Whittle : EXTRAGALACTIC ASTRONOMY

Home | Main | Index | Toolbox | PDFs

2. MORPHOLOGICAL CLASSIFICATION

Index | Questions | Images | References | Print

Next | Top

(1) Motivation & Aims

First step in new scientific area : classify objects/phenomena
1850 - 1950 : discovery of galaxies → classify them

One approach to classification is to simply gather similar types into separate bins.
Wolf (1908) introduced a purely descriptive system of this type : [image]

A better approach is to choose categories which themselves form a coherent system
An ideal classification system of this type would have the following :

- Classes bring order to diversity of galaxy forms
- Span/include majority of galaxies
- Unambiguous & easily identified criteria
- Relate to important physical properties
  ---> provide insight into internal processes, formation, & evolution

Next | Prev | Top

(2) Caveats with Current Systems

- Based on limited sample of galaxies (selection effects).
  Nearby bright field galaxies of high(ish) surface brightness.
- Based on photographic images in the BLUE

  - emphasises star formation (not mass distribution)
  - appearance can vary **greatly** with waveband.
    Eg care classifying with R or I images;
    difficult comparing galaxies at high-z since rest UV can look **very** different.
    → eg examples of UV vs Optical comparisons : [image]
- Requires reasonably good spatial resolution across the galaxy (~20 elements)
  (progressively more difficult for cz > ~8,000 km/s from ground).

Next Prev Top

(3) Applicability

90% of luminous (massive) nearby galaxies fit the Hubble scheme.

However, galaxies which are **not** well accomodated include :

- Dwarf galaxies (most common type in the Universe !)
- Many galaxies in dense cluster environments
- Disturbed or interacting galaxies
- Low Surface Brightness (LSB) galaxies
- galaxies at high-z (eg ~30% @ z~1 don't fit :- "peculiar")

Next Prev Top

(4) Overview of Hubble Sequence

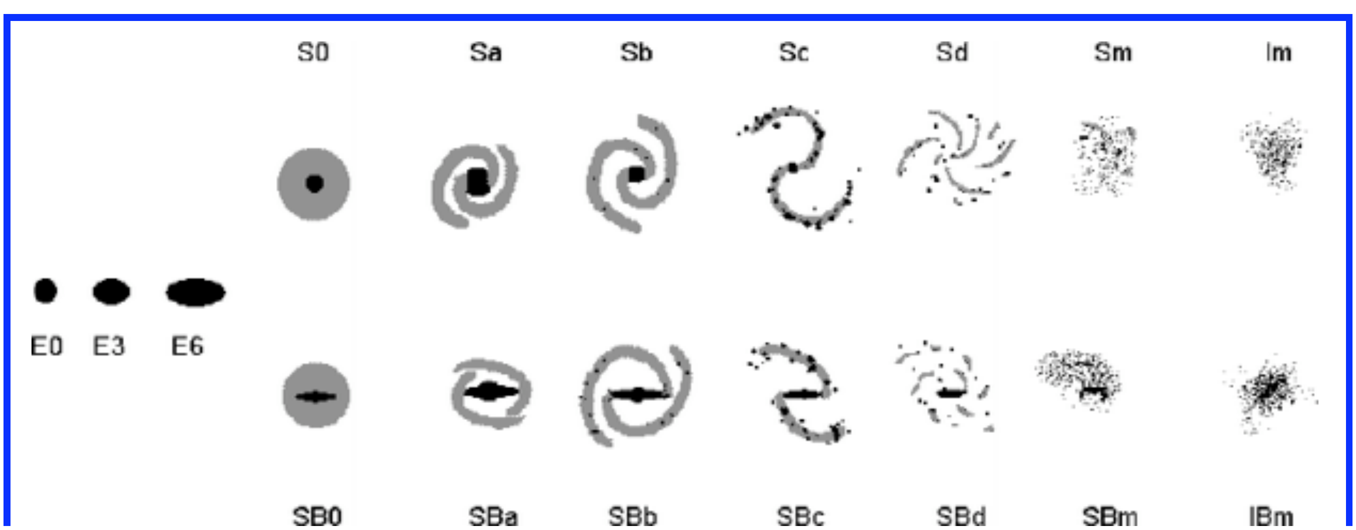
- Four Basic Components : **Spheroid**; **disk**; **bar**; **arms**.

