram of the stars in our solar neighborhood (the slow-moving stars), the other by that of the globular clusters. Characteristic of the first group (type I) are highly luminous O- and B-type stars and open clusters; of the second (type II), short-period Cepheids and globular clusters. Early-type nebulae (E–Sa) seem to have populations of the pure type II. Both types seem to coexist in the intermediate and late-type nebulae.

The two types of stellar populations had been recognized among the stars of our own galaxy by Oort as early as 1926.

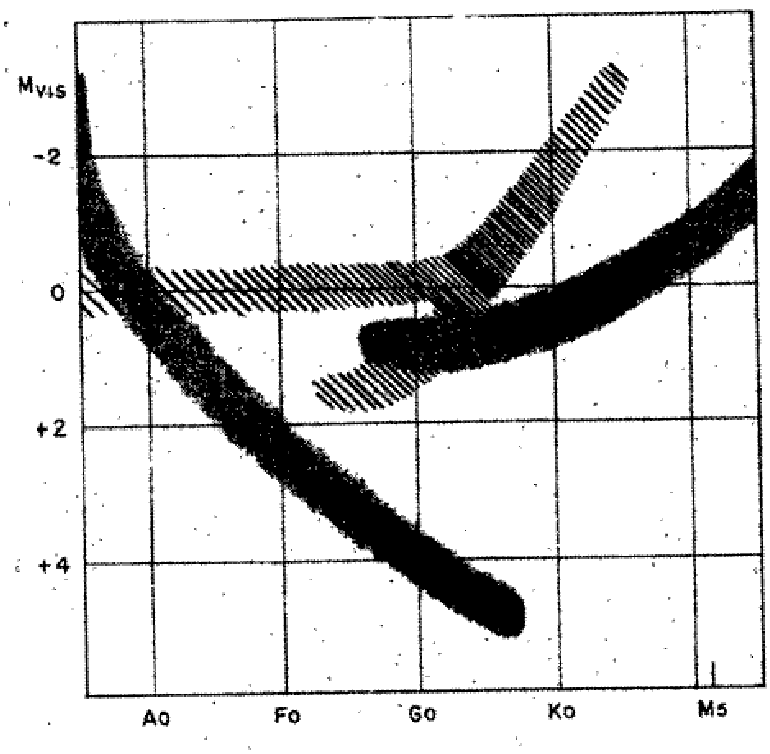
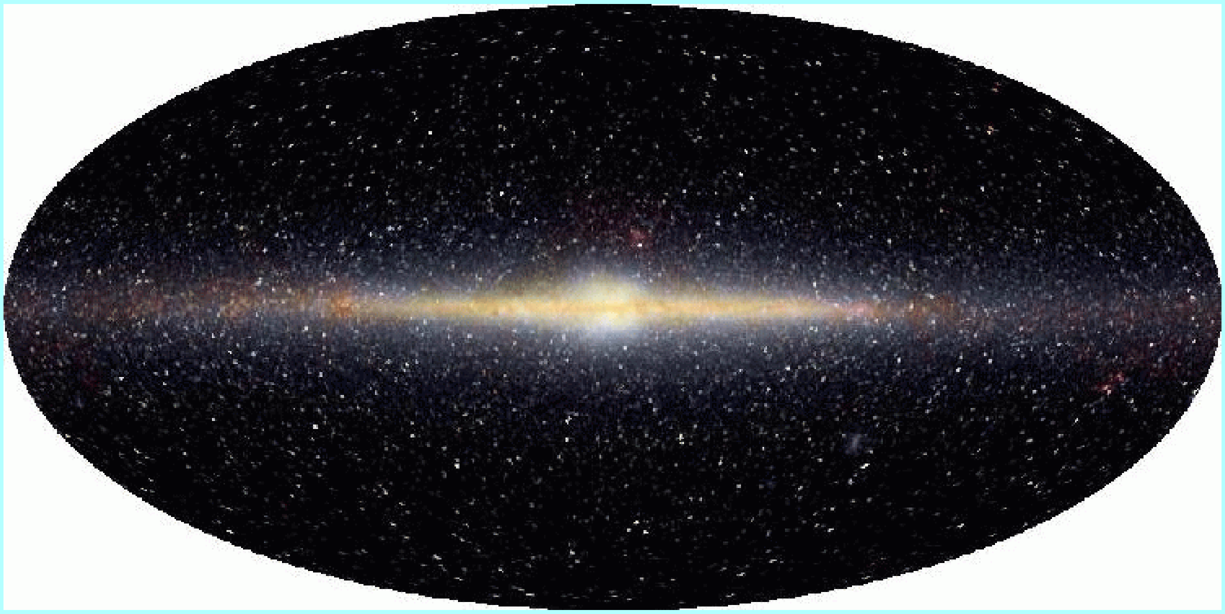
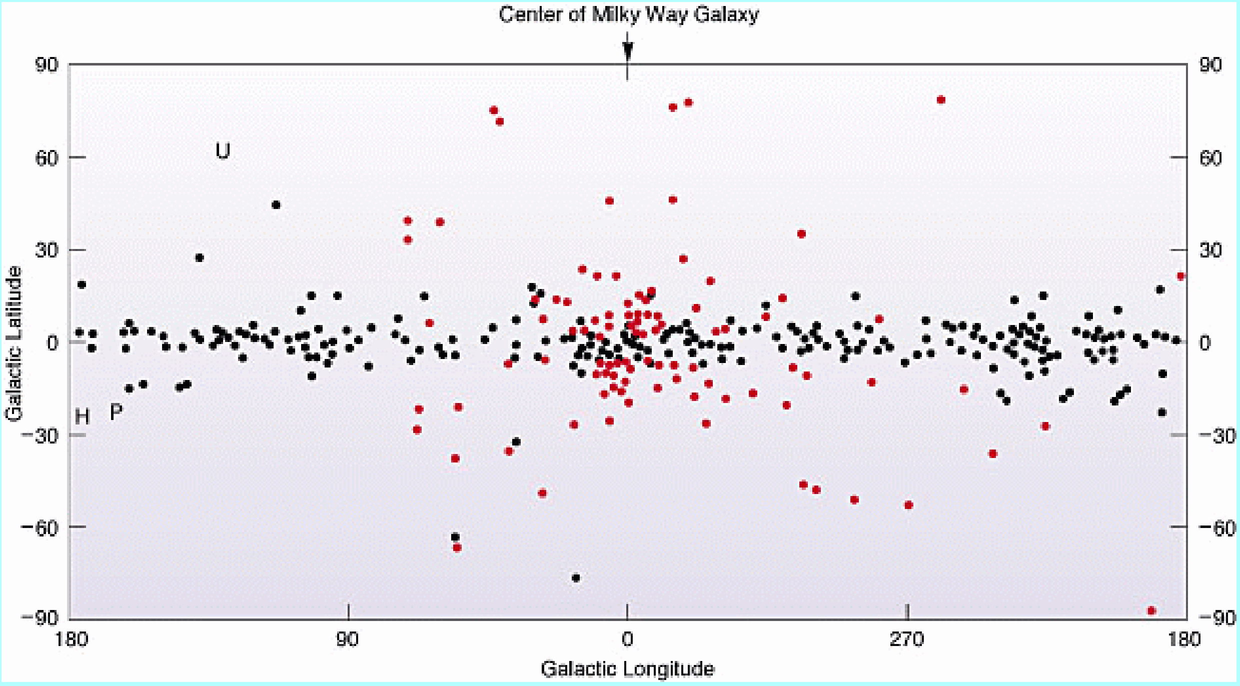


FIG. 1.—Shaded areas: ordinary H-R diagram (type I). Hatched area: H-R diagram of stars in globular clusters (type II).

The Galaxy as consisting of two basic populations can be seen in the near-infrared image of the Galaxy with the DIRBE experiment on board the Cosmic Background Explorer COBE and in the distribution on the sky of globular (red) versus galactic clusters.





In 1957 the Vatican Symposium on stellar populations defined five stellar populations with a decreasing age, increasing flattening and metal abundance.

Population	$\|z\|$ (pc)	$\|Z\|$ (km/s)	Typical members
Extreme Pop. I	120	8	Gas, Young stars associated with spiral structure, Supergiants, Cepheids, T Tauri stars, Galactic Clusters of Trumpler's Class I
Older Pop. I	160	10	A-Type stars, Strong-line stars
Disk Population	400	17	Stars of galactic nucleus, Planetary Nebulae, novae, RR Lyrae stars with periods below 0.4 days, Weak-line stars
Interm. Pop. II	700	25	"High-velocity stars" with z-velocities exceeding 30 km/sec, Long-period variables <M5e with periods below 250 days
Halo Pop. II	2000	75	Subdwarfs, Globular clusters with high z-velocity, RR Lyrae stars with periods longer than 0.4 days

The current situation.

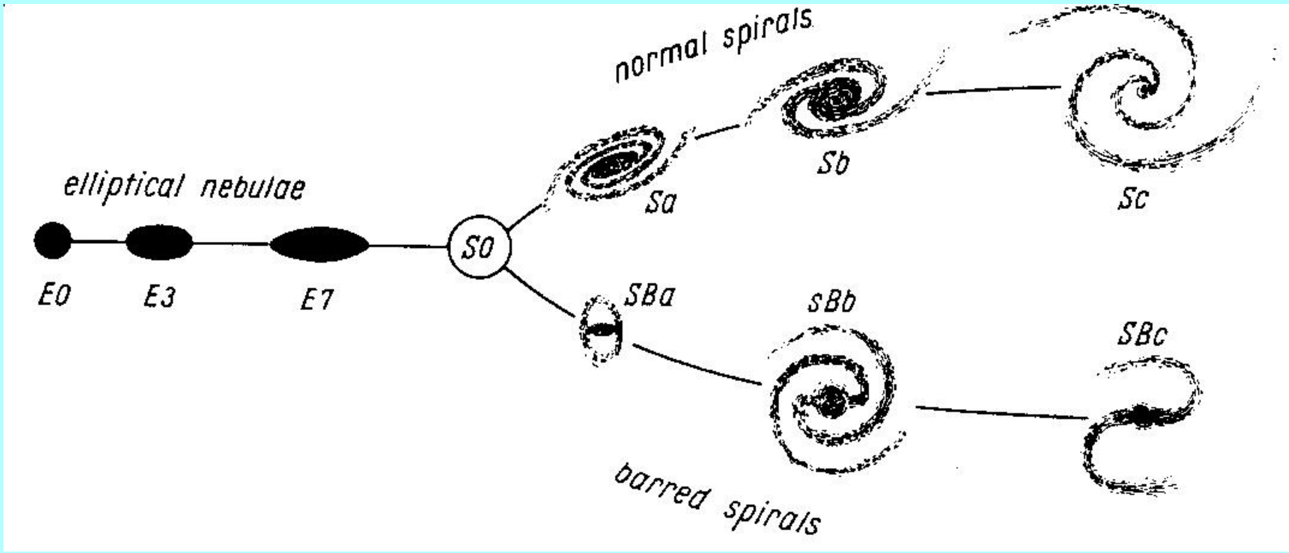
- Dark halo, presumably non-baryonic.
- Population II.
- Thick disk.
- Old disk, sometimes called thin disk.
- Population I.

Classification

Classification systems have been described in detail by Allan Sandage in Volume IX of "Stars and Stellar Systems".

This chapter can also be found on the Web*.

