Galaxy formation ⟷ Galaxy classification

Generally, the systematic categorization of properties of objects (taxonomy) is an early stage in the development of a science. Later work then focuses on physical (biological, ...) processes and origins.

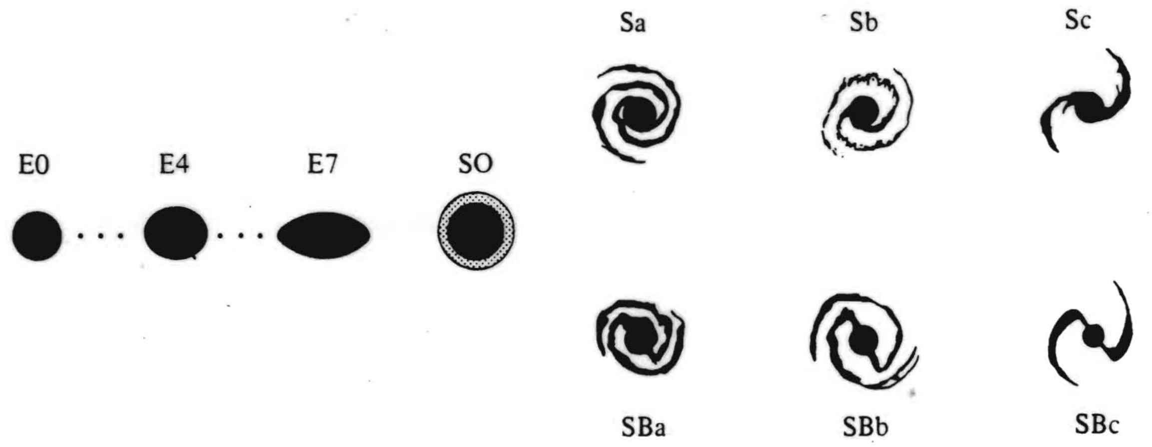
Q What are some examples, from within astronomy & from outside it?

Q What distinguishes a good classification scheme from a bad one?

An early (and influential) classification scheme for galaxies was based on morphology only: the Hubble classification.

Based on optical properties only

The Hubble sequence



...... for the obvious galaxies

Ellipticals : smooth, round → flattened
featureless, reddish
centrally concentrated; may be triaxial

SO's : intermediate between E & S
smooth, little dust usually, has disk

Spirals : classified by bulge-to-disk ratio
gas content also varies Sa – Sc
roughly half have bars
gas content ↔ ongoing star formation

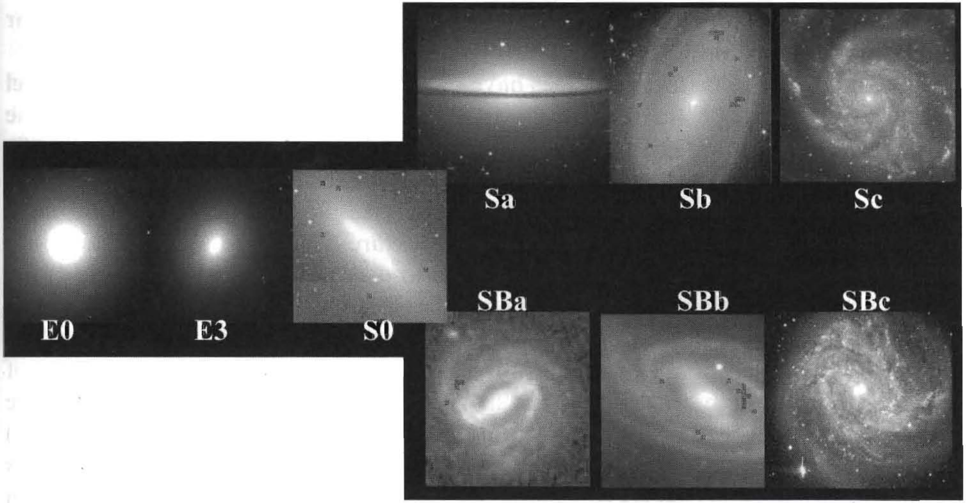


Figure 2.2. Hubble's tuning-fork diagram, filled in with galaxies. This collection of galaxies spans the classical Hubble types, illustrating the changes in bulge-to-disk prominence and spiral pattern along the sequences. Beyond this original set of types, and not shown here, are even less organized Sd/SBd spirals plus their corresponding irregular galaxies. These are optical images, close or identical to the photographic bands used to define Hubble's classifications. (Data by the author, from Kitt Peak and Lowell; from Greg Bothun; and taken from the Digitized Sky Survey, taken by the Oschin Schmidt Telescope on Palomar Mountain, with compression and distribution by STScI.)