Presence/absence & relative strength of these components defines class

- Principal criteria for spiral stage (Sa → Sb → Sc etc) :
  - Bulge/Disk ratio **decreases**
  - Pitch angle **increases** (psi = < arm tangent & circle; arms more open)
  - Resolution of arms into HII regions **increases**

Note : the **physical** reason these go together is now roughly understood (see Topic 6.4b)

Sketch of modern Hubble tuning fork (from Buta, EAA) :



Note : for historical reasons the terms **Early** (left) to **Late** (right) are used
(Hubble was impressed by Jean's theory of galaxy formation).
We do NOT now consider this a simple evolutionary sequence.

There have been several variations/revisions to this scheme :

Next Prev Top

(5) Brief History of Hubble Sequence

Fairly detailed histories are given in :
Sandage's article in Stars and Stellar Systems Vol. IX (1975) [o-link]
de Vaucouleurs' article in Handbuch der Physik, Vol 53 (1959) [o-link]

- 1926 : Hubble introduces simple tuning fork (ApJ **64** 321).
(**after**, of course, he establishes that spiral nebulae are extragalactic in 1924).
- 1936 : Hubble adds S0 & SB0 (*Realm of the Nebulae*).
(click for original tuning fork diagram.)

(a) Revisions by Sandage :

- 1961 : Hubble Atlas published (introduction describes classification system).
- 1975 : (Stars and Stellar Systems vol IX) Sandage extends and
includes features introduced by deVaucouleurs and also van den Bergh
- 1981 : Revised Shapley-Ames Catalog published (1246 galaxies classified by Sandage and Tammann).
- 1992 : Carnegie Atlas published (Sandage & Bedke, 1168 images); introduction describes system.
Similar to Sandage 1975, adding some other (more idiosyncratic) features.

(b) Revisions by deVaucouleurs :

- 1959 : Handbuch der Physik **53** 275, excellent article with examples
- The system explicitly introduces continuity along **three** axes :
stage, (**early-late**); family (**bar**); variety (**inner ring**) [image]
- Here's the whole system laid out as a [table]
- One virtue of this system : you can omit what is not possible to discern
eg SB(r)cd ..... SBcd ..... Scd ..... S... for progressive loss of detail.
- The deVaucouleurs system is used in the Reference Catalogue of Bright Galaxies :
RC1 (1964), RC2 (1976), and RC3 (1991) containing 2600, 4364, and 23,024 galaxies

Next Prev Top

(6) Description and Illustration of Types

(a) Elliptical : E

- Smooth & structureless (weak nuclear dust lanes sometimes present)
- Steep fall-off in light (SB(mag/ss) ~ $r^{1/4}$, see Topics 7.2 & 7.3)
- E<u>n</u> where n = 10(1-b/a) (eg E5 has b/a=1/2)
range E0 - E7
note : n is not fully intrinsic, partly projection (eg typical intrinsic is E4)
- small (~1%) deviations from pure ellipse : boxy → disky (parameter a_4/a ~ 0.01; +ve → -ve)

Kormendy & Bender (1997) suggest a revised sequence with increasing disk
E(boxy) -- E(disky) -- S0 -- etc : [image]
May be physically more important than n (see Topic 7.8)

Examples of Ellipticals and S0 galaxies : [image]