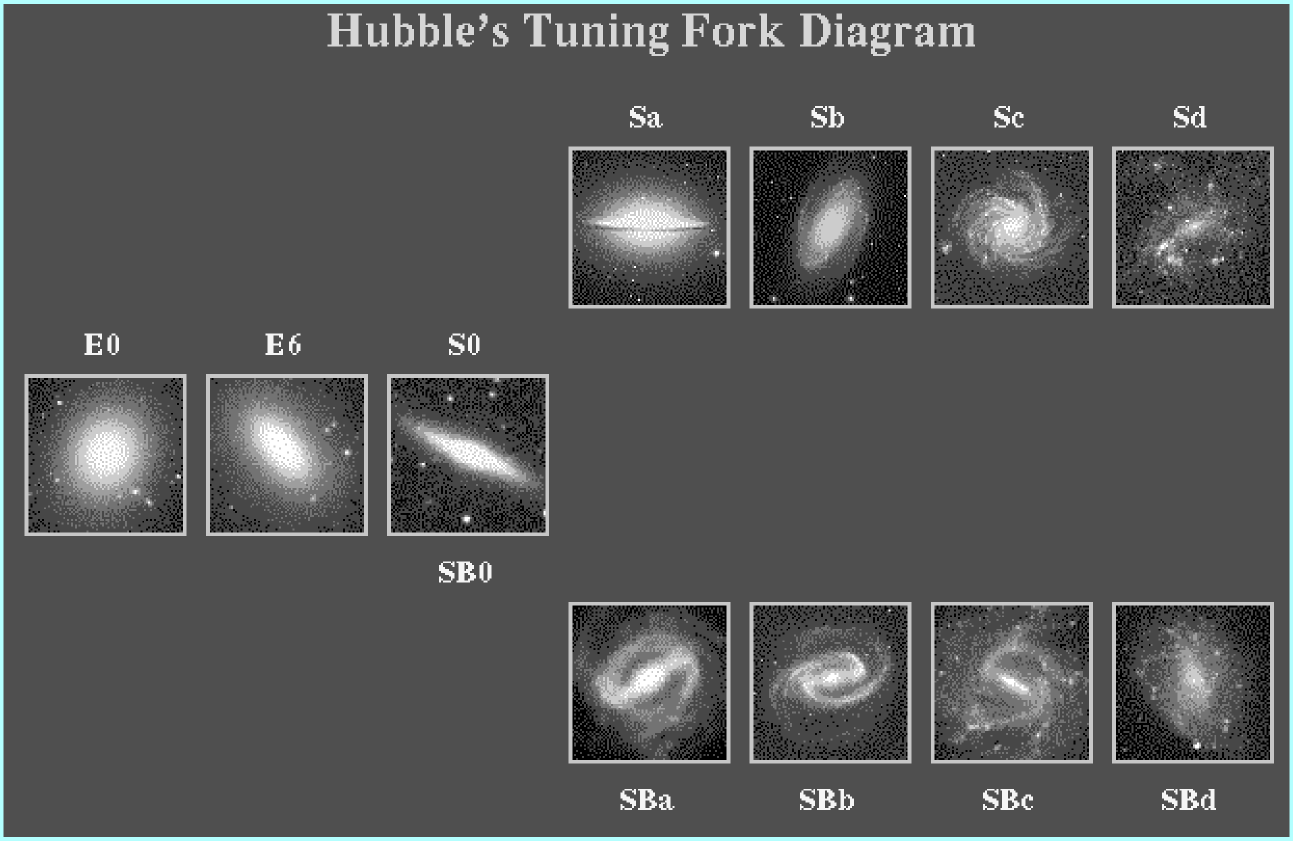
The Hubble classification scheme starts with Hubble's scheme of the 1920's (his well-known tuning fork).



*http://nedwww.ipac.caltech.edu/level5/Sandage/frames.html

Originally the S0 class was not included. Hubble introduced it in the 1930's.

Here is a modern WWW-version of the Tuning Fork.



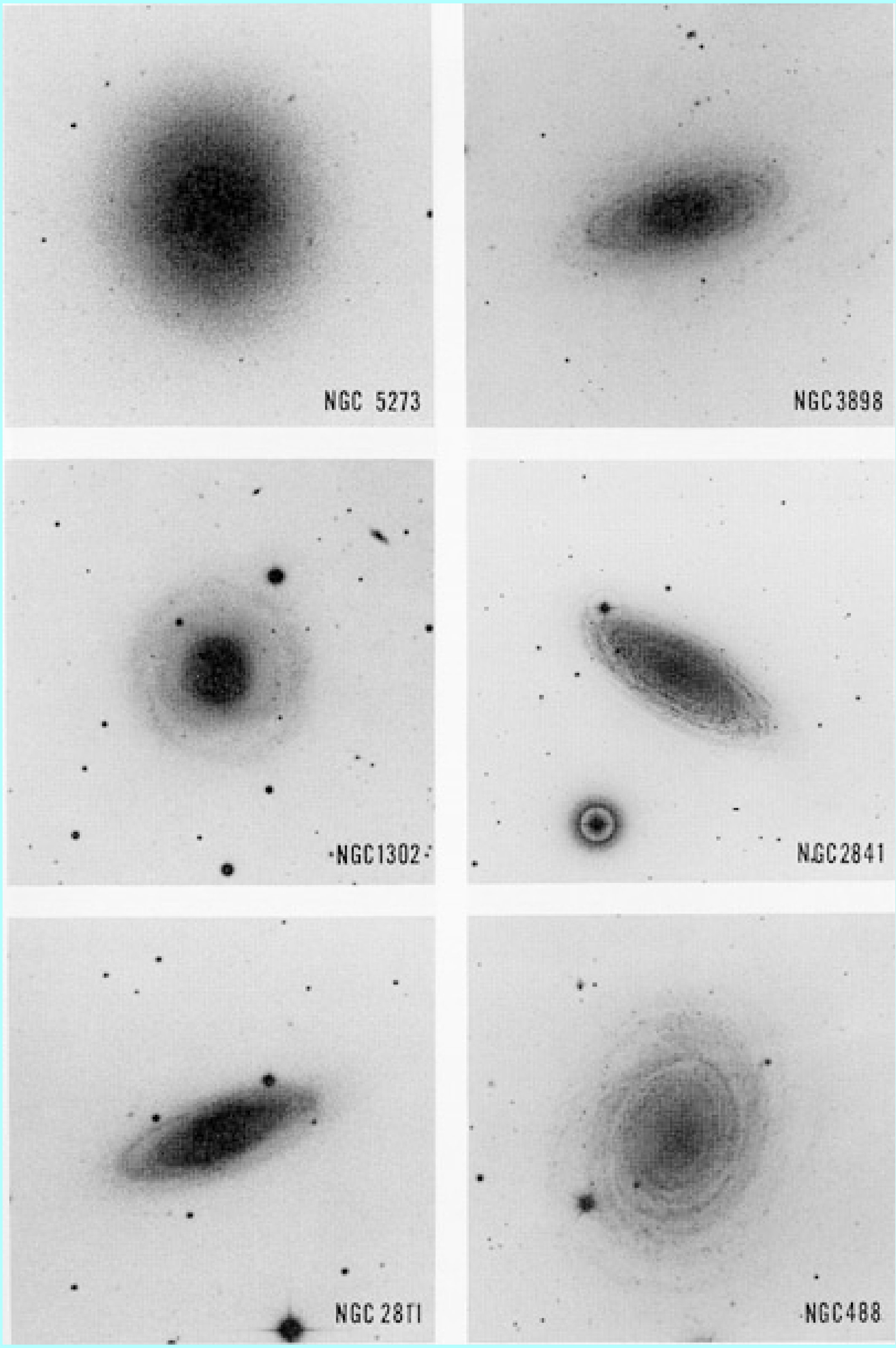
The Hubble Classification System has the following criteria:

- Ellipticals – E0 to E7 depending on the apparent flattening (En with $n = 10\times(a-b)/a$).
- Spirals either with or without a bar (S or SB) and subclasses a to c depending on
  - Bulge-to-disk ratio
  - Pitch angle of spiral arms
  - Development of arms ("strength" of HII regions)
- Irregulars Irr

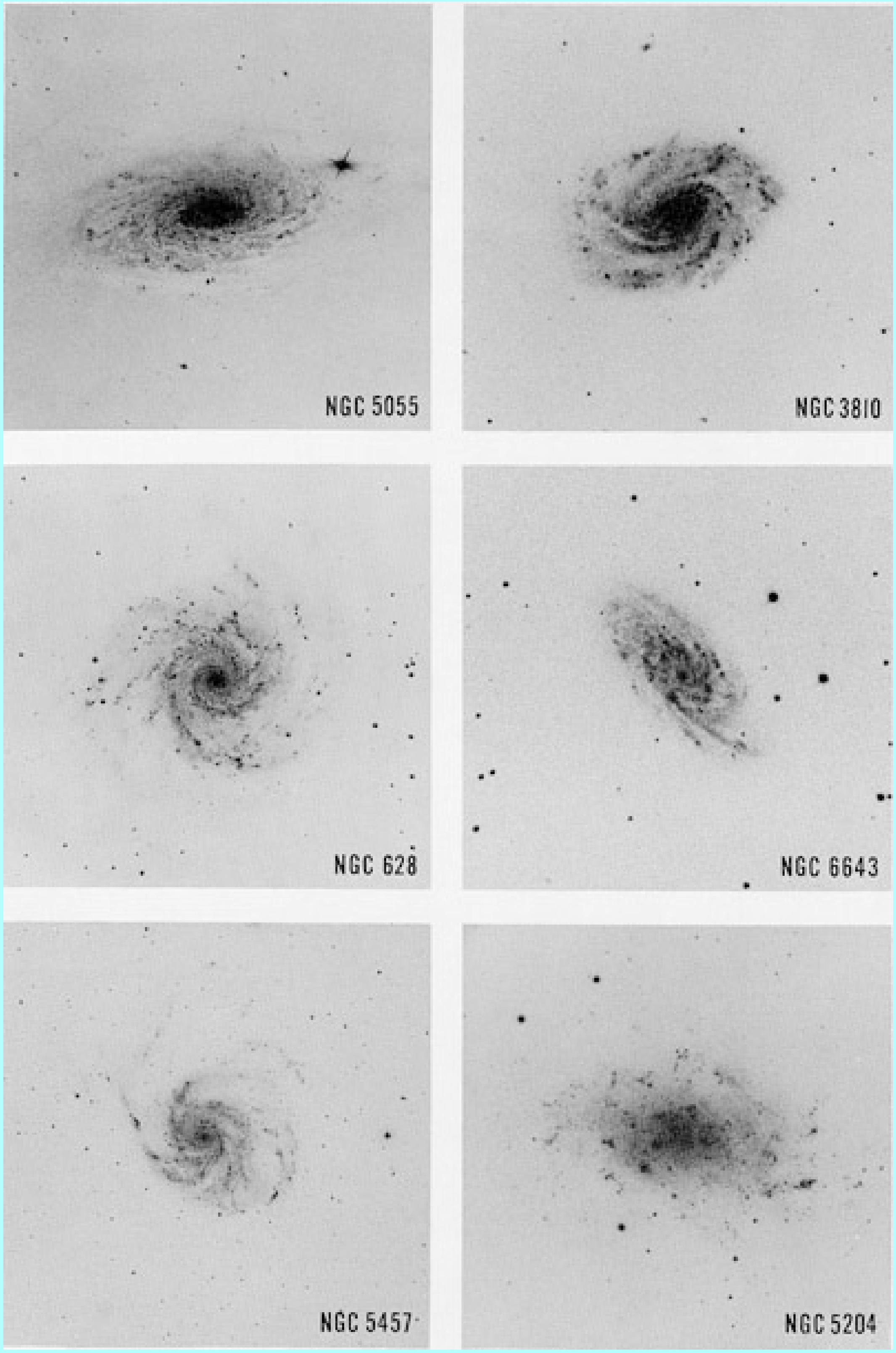
De Vaucouleurs later introduced Sd and Im ("Magellanic irregulars) to replace many of the Irr. Also he used the intermediate classification SAB.

The following figures from Sandage's paper illustrate the system.