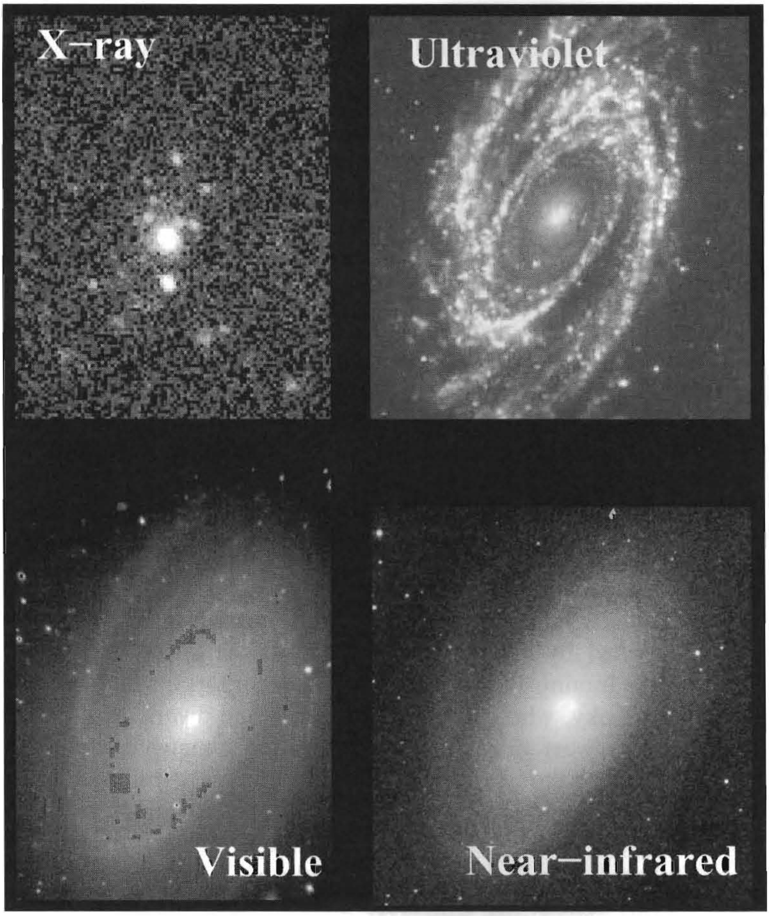


Figure 2.3. The changing appearance of galaxies in different parts of the electromagnetic spectrum is illustrated by this series of images, showing the nearby spiral galaxy M81. In X-rays, only the active nucleus and accreting compact objects in binary systems (white dwarfs, neutron stars, and black holes) appear, with no hint of the rich stellar structure. In the ultraviolet, only the hottest (unobscured) stars are bright, so that the spiral pattern can be traced via star-forming regions, but the central bulge of old stars has almost vanished. This appearance resembles some spiral galaxies seen at large distances, where the redder bulge light has shifted out of the optical bands. The familiar visible-light image shows both the spiral pattern and the old bulge population, while in the near-infrared, the spiral pattern and star-forming regions are much more subdued. This change in apparent structure with wavelength has been dubbed the "morphological K-correction". X-ray data are from ROSAT, extracted from the HEASARC archive at NASA's Goddard Space Flight center. The UV image is a combination of observations obtained by the GALEX satellite at wavelengths 1,500 and 2,300 Å, used courtesy of NASA. The optical images are reproduced courtesy of Greg Bothun. (The infrared data are from the 2-Micron All Sky Survey (2MASS), a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by NASA and the NSF.)

What Hubble Missed

Dwarf galaxies

There are dwarf equivalents of ellipticals and S0s. ~~spirals~~. Dwarf ellipticals are completely different: their luminosity is not as centrally concentrated

'Peculiar' galaxies

Defy classification; many of these are ongoing mergers

Later types: Sd, Sm, Irr

Magellanic spirals intermediate between spirals & irregulars.

