Chapter 3

Morphology and Environment

Galaxy morphology is a traditional subject with a modern field of research trapped inside. Galaxies have traditionally been classified by comparison with well-defined reference samples. The environment of a galaxy is correlated with its morphology; loose groups and poor clusters contain mostly disk galaxies, while compact groups and rich clusters have large numbers of elliptical galaxies. Classification schemes based on local examples, including the Hubble system, are being replaced by quantitative measures of morphology as investigations probe the universe at redshifts of $z = 0.5$ and beyond.

3.1 Classification Systems

Here I summarize four general and widely-used schemes of galaxy classification. These systems are more completely described by Sandage (1975) and van den Bergh (1998); also see Mihalas & Binney (1981; hereafter MB81, pp. 286–345), BT08 (pp. 20–29), and Binney & Merrifield (1998; hereafter BM98, pp. 145–172).

3.1.1 The Hubble System

Hubble's classification system is described in the *Hubble Atlas of Galaxies* (Sandage 1961). The wonderful large-scale galaxy photos in this atlas serve as examples of each type; galaxies of unknown type are classified by comparison with these examples.

The classic 'tuning-fork' diagram (Fig. 3.1) illustrates the main types within Hubble's scheme. **E** galaxies are nearly featureless objects with elliptical isophotes. **S0** & **SB0** galaxies are essentially

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          S0 --- Sa --- Sb --- Sc
         /                       .
E0 --- E7                         Ir
         \                       .
          SB0 -- SBa -- SBb -- SBc
```

Figure 3.1: Hubble's 'tuning-fork' diagram.

disk galaxies without spiral structure. **S** & **SB** are spiral galaxies, while **SB0** & **SB** galaxies have strong central bars. Finally, **Ir** galaxies have irregular forms; these objects may be connected to late-type spirals through the provisional Sd type.

E galaxies are graded from **E0** to **E7** by apparent axial ratio. Let a and b be the major and minor axies of a typical isophote; the number following the **E** symbol is $\lfloor 10(a-b)/a \rfloor$. Thus E0 galaxies are nearly round, while E7 galaxies are highly flattened. Of course, the flattening we observe depends on viewing angle – the same galaxy might be classified as E0 when viewed pole-on, and E7 when viewed edge-on!

In contrast, the grading of **S** galaxies into subtypes **Sa**, **Sb**, and **Sc** (and the parallel grading of **SB** galaxies) is based on (i) relative bulge size, (ii) pitch angle of spiral arms, and (iii) 'resolution' of arms. For example, typical Sa and SBa galaxies have large bulges and tightly-wound spiral arms which appear rather smooth, while typical Sc and SBc galaxies have small bulges and loosely-wound spiral arms which are highly resolved. For the most part, bulge size, pitch angle, and resolution are well correlated, but atypical cases exist and confound Hubble's scheme. For example, it's not clear what subtype to assign a galaxy with a large bulge and a loosely-wound spiral pattern!

The grading of E galaxies by apparent axial ratio is objective and unambiguous; it is also rather superficial. On the other hand, the grading of S and SB galaxies, while somewhat subjective, reflects real physical distinctions.

The status of S0 galaxies is problematic. These galaxies were originally introduced to provide a smooth a transition between the E and Sa types. But typical S0 galaxies are one or two magnitudes fainter than typical Sa or E galaxies, respectively (van den Bergh 1998, p. 61). Moreover, S0 galaxies have a range of bulge sizes roughly paralleling the progression of bulge sizes along the Sa – Sb – Sc sequence.

3.1.2 The de Vaucouleurs System

The *Reference Catalog of Bright Galaxies* by de Vaucouleurs & de Vaucouleurs (1964) adopted a galactic classification scheme with a finer level of discrimination than Hubble's system. This system locates each galaxy within a lemon-shaped 3-D classification volume; the major axis of the lemon defines a progression from *ellipticals* to *lenticulars* to *spirals* to *irregulars* roughly analogous to Hubble's E – S0 – S – Ir sequence. Each slice perpendicular to the major axis defines a 2-D space of possible forms including various combinations of spirals, bars, and rings. The de Vaucouleurs system also interpolates Sd and Sm types between spirals and irregulars.

For convenience, later editions of the *Reference Catalog* (de Vaucouleurs, de Vaucouleurs, & Corwin 1976; de Vaucouleurs et al. 1991) define a numerical type T which basically locates a galaxy's position along the major axis of the classification volume. The relationship between T and galaxy type is shown in Table 3.1.

3.1.3 The DDO System

The DDO system, developed by van den Bergh (1960a,b), introduces 'quality and length of spiral arms' as a proxy for luminosity. This explicitly recognizes that luminosity and morphological type are not entirely decoupled from one another. Most of the galaxies used to define Hubble types are relatively luminous, but fainter galaxies don't always conform to Hubble's scheme. Fine distinctions

de Vaucouleurs	E	E^+	$S0^-$	$S0^\circ$	$S0^+$	S0/a	Sa	Sab
T	-5	-4	-3	-2	-1	0	1	2

de Vaucouleurs	Sb	Sbc	Sc	Scd	Sd	Sdm	Sm	Im
T	3	4	5	6	7	8	9	10

Table 3.1: Definition of numerical type *T*, from the RC3.

along the Sa – Sb – Sc sequence collapse into a coarse scheme of ‘early’ (S$^-$), ‘intermediate’ (S), and ‘late’ (S$^+$) types at lower luminosities. At very low luminosities only rough distinctions between E, S, and Ir galaxies can be recognized.

In the ‘trident’ diagram (Fig. 3.2) the horizontal axis indicates degree of central concentration or bulge/disk ratio; **E** galaxies are the most concentrated, while **Ir** galaxies are the most spread-out. The vertical axis indicates strength of spiral structure; **S0** galaxies show no spiral patterns, **A** galaxies have low-contrast spirals, and **S** galaxies have strong, well-defined spirals. Barred disk galaxies are indicated by a **B** after the S0, A, or S. Finally, late-type galaxies are graded by the appearance of their spiral arms into luminosity classes **I** to **III** (for Sb galaxies) or **I** to **V** (for Sc galaxies).

The primary dimensions of this system all correlate with physical characteristics of galaxies. As in Yerkes system, central concentration correlates with stellar population. The sequence S0 – A – S is a progression in neutral hydrogen gas content. The luminosity classes roughly correspond to 1 mag steps in absolute magnitude, with class I being most luminous.

3.1.4 The Yerkes System

Developed at Yerkes observatory (Morgan 1958), this scheme is motivated by a correlation between the central concentration of a galaxy’s light and the dominant spectral class of its stellar population (Morgan & Mayall 1957). Galaxies with spread-out luminosity profiles exhibit spectral absorption features typical of A stars, while those with highly-concentrated profiles generally have spectral features of K stars. While this classification scheme is based on the appearance of galaxies, it labels them according to anticipated spectral type. The complete scheme employs three classification dimensions:

- *concentration*, designated by the letters **a**, **af**, **f**, **fg**, **g**, **gk**, **k**;