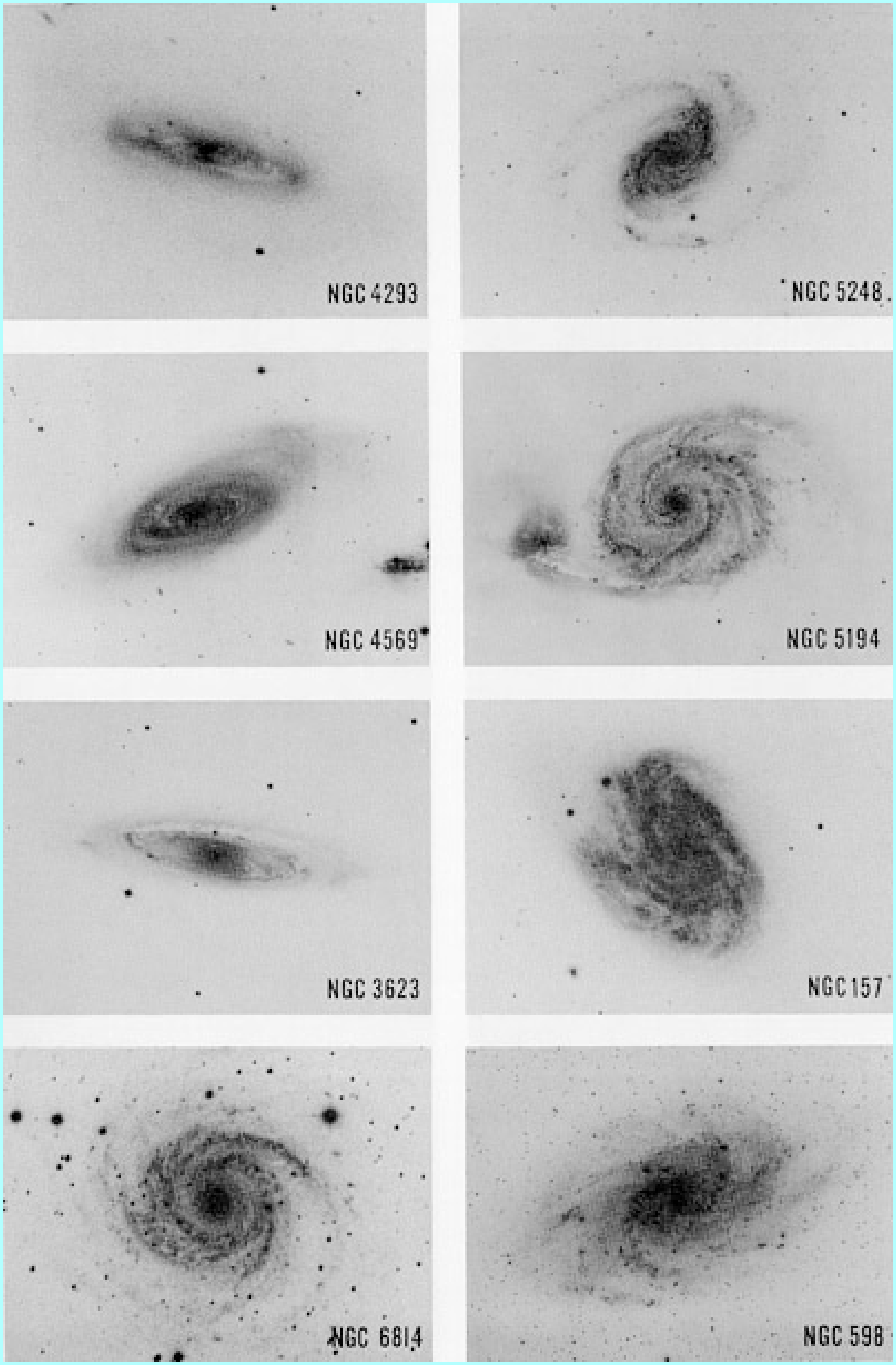
S0 and Sa with thin arms.



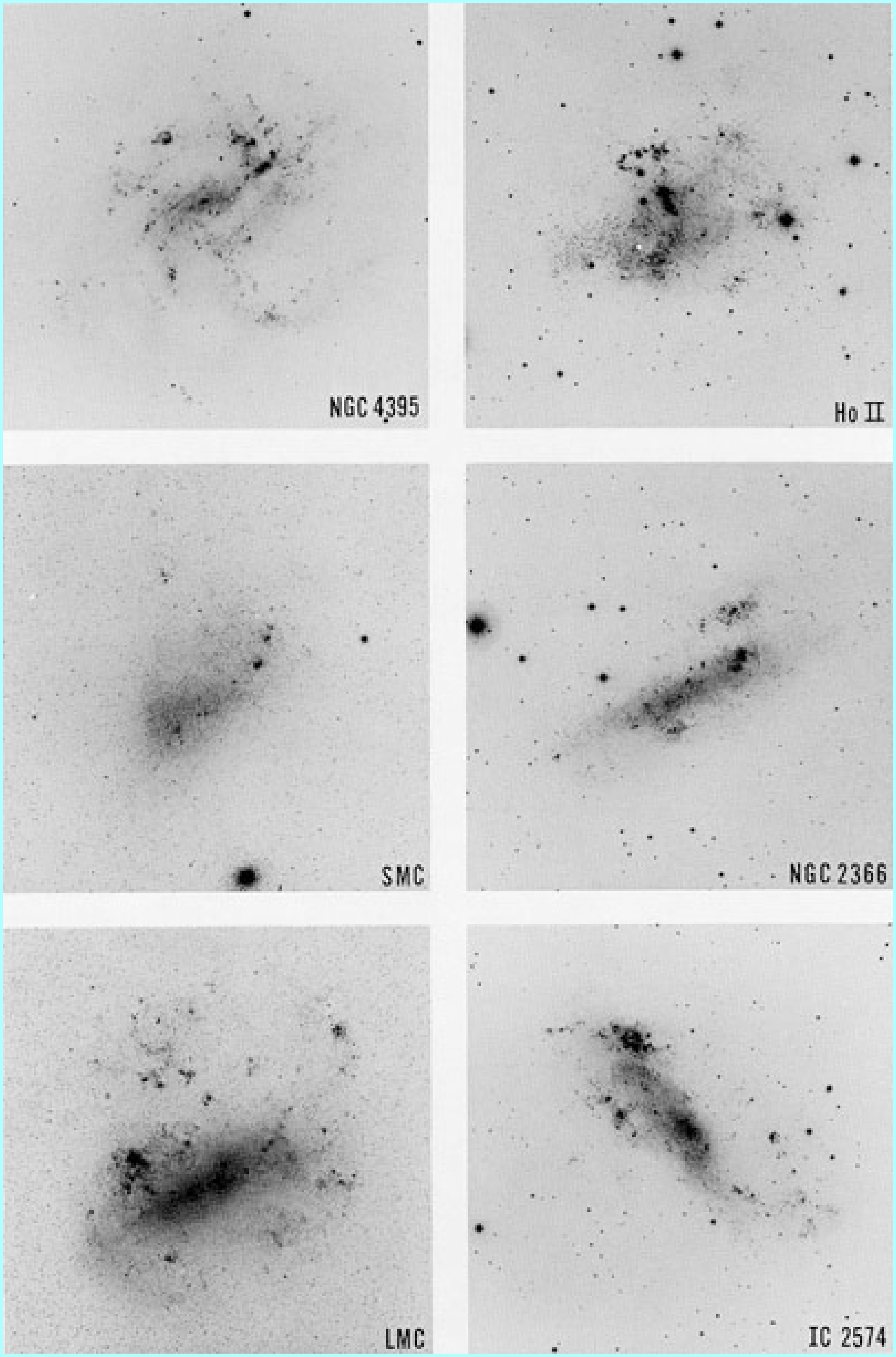
Sb and Sc with thin arms.



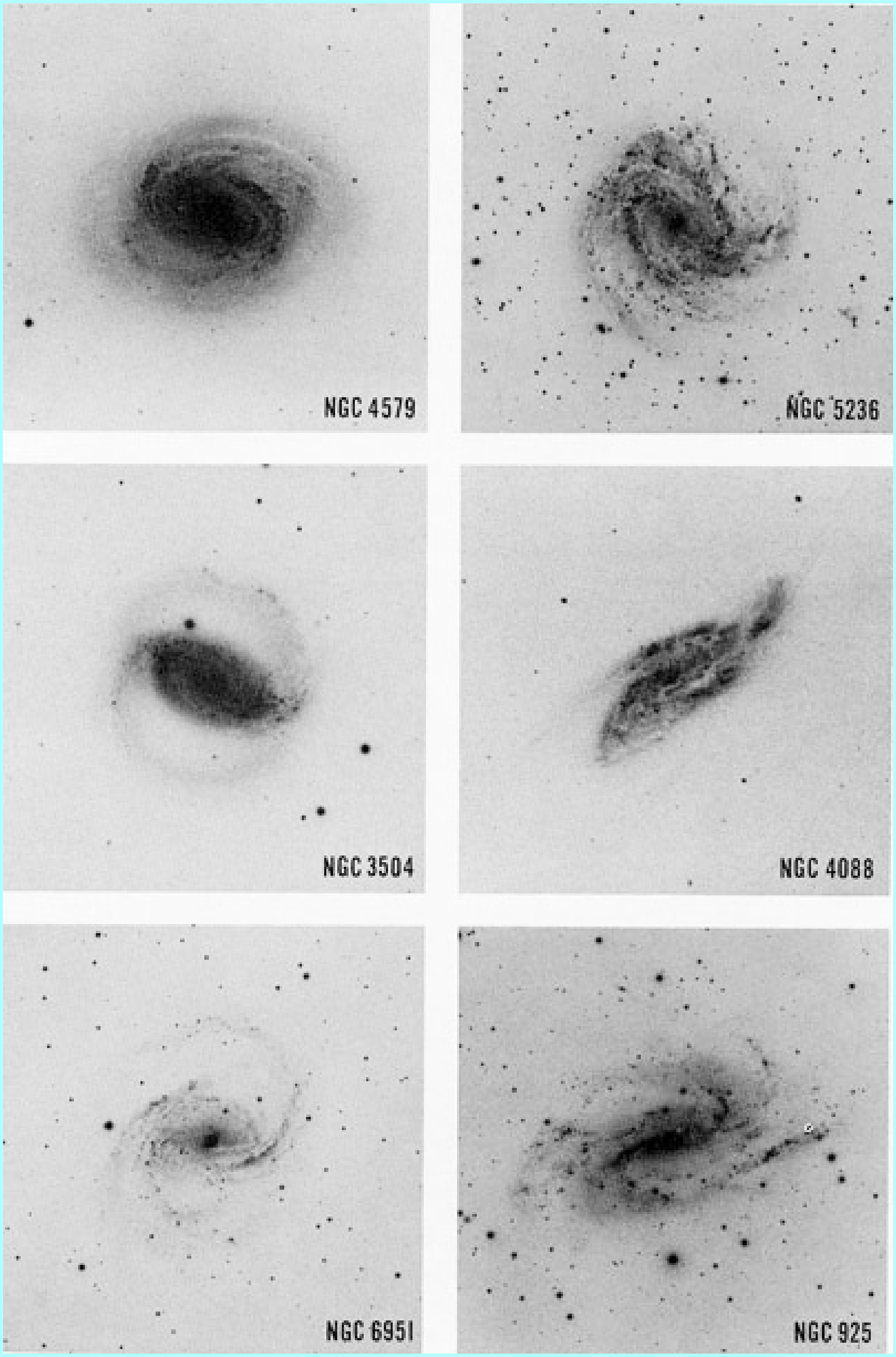
Sa to Sc with heavy arms.