Low surface brightness galaxies (LSBs)

There are galaxies with low luminosity density (# of stars per unit area) which are dwarf ellipticals, and some disk galaxies too. Perhaps half of all galaxies are LSBs

Night sky brightness

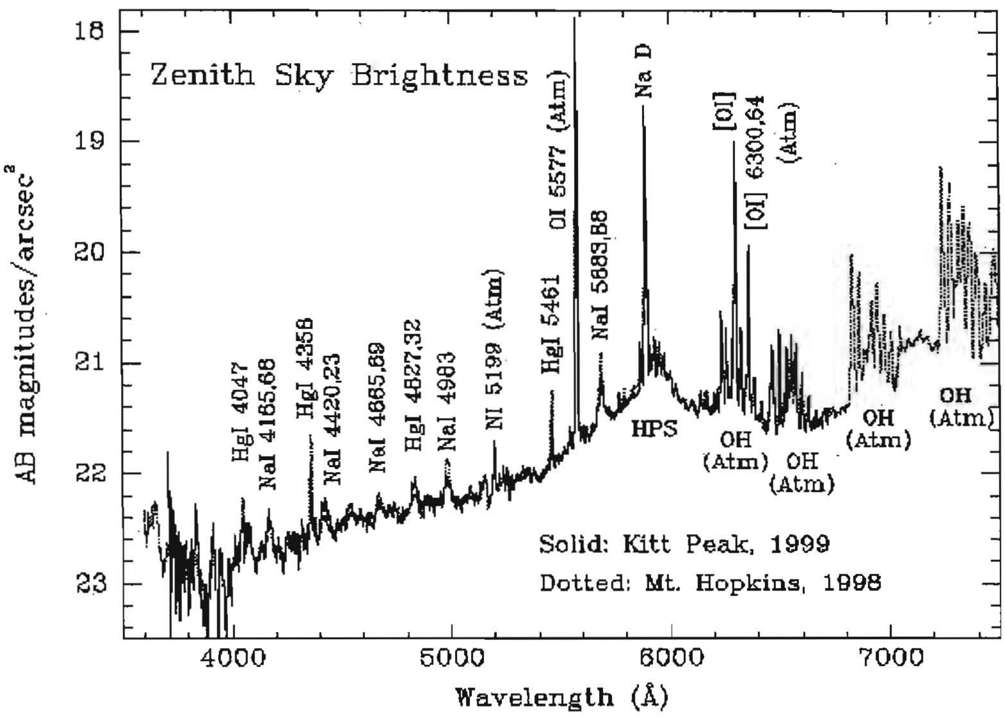
Even when there is no moon, the night sky has a finite brightness.

For very faint objects, this limits observations more than photons collected

Sources

- City lights
- Airglow — emission lines from upper atmosphere, irregular, variable worst in infrared
- Faint & unresolved stars in our Galaxy
- Distant, faint, unresolved galaxies
- Zodiacal light

The Spectrum of the Night Sky



In 1990 I published a study of the Kitt Peak night sky using absolute spectrophotometry (Massey, Gronwall, & Pilachowski 1990 PASP, 102, 1046) . About 10 years later, Craig Foltz and I revisted the issue (Massey & Foltz 2000 PASP, 112, 566) . Typical night-sky spectra can be found at here for the blue and here for the red.