(b) Lenticulars : S0

- ~ structureless
- central concentration (**bulge**) + envelope (**disk**) of less steep gradient
- sometimes a **lens** inbetween (elliptical with ~flat brightness and sharp edge).
- sometimes a **bar**
- difficult to classify (unless edge on), easy to confuse with Ellipticals
  S0s have a flatter light distribution then Es
  in uncertain cases, the designation E/S0 is commonly used
- **Sandage** subdivides S0s by dust quantity (S0) and bar strength (SB0) :
  - $S0_1$ (no dust), $S0_2$, $S0_3$ (complete dust ring).
  - $SB0_1$ (poorly defined bar), $SB0_2$, $SB0_3$ (strong bar)
  - note : true E with (small) dust disk classified as SO by Sandage (even with no star disk)
- **deVaucouleurs** subdivides early types along the stage axis :
  - E^+, $S0^-$, $S0^o$, $S0^+$, S0/a

(c) Spirals

- Comprise : Bulge + (bar) + (ring) + disk + arms
- **Stage**
  - a,b,c,d,m, with intermediates (eg Sab, Sdm) defined principally by
    1. bulge/disk (B/D) ratio ([image])
    2. pitch angle (psi) ([image])
    3. resolution of arms into HII regions
  - **Sandage** emphasises psi over B/D ratio (eg Hubble atlas explicitly ignores B/D)
    deVaucouleurs emphasises B/D ratio over psi
    Since B/D and psi dont correlate perfectly, Sandage and deVaucouleur types
    can sometimes **differ** (eg compare RSA and RC3)
  - There is evidence, however, that the Hubble sequence is primarily a **bulge** sequence : ([image]
  - **deVaucouleurs** introduces T integer (-5 to +10) which tracks the stage (E to Im)

Type	E	E+	$S0^-$	$S0^o$	$S0^+$	S0/a	Sa	Sab	Sb	Sbc	Sc	Scd	Sd	Sdm	Sm	Im
T	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10

  - Edge-on systems have postfix (sp) for "spindle" (and stage estimated from B/D ratio)
  - **Sandage** adds the "Luminosity Class" of van den Bergh,
    this ranks (I-V) the prominence/clarity/strength of the arms (see below)
- **Bars**
  - **deVaucouleurs** explicitly notes **non-barred** galaxies (SA)
    and also introduces intermediate bars (SAB) : eg SAcd, SABa, SBb
  - **Sandage** keeps original Hubble notation, eg Scd SBb
    he has no intermediates
  - if bar present then arms usually start at end of bar

Examples of spiral stages, both barred and unbarred (Sa, SBa, Sb, SBb, Sc, SBc)

- **Rings**
  - Nuclear rings, usually associated with star formation (not coded)

- Outer ring : prefix R; outer pseudo-ring : prefix (R)
- Inner ring : (s), (rs), (r) : no, weak, strong inner ring
- if inner ring present then arms usually start from the ring
- Bars and inner rings closely associated : both linked to **resonances**
  however, (r) in SA and SB may have different physical origins

Examples of all combinations of SA,SAB,SB with (s),(rs),(r) : [image]
Examples of all kinds of rings (Nuclear, Inner, Outer) : [image]
The deVaucouleurs bar/ring system illustrated at Sb : [image]

Milky Way classification
NGC 6744 = Milky Way look-alike

(d) Irregulars

These are **unsymmetrical** (not to be confused either with asymmetrical or peculiar).
There are TWO kinds :

(i) Like Magellanic Clouds (SBm : LMC and Im : SMC)

- very late type, no nucleus, low luminosity, often dwarfs
- Labelled Irr I by Hubble (and Hubble Atlas)
- Labelled Sm, Im (SBm, IBm) by deVaucouleurs (and Carnegie Atlas)

Examples of Late Spirals and Magellanic Irregulars

(ii) Like M82 (image)

- often early type spectra, probably mergers, amorphous appearance
- Labelled Irr II by Holmberg, Hubble (and Hubble Atlas)
- Labelled I0 by deVaucouleurs (RC2, RC3; T=90, not part of the scale)
- Labelled Am = amorphous by Sandage

(e) Dwarfs

There are THREE kinds :

(i) Dwarf Irregulars (dIrr)