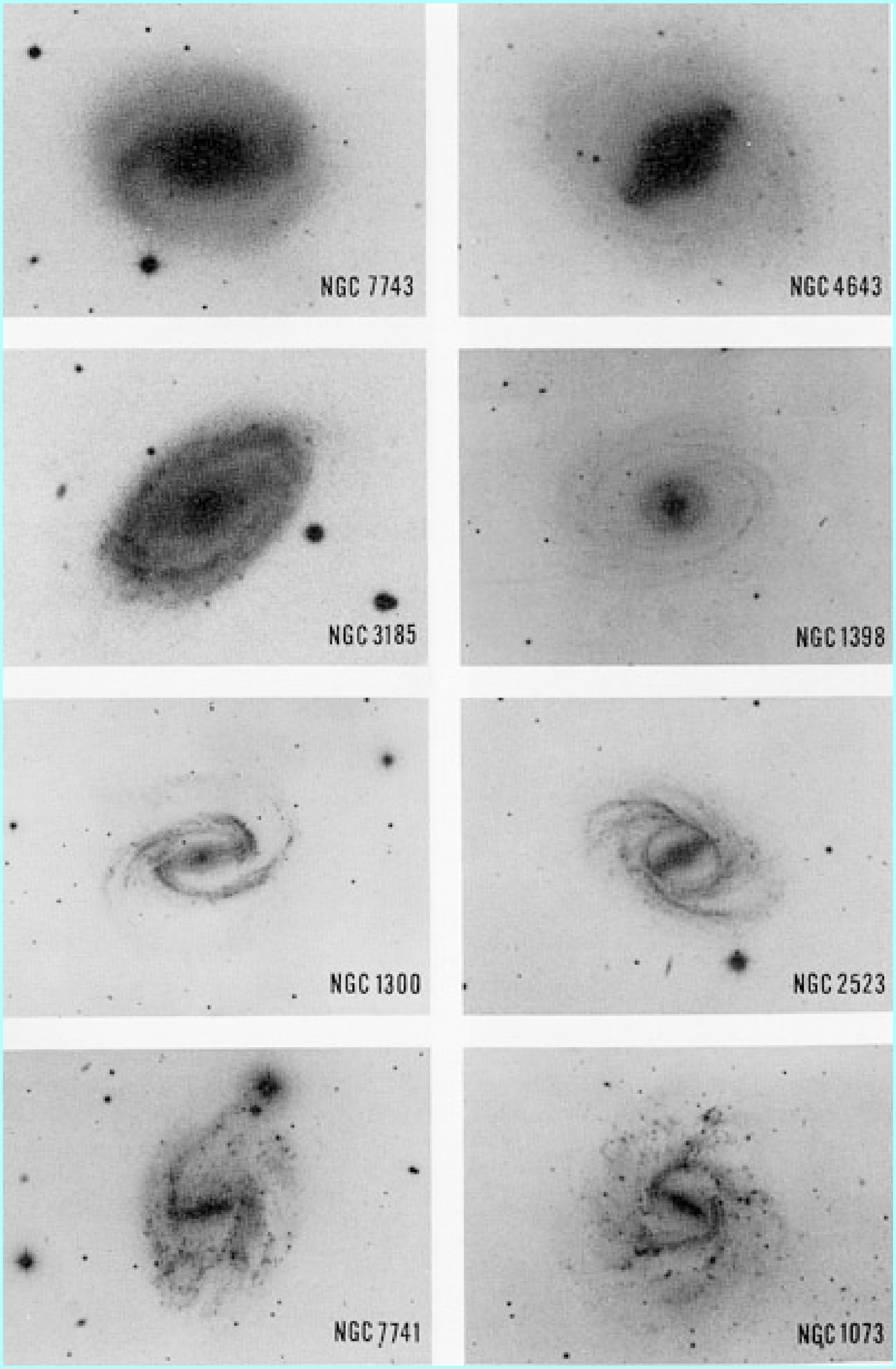
Irregulars Irr , later called Sd and Sm.



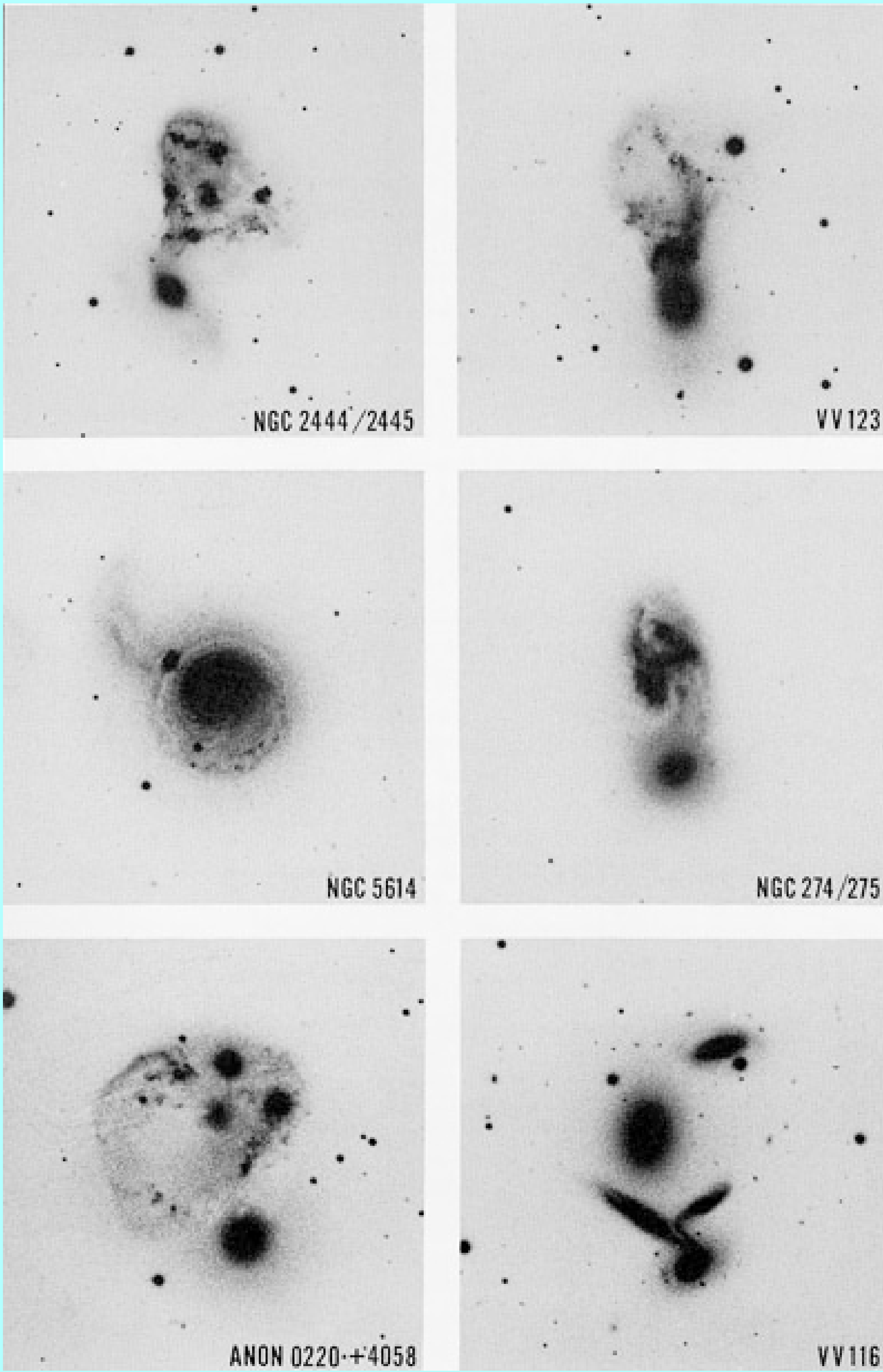
Spirals with small bars (SAB).



Spirals with heavy bars (SB).

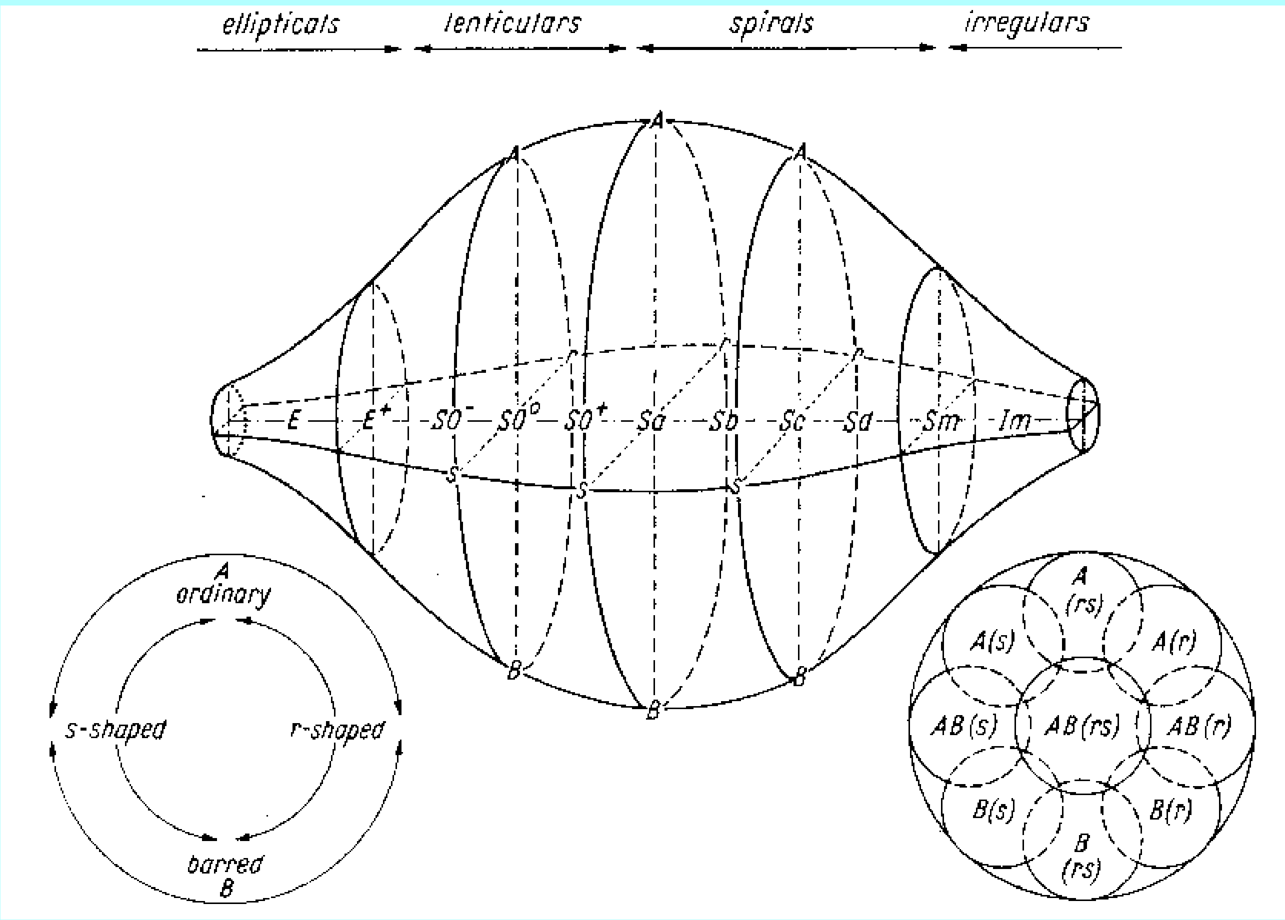


It is not possible to classify interacting galaxies.