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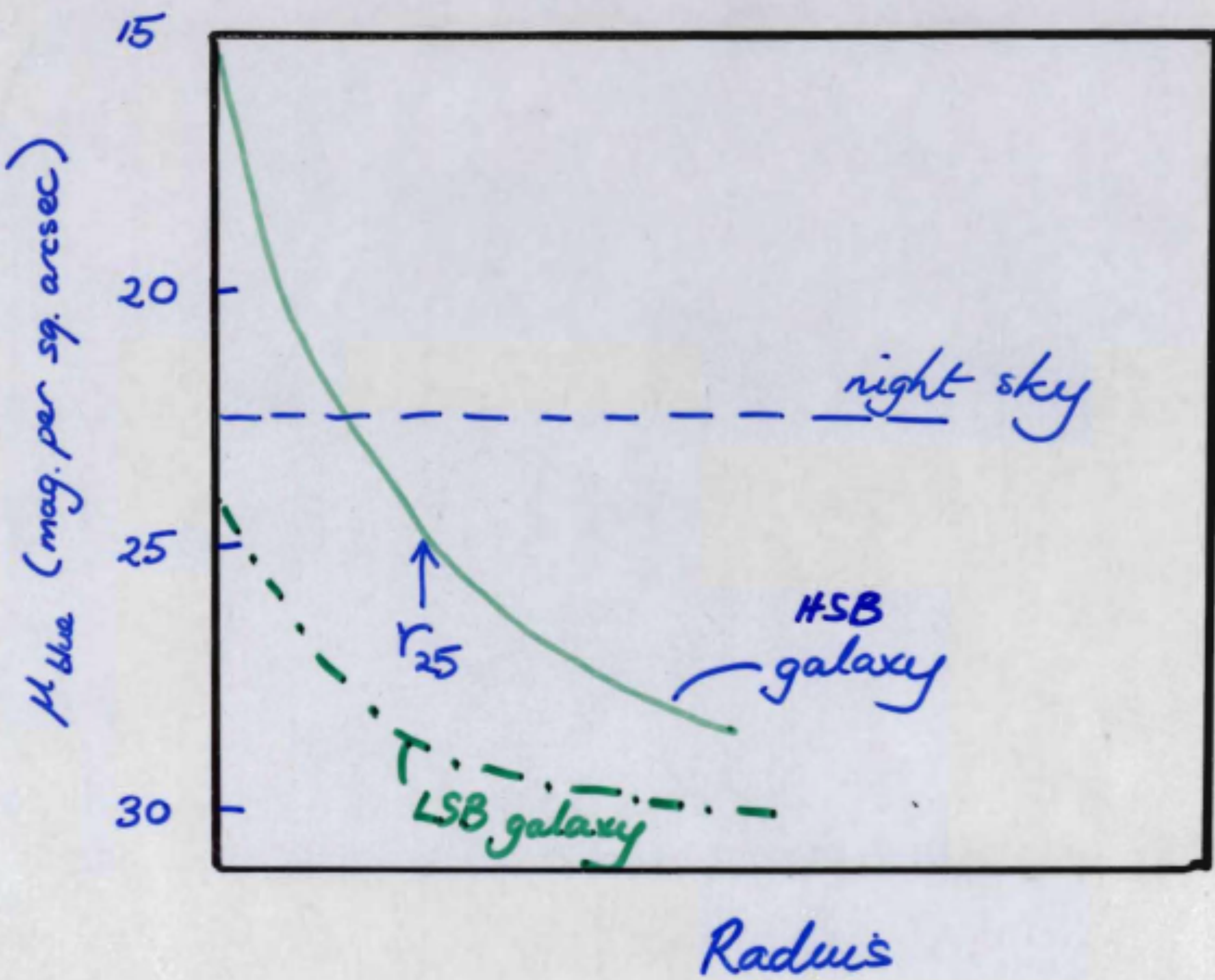
Last updated April 24, 2004



Observations in 90's : CCD imagers (optical λ)
IR arrays ($1-5\mu$)

Only the brightest portion of most galaxies is brighter than night sky.

Low surface brightness galaxies

Note that ellipticals (and bulges) generally have higher central surface brightness than disks

* Surface brightness doesn't correlate with mass *

although the lowest surface brightness galaxies originally discovered were dwarf spheroidals

But there are massive galaxies with low surface brightness .....

Bothun et al AJ 94, 23 (1987)

de Blok et al MNRAS 274, 235 (1995)