```
    S0a -- S0b -- S0c
  /
 /
E - Aa --- Ab --- Ac
 \
  \
    Sa --- Sb --- Sc --- Ir
```

Figure 3.2: van den Berghs’ ‘trident’ diagram.

- *form*, which may be **S** (spiral), **B** (barred), **E** (elliptical), **I** (irregular), **R** (rotationally symmetric), or **D** (diffuse outer envelope);
- *flattening*, ranging from 0 to 7 as in Hubble's system.

cD galaxies are a special case, with very extended outer envelopes not apparent in short exposures. Here the 'c' prefix indicates a supergiant galaxy.

3.2 Environmental Connections

Galaxies are not distributed at random – they occur in pairs, groups, and clusters containing up to $\sim 10^3$ members. These systems define the environments in which galaxies are formed and transformed.

3.2.1 Galaxy environments

- Loose groups contain the majority of all bright galaxies. Our own Local Group is a good example of a very loose group – it contains three fairly conspicuous spirals and many small galaxies, most of which are dwarf spheroidal or irregular systems (see SG07, Table 4.1). There is tantalizing evidence for intergalactic neutral hydrogen in the form of so-called "high-velocity clouds". The local group is still collapsing from a point of maximum expansion. Some loose groups, such as the M81 system, are less extended and have undergone some dynamical evolution.
- Compact groups are moderately rare systems typically containing a few bright galaxies (e.g. Hickson 1997). Galaxies within a compact group are separated by only a few galaxy diameters, and in many cases display evidence of tidal interactions. Intergalactic gas in compact groups is sometimes detected in HI or X-rays.
- Galaxy clusters containing hundreds to thousands of members span a range of morphologies. Some are irregular systems lacking definite centers, while others appear regular and symmetric. The regular systems contain large amounts of hot ($\sim 10^7\,$K) gas which emits X-rays; this material is polluted with significant quantities of "metals".

3.2.2 Morphology & environment

The range and frequency of different morphological types turns out to be a sensitive function of the environment. Some key results:

- The Local Group is probably the only sample which includes a significant number of very faint galaxies. Of the ~ 35 galaxies now considered members of the Local Group, *only* the brightest three (M31, the Milky Way, and M33) are spirals; the remainder are more or less equally divided between irregular and dwarf elliptical galaxies (Hodge 1995).
- In contrast, magnitude-limited samples of galaxies outside of rich clusters are strongly biased to late-type (Sc) spirals. A typical field sample might consist of 80% S galaxies, 10% S0 galaxies, and 10% E galaxies.

- Compact groups are sometimes dominated by luminous ellipticals, and generally show a preference for early-type galaxies.
- Irregular clusters are generally dominated by disk galaxies. In some cases these galaxies are tidally interacting with each other.
- Within rich regular clusters the population of bright galaxies is dominated by early-type systems (Dressler 1980). The morphological mix appears to vary smoothly with galaxy density; at intermediate densities the mix is 40% S, 40% S0, and 20% E, while at high densities the mix is 10% S, 50% S0, and 40% E. At the center of a rich cluster one generally finds an unusually luminous and extended elliptical galaxy – a cD galaxy.

3.3 Automated Classification

Visual inspection of galaxy images is inherently time-consuming, and different observers may not agree on the classification of ambiguous cases. These considerations motivate the development of algorithms which can automatically and impartially classify galaxy images. Such algorithms play an important role in analyzing large surveys (e.g. 2MASS, SDSS, GOODS, COSMOS, PanSTARRS) now under way.

Most classification algorithms begin by extracting a set of key parameters from an image:

- The **concentration** parameter, C, places the Yerkes system on a quantitative basis (Abraham *et al.* 1994). One definition is $C \equiv 5\log(r_{80}/r_{20})$, where r_{80} and r_{20} are radii containing 80% and 20% of the total flux (Bershady et al. 2000).