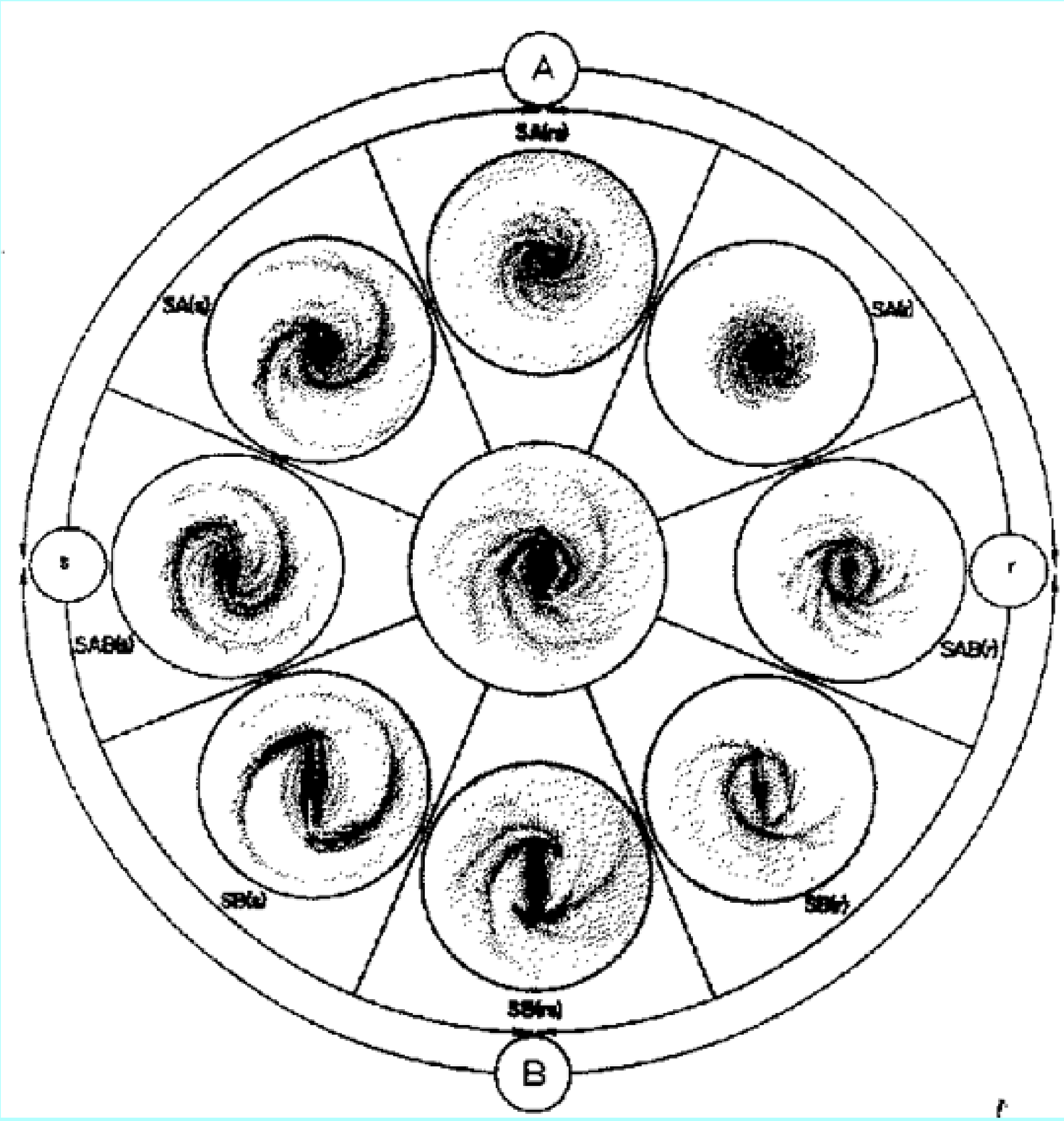


De Vaucouleurs also introduced the varieties r (arms begin from an internal ring, often at the end of a bar) and s (no internal ring).

His three-dimensional system then looked as follows.

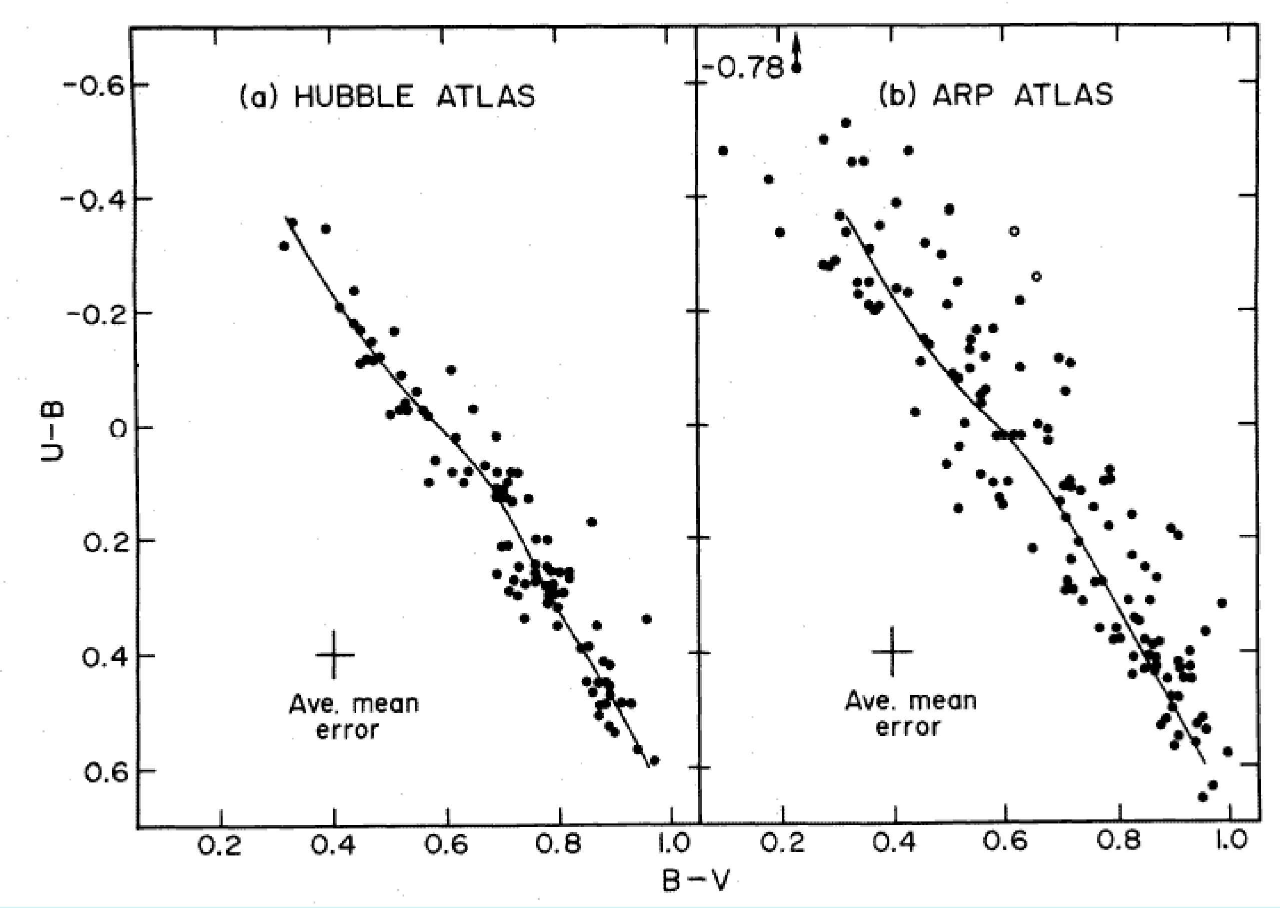


Or in cross-cut at Sb/SBb:

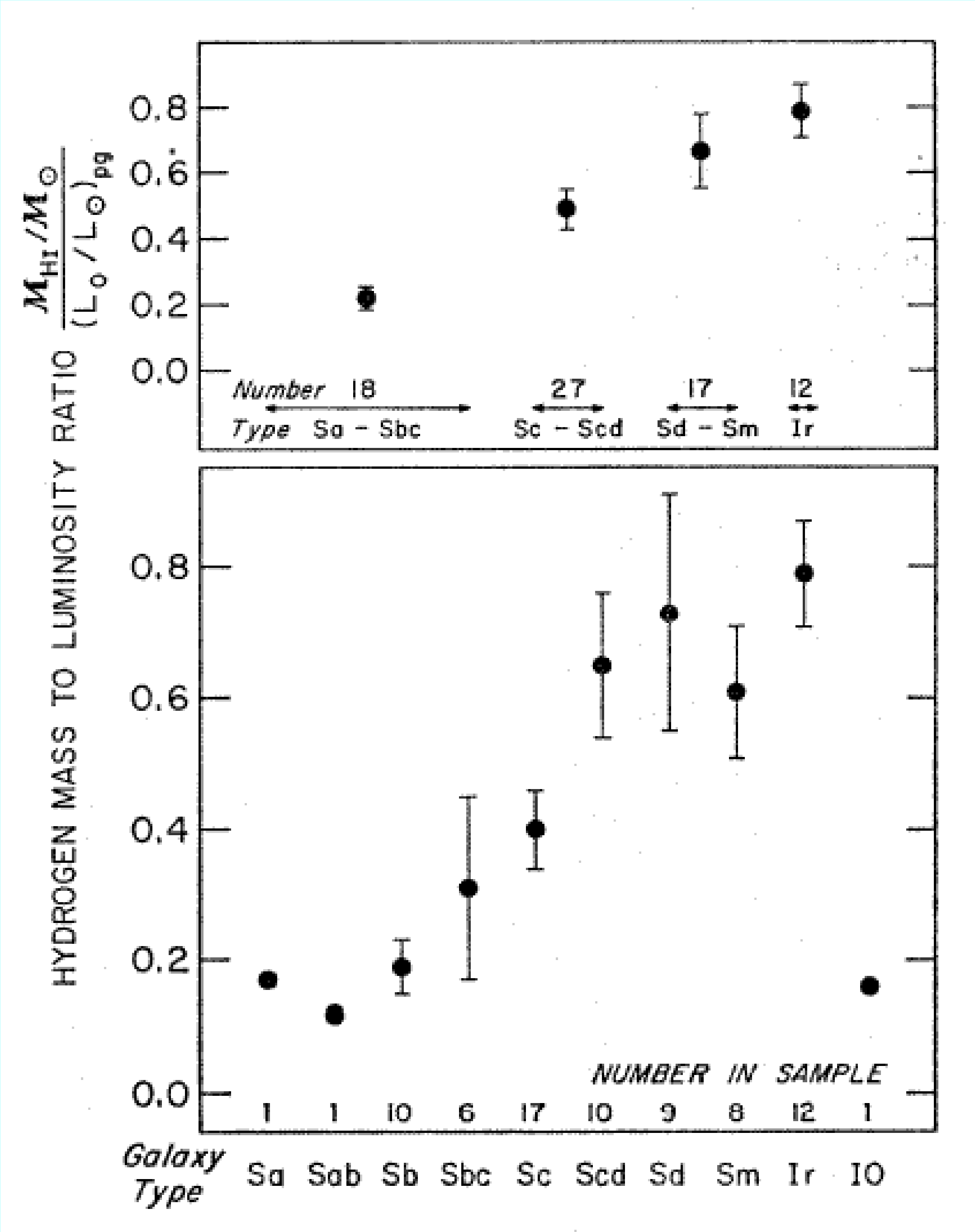


Hubble classification correlates with integrated colors and relative HI content, so is apparantly related to the history of star formation.

The colors of E-galaxies are about $(B-V) \sim 0.9$, $(U-B) \sim 0.6$ and those for late type galaxies $(B-V) \sim 0.4$, $(U-B) \sim -0.3$.



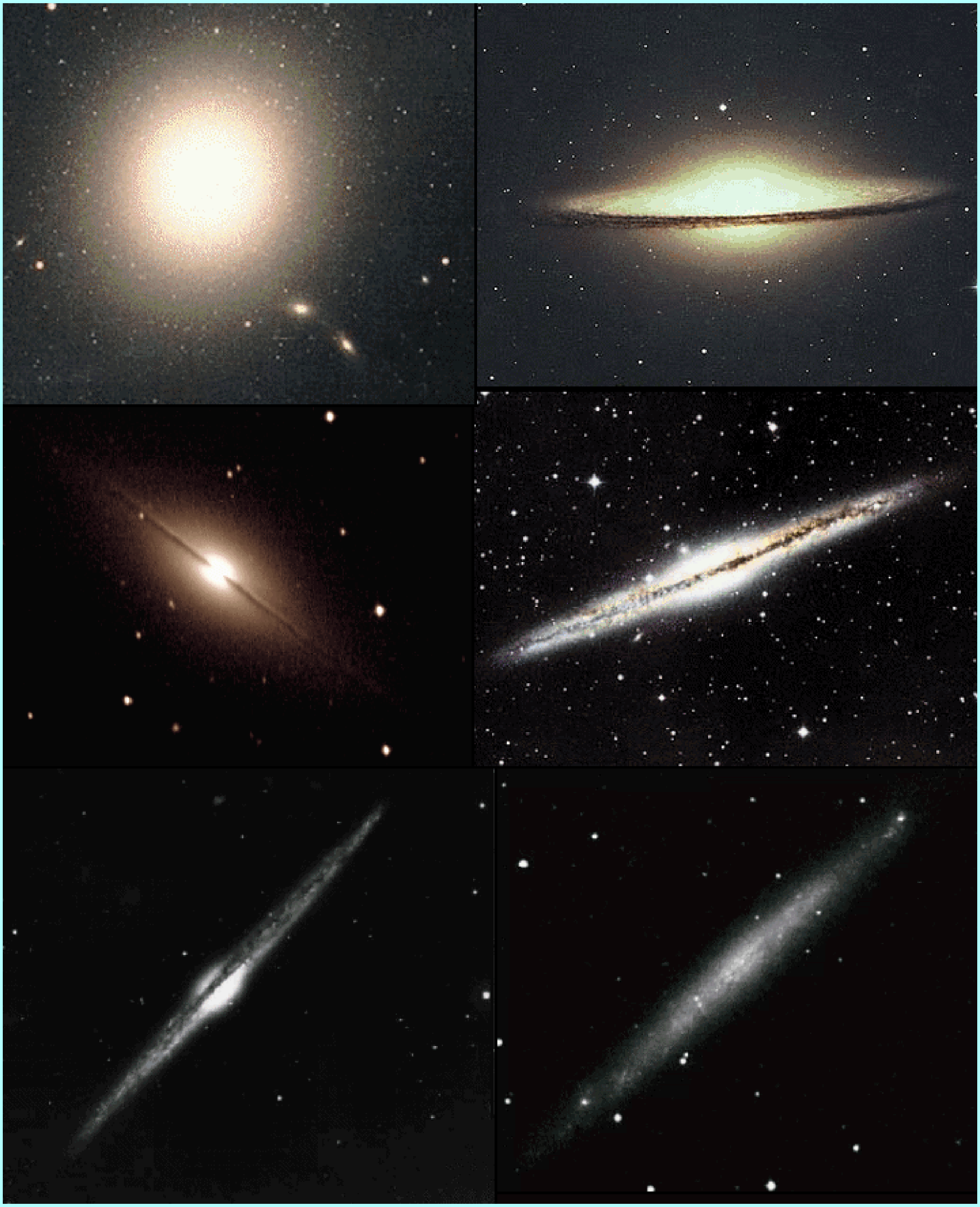
The Hubble Atlas has normal galaxies; the Arp Atlas has disturbed and interacting galaxies.