Malin 1

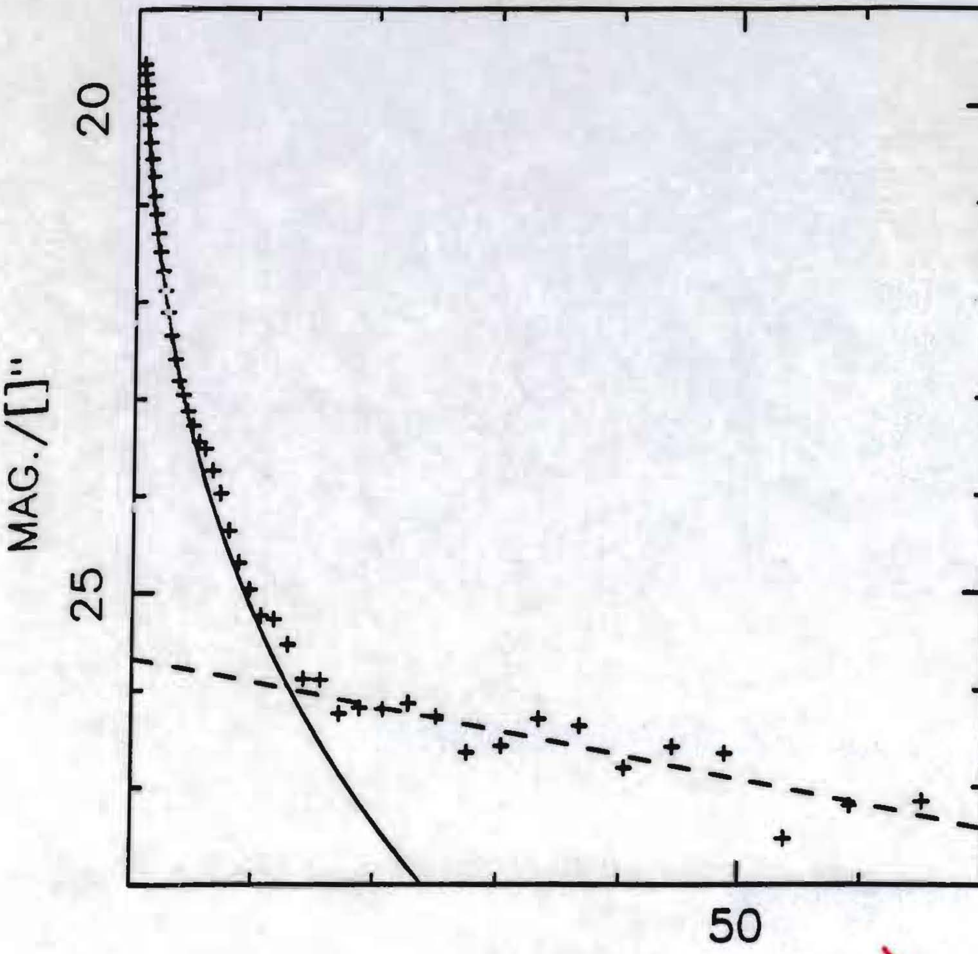


FIG. 3. V band luminosity profile. The solid line indicates the best-fitting $r^{1/4}$ component while the dashed line corresponds to the exponential disk. The fits are schematic only, as the total luminosity profile does not readily deconvolve into distinct components. Radius is in arcsec.

Malin 1 has relatively normal bulge

Disk is large, and almost constant in surface brightness with radius

(originally thought to be a dE in Virgo)

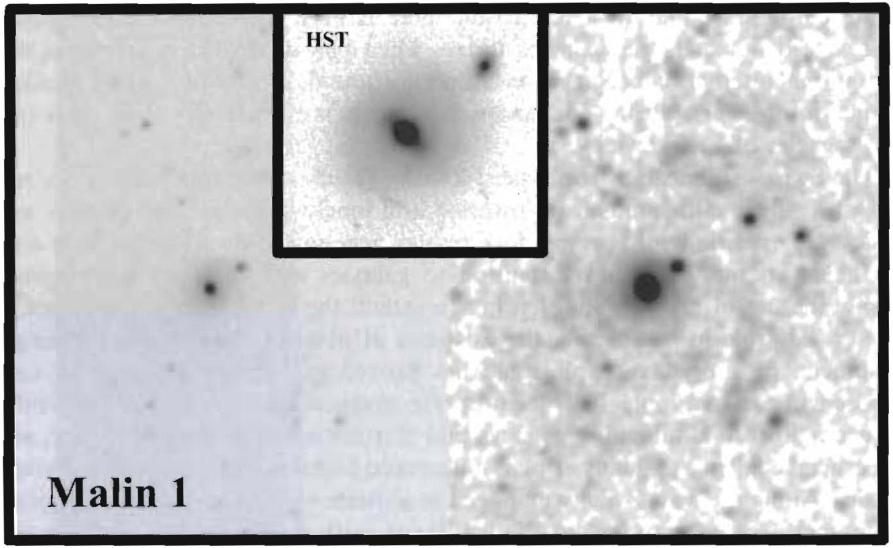


Figure 2.4. The prototype giant low-surface-brightness (LSB) galaxy Malin 1. A typical exposure depth (*left*) shows only the nucleus and bulge of the galaxy. Smoothing the image and stretching the intensity by a factor of ten (*right*) reveals the extensive and patchy spiral structure which extends over a much wider area, visible over a diameter of 200 kiloparsecs and well into the massive disk of neutral hydrogen. (The inset is from a Hubble image in red light, showing the distinct bar and spiral structure marking a "normal" disk at the center of the huge LSB structure. The wide-field blue-light image was obtained by Greg Bothun at the 1.3-meter telescope of MDM Observatory. HST image from the archive, from a program with Chris Impey as PI.)