- The **asymmetry** parameter, A, is essentially the fraction of light in features which are not symmetric with respect to a rotation of 180° (Abraham *et al.* 1996).
- The **smoothness** parameter, S, is the fraction of the light in small-scale features; it's computed by subtracting an image smoothed by some fixed fraction of a galaxy's radius from the original image (Conselice 2003).
- The **Gini** coefficient, G, measures the degree to which the flux is concentrated in small regions, which may not correspond to the center of image (Abraham et al. 2003). $G = 0$ if all pixels have the same flux, while $G = 1$ if essentially all the flux is concentrated in a single pixel.
- The **second-moment** parameter, M_{20}, is the second-order moment of the 20% brightest pixels normalized by the second-order moment of the entire image (Lotz, Primack, & Madau 2004).

The Gini coefficient has been extensively used in recent studies. However, it appears to be sensitive to the signal-to-noise level of the image and the aperature containing the galaxy to be classified (Lisker 2008). Comparing G values from different data-sets is not recommended.

Classification schemes using only one or two parameters yield results which are relatively easy to interpret; a single parameter locates galaxies along a 1-D continuum, while a pair of parameters may be plotted against each other. However, it's harder to map three or more parameters to discrete galactic types. Naim et al. (1995) use artificial neural nets to classify galaxies into the numerical T types (Table 3.1); their scheme has an uncertainty of ± 1.8 in T, comparable to the dispersion between expert observers.

3.4 Distant Galaxies

It's not trivial to compare distant galaxies with nearby systems. Galaxies at redshift of about $z = 0.5$ produce images only a few tens of pixels across even with HST. Cosmological effects cause surface brightness to fall off as $(1+z)^{-4}$. Rest wavelengths covered by a fixed pass-band shift to the blue with increasing z. All these effects can included when simulating the appearance of nearby objects at high z. Still, '*attempts to classify galaxies at large redshifts represent a considerable extrapolation from, rather than an interpolation between, nearby morphological type and class standards*' (Abraham *et al.* 1996). Instead of forcing distant galaxies into classification schemes based on nearby samples, it makes more sense to adopt a quantitative approach and define image parameters which may be used to classify these galaxies.

Galaxies from the HST Medium Deep Survey have been classified by two independent observers and by measurement of the parameters C and A (Abraham *et al.* 1996). The two observers, 'RSE' and 'vdB', generally agree, except in their classifications of peculiar and merging systems. For galaxies fainter than about $I = 21\,\mathrm{mag}$ the C parameter alone yields classifications as accurate as those provided by human observers. For brighter galaxies, C by itself fails to distinguish E from S0 galaxies, and Sb or Sc spirals from Sd and Ir galaxies. The latter degeneracy can be lifted by including the asymmetry parameter A. The analysis of the MDS galaxies suggests that while the populations of E and S galaxies have evolved relatively little between about $z = 0.5$ and the present, there has been a significant decrease in the number of highly asymmetric galaxies. Many of these asymmetric systems may actually have nearby analogs; they somewhat resemble the interacting, merging, and peculiar systems which are explicitly excluded from classification schemes for 'nearly normal' galaxies.

Galaxies detected in NICMOS observations of the HDF North at $z \sim 2$ have been classified using a variety of parameters (Lotz et al. 2003). As a group, these distant galaxies yield G and A values larger than expected from local S or E galaxies; they appear similar to nearby merger systems.

Problems

3.1. Go to `http://www.ifa.hawaii.edu/faculty/barnes/ast626_09/me/` and classify the galaxy images found there according to Hubble's system. Use the contour function to measure axial ratios for the E galaxies. Note: these are 16-bit `FITS` files; you must adjust the contrast and/or brightness of your display to view the image properly.