It follows that the Hubble sequence is one according to the relative importance of the two fundamental populations.

Some pictures of galaxies with modern telescopes.

A set of pictures of edge-on galaxies along the Hubble sequence.



Van den Bergh introduced luminosity classes on the basis of the development of the spiral structure. For late types it partly coincides with de Vaucouleurs' types:
Sd $\sim$ ScIII-IV ; Sm $\sim$ ScV/IrrV.

In the picture below on the left an ScI and on the right an ScIII.

There is indeed a general correlation between luminosity and vandenBergh class within a particular Hubble type.

The Yerkes or Morgan classification is now mainly of historical interest.

The complete scheme uses three criteria:

- Concentration of the light to the center, which was found to correlate with the occurence of features in the absorption spectra. It is designated by the closest stellar spectral type as a, af, f, fg, g, gk or k.

- Form as S (spiral), B (barred), E (elliptical), I (irregular), R (rotationally symmetric), or D (diffuse outer envelope).

- Flattening, indicated by a number from 0 to 6.

Also the prefix c is sometimes used for a supergiant galaxy.

The only surviving indication is cD for giant galaxies in the centers of clusters.

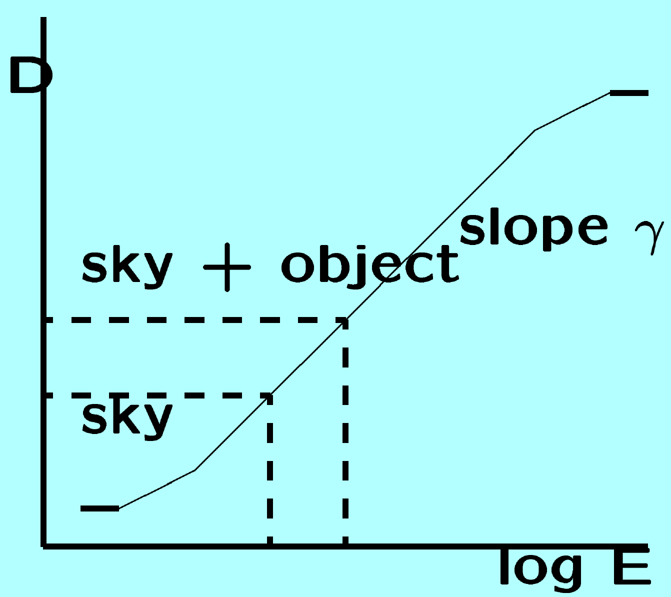
Surface photometry

a. Photographic (mostly for historical interest).

It relies on the possibility to derive an accurate characteristic curve of the photographic plate.

This is done by taking on the same plate exposures of a set of spots with known intensity ratios or a continuous wedge with known intensity gradient.

This has to be done for about the same exposure time because of low intensity reciprocity failure.



The procedure of photographic surface photometry is:

- Digitize the plate. You need a machine to accurately measure the "photographic density" D over many pixels. Density is minus the logarithm of the percentage of light coming through the emulsion, so $D = 0$ means completely clear, $D = 1$ only 10%, etc.

- Determine the characteristic curve. This is the relation between D and the "exposure" E. This is the total amount of light that fell onto the emulsion.

- Fit the sky background. This is a polynomial fit to the density of sky outside the object and in between stars.

- Zero-point calibration of the magnitude scale. This must be done separately from aperture photometry (usually from the literature).

The photographic plate is a-linear and has a limited dynamic range.

However, note that in the linear part of the characteristic curve

$$D = \gamma \log E + \text{constant}$$

$$D_{\text{sky}} = \frac{\gamma}{2.5}\mu_{\text{sky}} + \text{constant}$$

with μ in mag arcsec $^{-2}$.

$$I_{\text{object}} = I_{\text{sky}} \left(\frac{\ln 10}{\gamma}\right) \Delta D$$

$$D_{\text{sky + object}} = D_{\text{sky}} + \Delta D$$

Take $\Delta D \ll D_{\text{sky}}$, then

$$\Rightarrow \mu_{\text{object}} - \mu_{\text{sky}} = 2.5 \log \left(\frac{\ln 10}{\gamma}\right) + 2.5 \log \Delta D$$

For two faint outer parts

$$\mu_1 - \mu_2 = 2.5 \log \left(\frac{\Delta D_2}{\Delta D_1}\right)$$

So for faint objects the magnitude scale is independent of γ.

b. Digital.

Charge Coupled Devices (CCD's) are now the detectors used almost exclusively.

Each pixel has a number of electrons proportional (or almost equal) to the number of photons received.

The procedure of CCD surface photometry is:

- Bias subtraction. Even when not exposed, the CCD records electrons. So, you have to take separate "bias-frames" with the shutter closed.

- Remove bad pixels. These are due to cosmic rays. In practice the maximum exposure is of order half an hour. So, you take separate frames and add these later.

- Flat-fielding. Correction for sensitivity changes between pixels. For this you take an exposure on a uniformly illuminated screen in the dome or an exposure of the twilight sky.

- Sky subtraction. Fit the background sky and subtract.

- Calibration. You take frames during the same night of standard stars with known magnitudes.

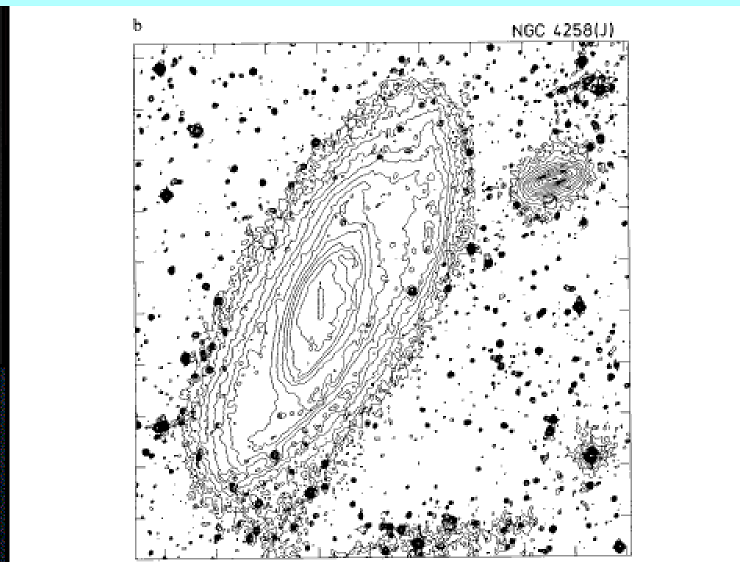
Photographic plates have a large size in terms of pixels and a-linearity is not a fundamental problem.

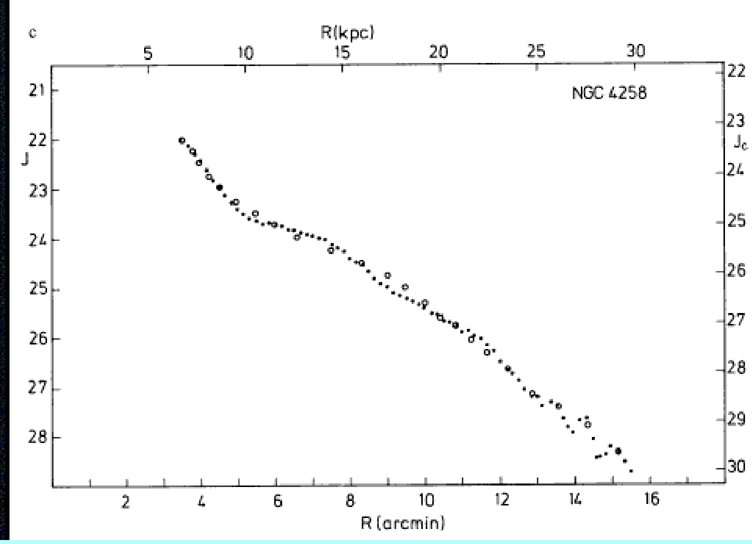
The disadvantages of photographic plates that have been overcome by digital techniques are:

• Need to digitize.
• Low quantum efficiency (no more than 15% or so, while CCD's go up to close to 100%).
• Background non-uniformities cannot be corrected for.
• Limited dynamic range.
• Separate zero-point calibration required using aperture photometry.

Here are some examples of photographic surface photometry.

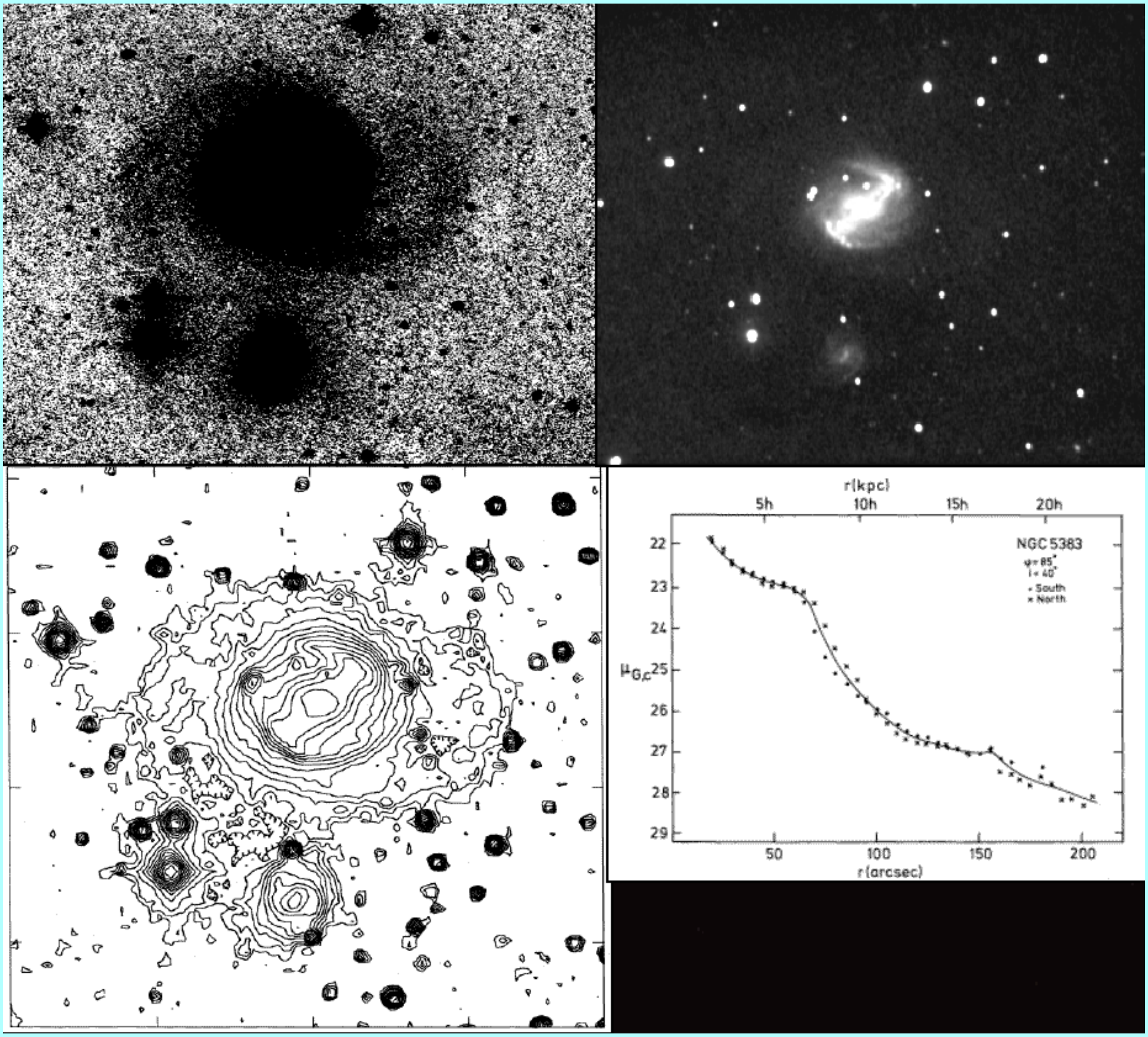
NGC 4258 is a large spiral. Here we have the photographic J-band (close to standard B).* The scale on the azimuthally averaged radial profile is in magnitudes per square arcsec. For the sky this is about 22.5 at a dark site.