Galaxy classification

The Hubble classification serves as the basic language of the field.

The morphological sequence reflects fundamental physical differences in structure & evolution.

(or does it ??)

Most galaxies can be classified into relatively few categories.

Multivariate analysis techniques show 2 principal categories of galaxy parameters:

- measures of absolute scale, such as size, mass, luminosity
- measures of form (morphology)

The first requires good distance estimates, so Hubble concentrated on the second.

Physical properties along the Hubble sequence

Roberts & Haynes Ann. Rev. Astron. Astrophys 32 115 (1994)

* Note there are strong surface brightness selection effects in the catalogs this study is based on.

2 samples — magnitude (flux) limited
— volume limited

Intrinsically bright galaxies are over-represented in the magnitude-limited sample; ~~flux~~ volume-limited sample is smaller.

Error bars show interquartile range .... there is a large range in most properties at each Hubble type ..... but there are trends.

NB

Gas content

This shows a galaxy's potential for star formation

HI : neutral atomic hydrogen

(H II : ionized hydrogen , H_2 molecular hydrogen)

Late-type spirals and irregulars have a larger mass fraction of gas (as HI)

From colors it can be seen that such galaxies are usually actively forming stars.

Ellipticals & SO's — little HI.

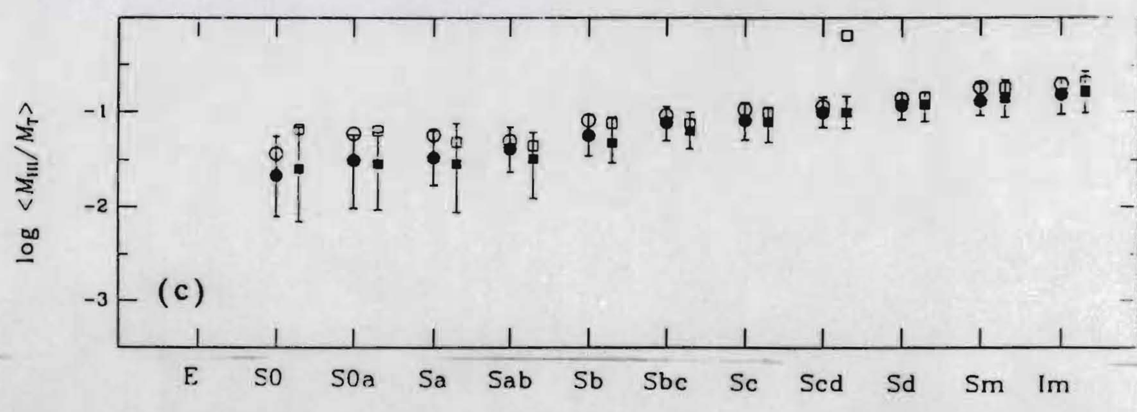


Figure 4 Same as Figure 2, for (*a*) log total HI mass M_{HI}, (*b*) log HI mass-to-blue luminosity ratio M_{HI}/L_B, (*c*) log HI mass fraction M_{HI}/M_T, (*d*) log FIR luminosity L_{FIR}. The dashed lines indicate significantly fewer data for these types.

Colon

Hubble first noted trend in color: ellipticals are reddest, irregulars bluest ...... a clear trend.

Color indicates age of galaxy's stars: in general, the youngest stars are blue, old and middle-aged stars tend to be redder.