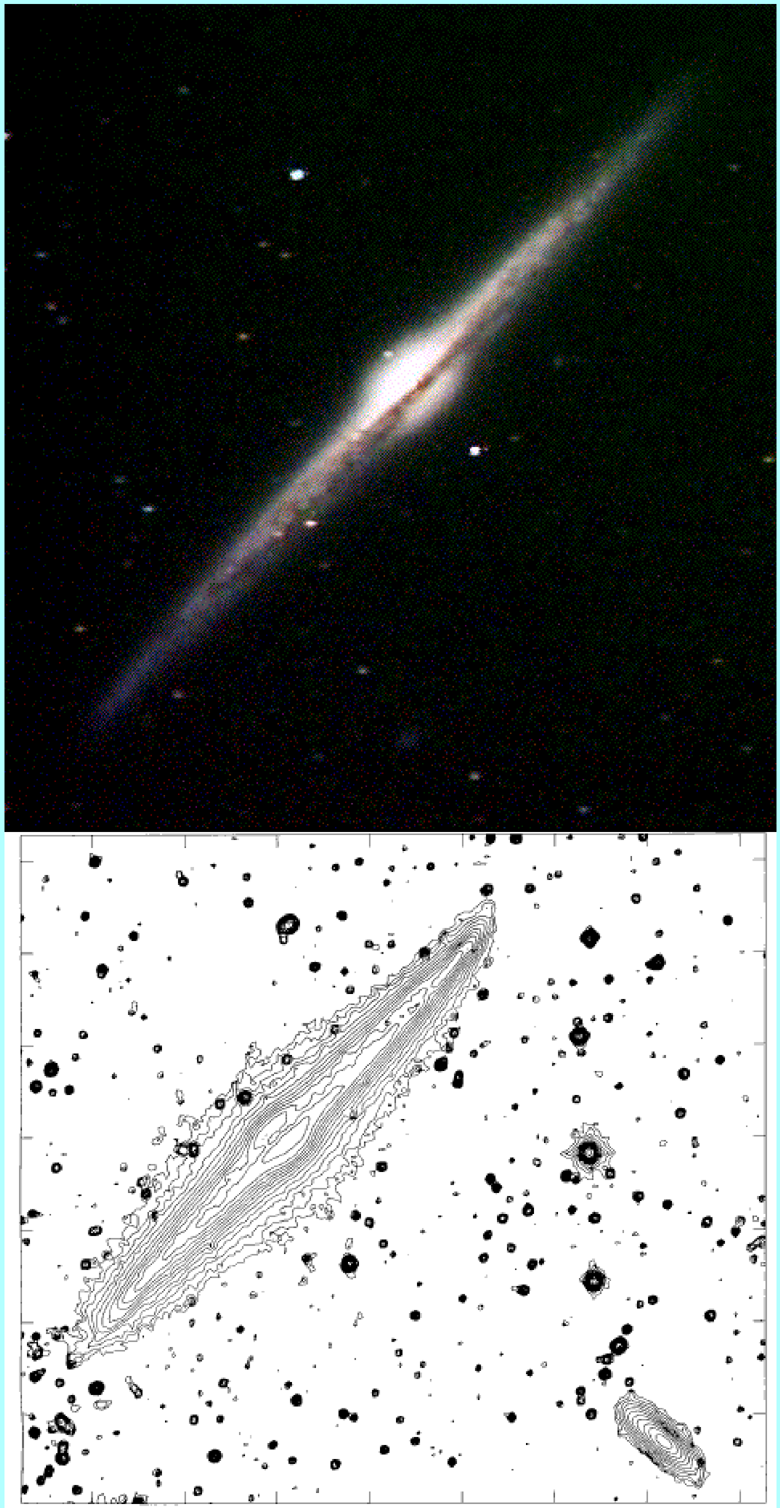
*van der Kruit, A.&A.Suppl. 38, 15 (1979)

The barred spiral NGC 5383.*



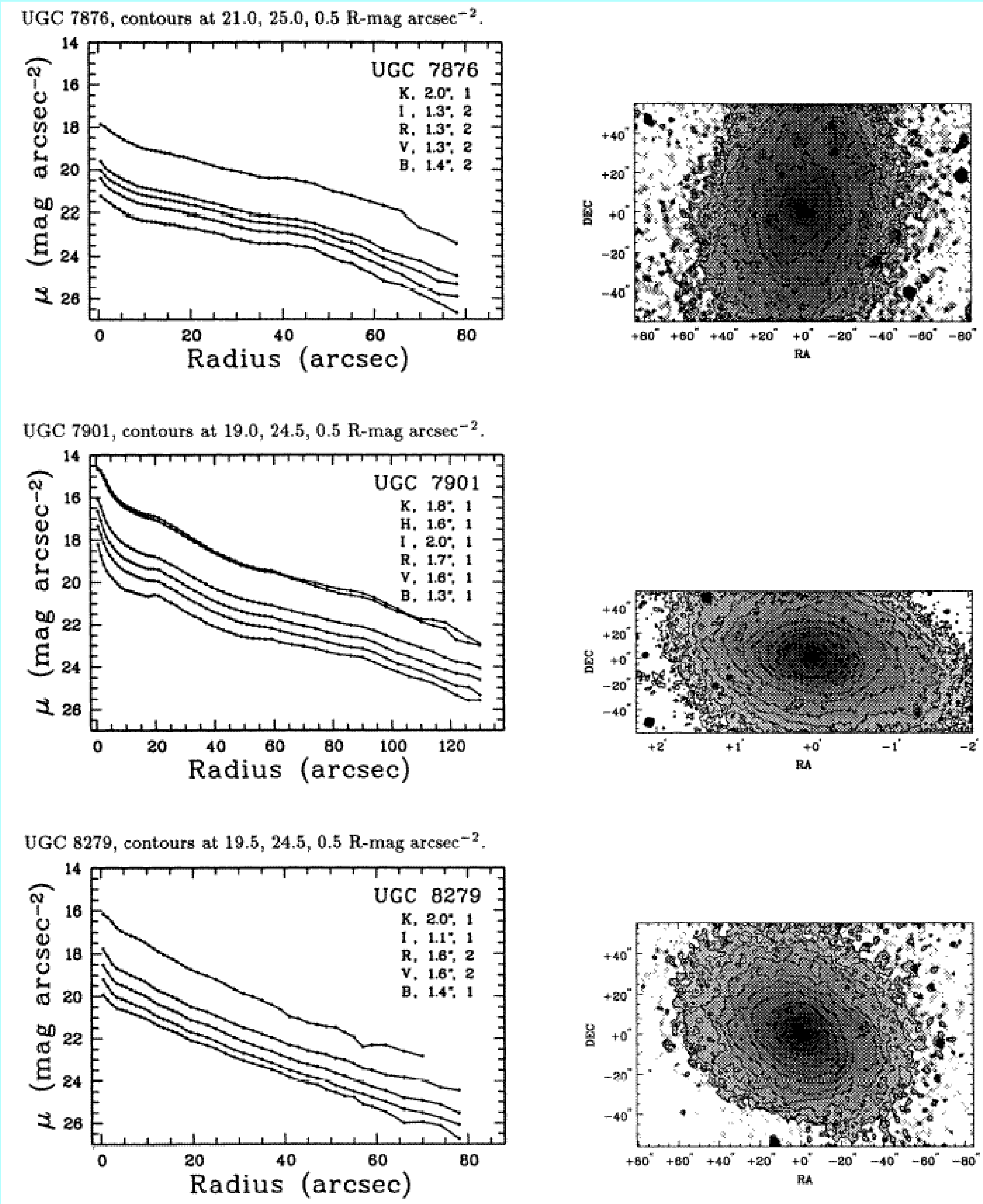
*van der Kruit & Bosma, A.&A. 70, 63 (1978)

The edge-on galaxy NGC 4565.*



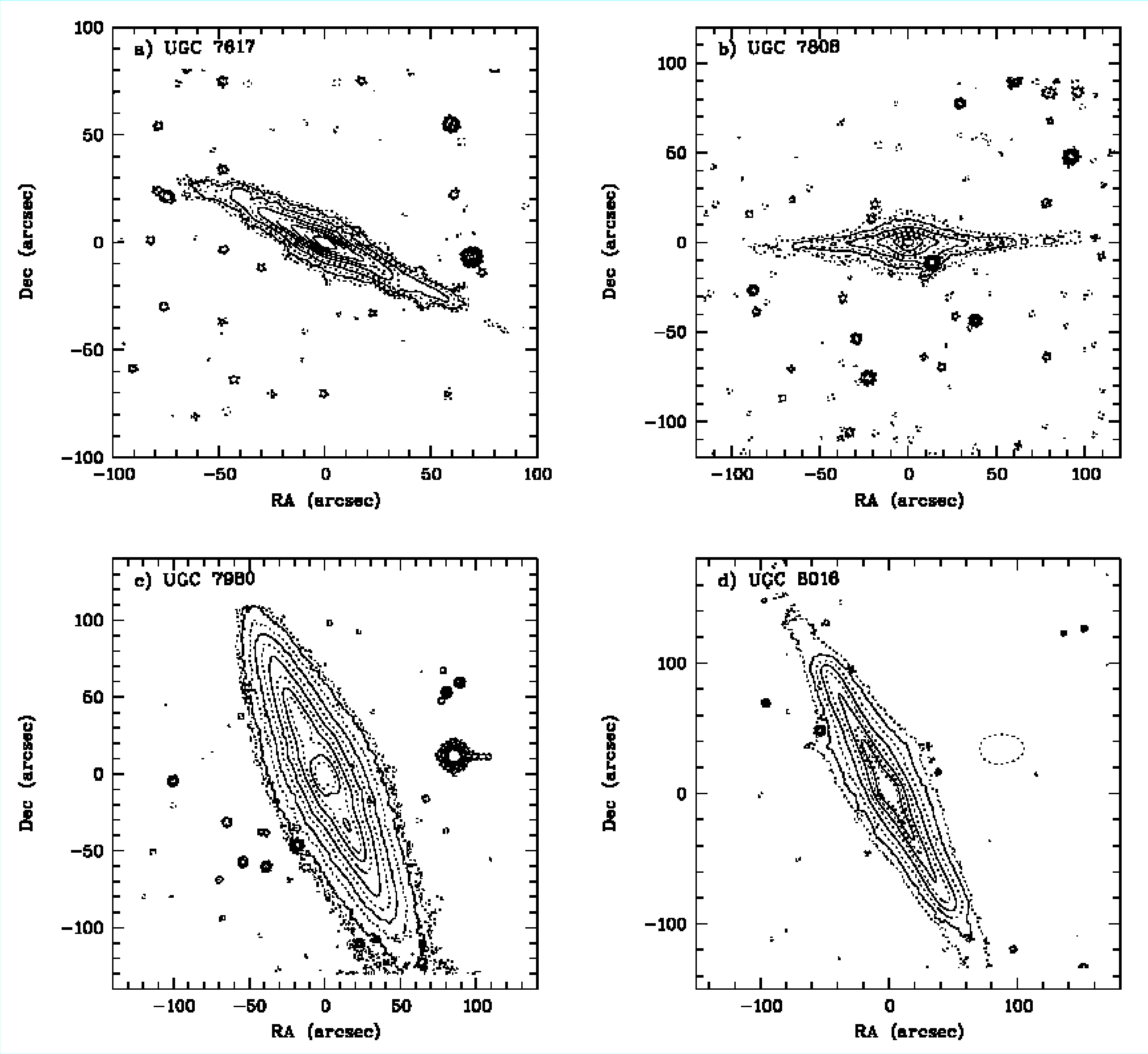
*van der Kruit, A.&A.Suppl. 38, 15 (1979)

The following shows some results from CCD photometry.*



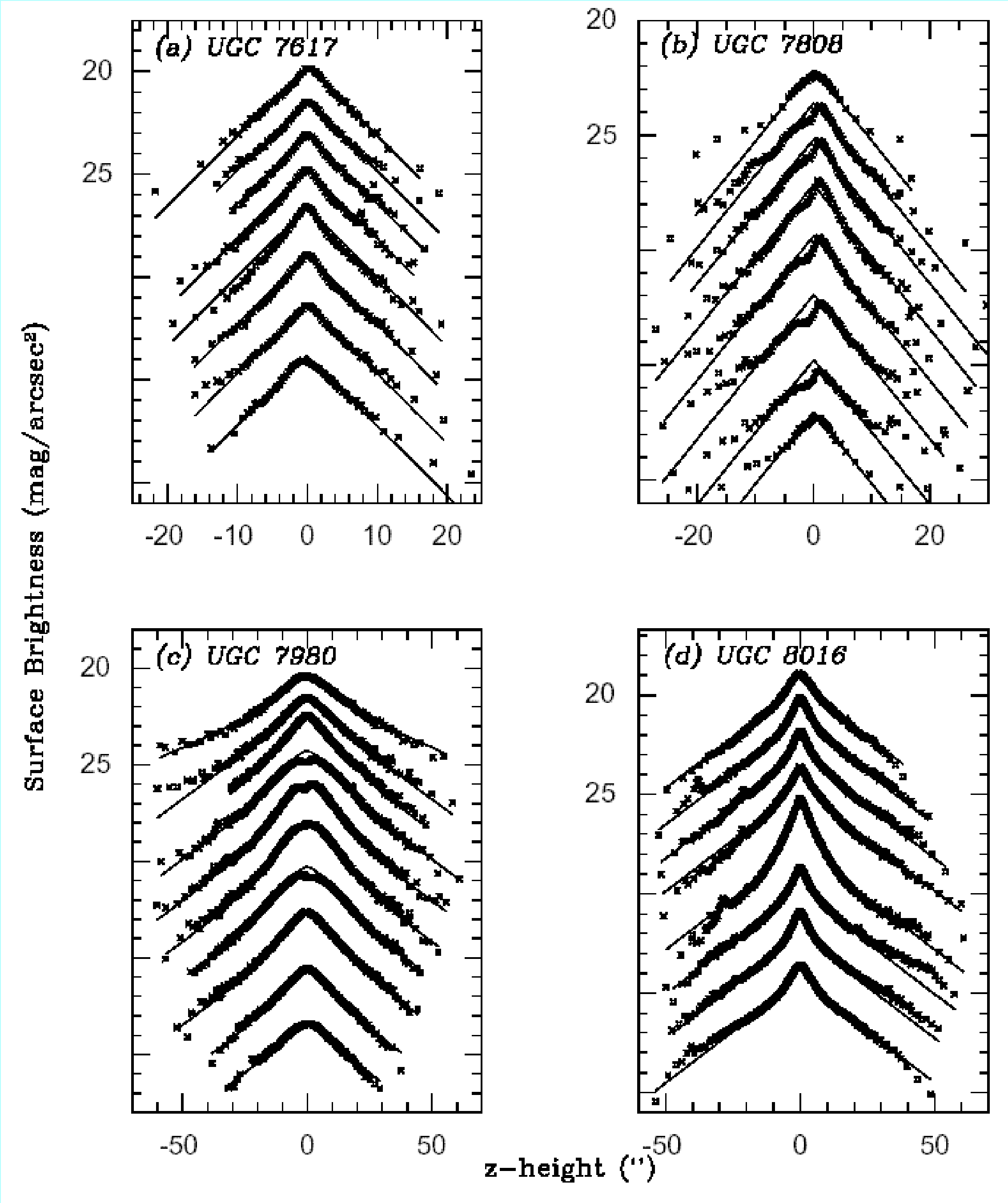
*de Jong & van der Kruit, A.&A.Suppl. 106, 451 (1994)

Here a set of edge-on galaxies.*



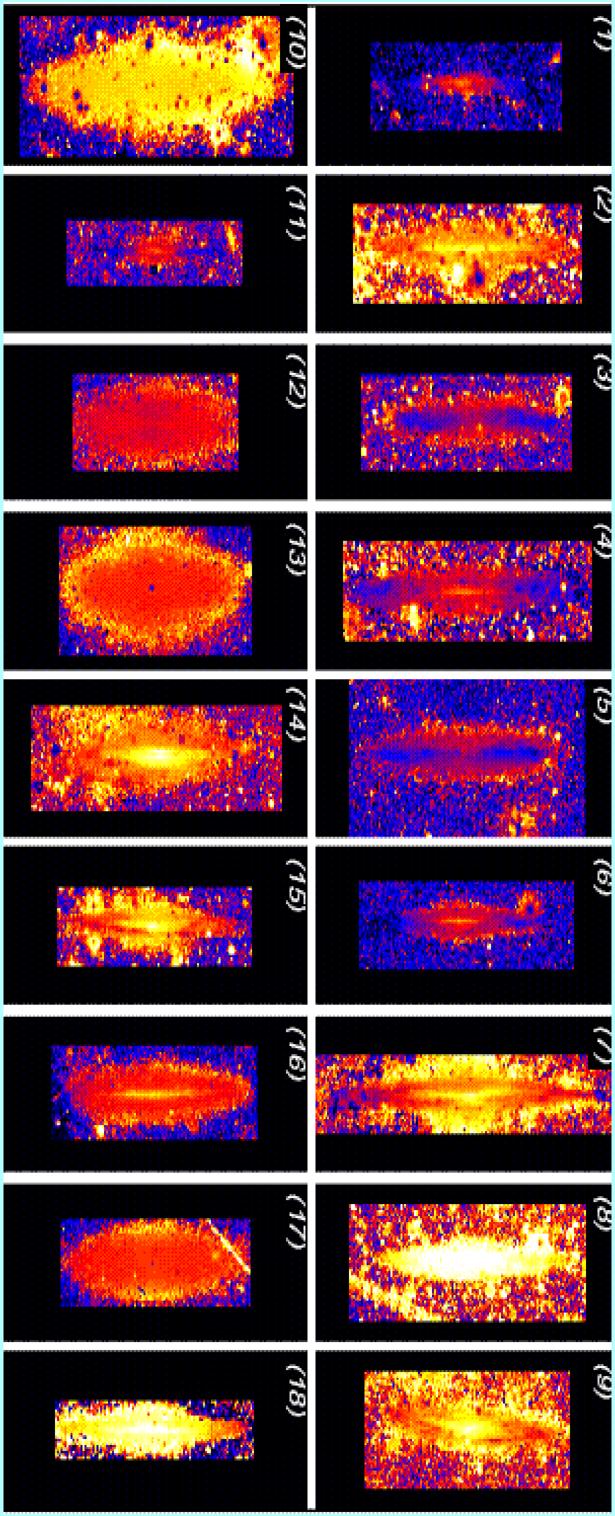
*de Grijs & van der Kruit, A.&A.Suppl. 117, 19 (1996)

Vertical profiles in edge-on galaxies at various distances from the center.*



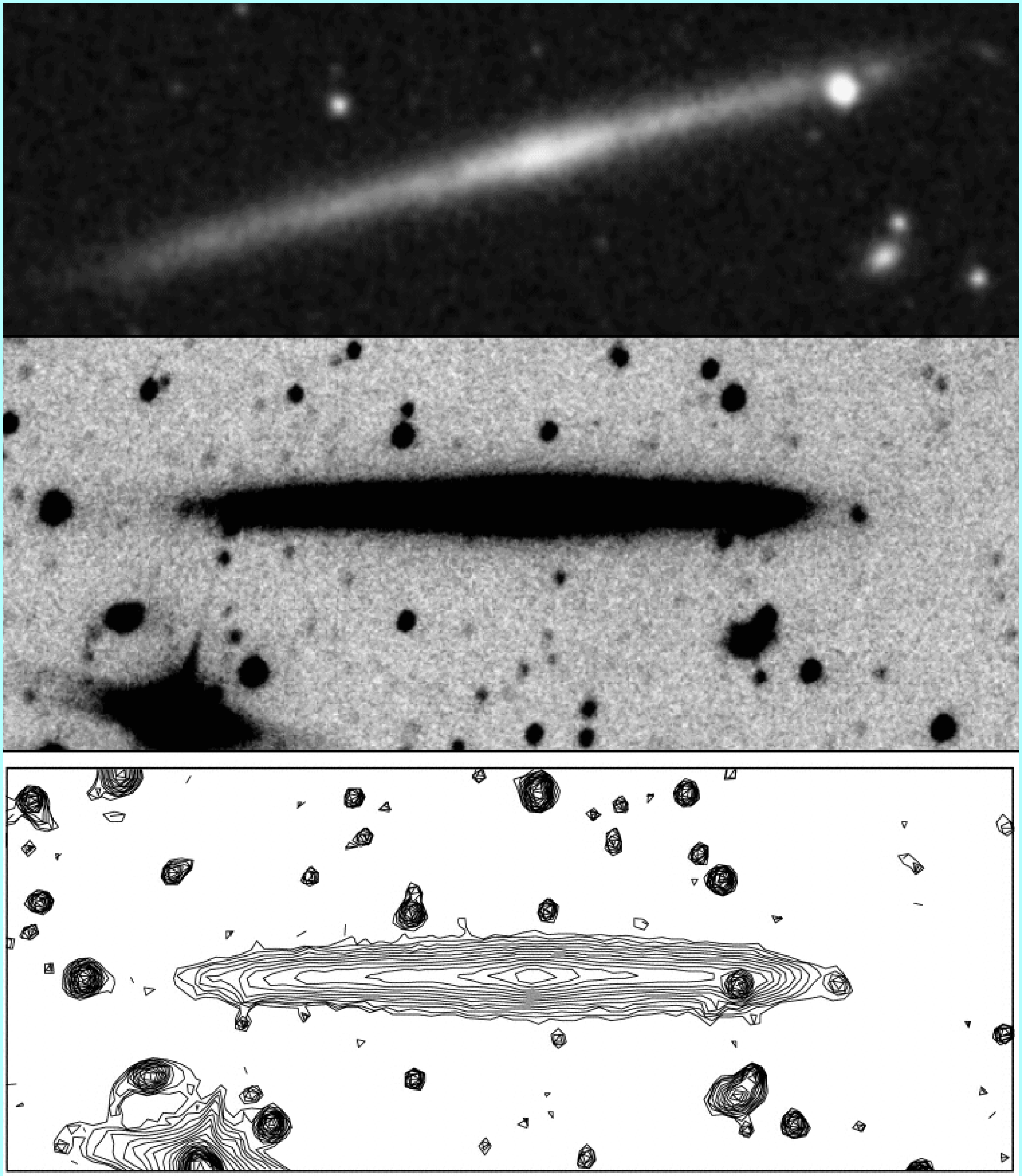
*de Grijs & van der Kruit, A.&A.Suppl. 117, 19 (1996)

Maps of color index in edge-on galaxies.*



*de Grijs, Peletier & van der Kruit, A.&A. 327, 966 (1997)

The “super-thin” edge-on galaxy IC 5249.*



*van der Kruit, Jiménez-Vicente, Kregel & Freeman, A.&A. 379, 374 (2001)