Note also that young stars are very bright — even irregular galaxies usually have some old stars but they are faint by comparison

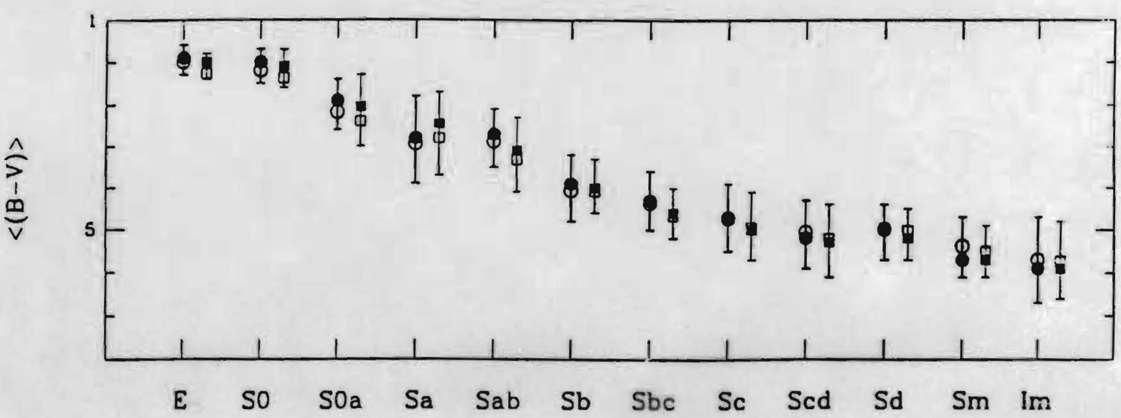


Figure 5 (B – V) color vs morphological type. (Same symbols as in Figure 2.)

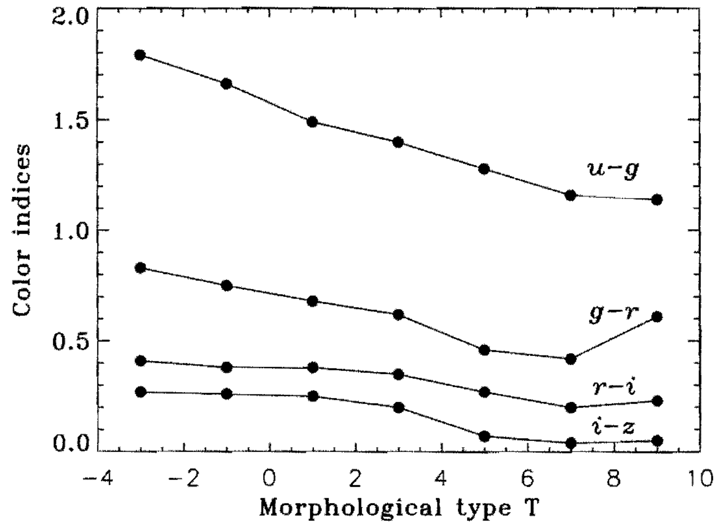


Figure 2.7. The color of galaxies along the Hubble sequence. The star-forming history of galaxies is traced by their broad-band colors. This is illustrated in these mean colors from a sample of 456 bright galaxies in the Sloan Digital Sky Survey, with the bands approximately at 3,500 Å (u), 4,800 Å (g), 6,250 Å (r), 7,700 Å (i), and 9,100 Å (z). Smaller differences among these magnitudes (color indices) denote a bluer spectral shape. The difference is most conspicuous at shorter wavelengths (as in $u - g$ color), since stellar evolution is most rapid for the more massive bluer stars. (Data from Shimasaku *et al.*, *Astronomical Journal*, **122**, 1238, 2001.)

has seen use in asking how local galaxy samples populate the *CAS* space, and in comparing this with samples at high redshift.

Such a pattern of grouping and quantifying galaxies through some small set of observable quantities, such as color, image concentration, and an index of image symmetry, takes us into the more abstract field of quantitative classification. For many years, a need has been expressed for fully quantitative and numeric ways to classify galaxies, not necessarily to supplant but more completely to supplement the classical morphological schemes such as the Hubble and de Vaucouleurs systems. Such parameters could, if we are fortunate, be linked directly to the dynamical components of galaxies, and be defined in ways that make them more robust to data quality and resolution than the usual visual classifications. As candidate systems have been proposed and evaluated, it is one measure of the lasting influence of the Hubble system that most of the quantities they derive have been shown plotted as functions of ... Hubble class. We may consider such interesting additional quantities as color of the stellar population, gas content per unit optical luminosity, normalized star-formation rate from Hα or far-infrared indicators, or mean rotational velocity, and in each case we see a clear correlation with galaxy type (as seen in sample quantities in Figure 2.7). The color dependence can be so strong that color is often used as the independent variable in studies of galaxy populations, as a proxy for the star-forming history of a system (Chapter 4).