- no clear disk or spirals or nucleus
- patchy star formation on fainter old population
- often HI rich (or even dominated) (picture)
- extreme examples are BCD (Blue Compact Dwarfs; example)
  these have strong star formation >> HII bubbles

Example Dwarf Irregulars in Virgo

(ii) Dwarf Ellipticals (dE) and Dwarf Spheroidals (dSph)

- r_e ~ 0.1 - 1 kpc, but large range in surface brightness
- higher/lower surface brightness corresponds to dE/dSph
- smooth, morphologically similar to ellipticals
- most common galaxy type in Universe
- dE & dSph do NOT follow Elliptical 2 & 3 parameter correlations (Topic 7)
  ---> probably different origin to Ellipticals

Example Dwarf Sphoidal
Example Dwarf Elliptical
Example Dwarf Ellipticals in Virgo

(iii) Compact Ellipticals (cE)

- The best example is M32
- These DO follow 2 & 3 parameter correlation of Ellipticals
  ---> similar origin to ellipticals ? just much lower luminosity.
- Quite rare.

(f) Peculiars

5%-10% galaxies are classified as "peculiar"
These dont fit easily into E, S0, S, I or dwarf categories
Nor are they mildly unusual, with postfix "pec", which is common (eg M87 : E0pec)
Catalogues : Vorontsov-Vel'yaminov (1956) and Arp (1963).
Most are the result of interactions.
Induced star formation (and associated dust) leads to a large spread in color.

Several categories.

- "Jets" : mostly tidal (rarely synchrotron; M87, 3C 273) (eg Arp 242; picture)
- Spiral-spiral : plumes and tidal tails (eg Antenna; picture)
- Spiral-elliptical : single tail & diffuse spray (eg Arp 112; picture and other Arp galaxies)
- Shells : ~40% of Es; cannibalism of "cold" spiral (eg Arp galaxies)
- Merger remnants : ~elliptical; vestigial tails; shells;
  double nuclei; gas & dust; (examples)
- Ring galaxies : passage of one galaxy through nuclear regions of the
  disk of another (eg Cartwheel; wide angle and HST; and Arp galaxies)
- Polar rings : ~0.5% S0 galaxies have a ring (stars &/or gas) perpendicular to the disk plane.
  The rings probably result from capture of a galaxy into a stable orbit (eg NGC 4650A; picture) .

Examples of Amorphous Irregular; Polar Ring; Interacting Pair; and Merger.

Next Prev Top

(7) Relative Frequency of Types

A detailed discussion requires analysis of catalogue selection effects :

eg flux-limited sample will **under-represent** Sd Sm Im dE dSph
because of their low luminosity.

Here we simply take a cursory census of the RSA catalogue.
Broken down by stage and bar, we have

Ordinary		Barred	
E+E/S0	173	...	...
S0+S0/a	142	SB0+SB0/SBa	48
Sa+Sab	123	SBa+SBab	42
Sb+Sbc	187	SBb+SBbc	96
Sc	293	SBc	77
Scd+Sd	26	SBcd+SBd	8
Sm+Im	13	SBm+IBm	9

S	16	...	...
Special	18	...	...
Totals	991	...	285

- Very few cannot be typed (~2.5% are just S or Special)
- Roughly equal numbers of each Hubble type, from S0 to Sc.
- Significantly fewer late type galaxies (Scd to Im), because lower luminosity.
- Roughly constant fraction of ~25% Barred galaxies along the sequence
- ~50% Sa-Sc galaxies have some kind of inner ring, fewer outside this range

Next Prev Top

(8) Other Classification Systems/Extensions

(a) DDO (van den Bergh 1960) Luminosity Classes

- Based on a correlation between orderliness/prominance of spiral arms and absolute magnitude
  See RSA for pictures illustrating the luminosity classes : [o-link]
  Classes I,II,III,IV,V (with intermediates); names correspond to stellar luminosity class
  I = "supergiant" : strong clear arms; (eg NGC 3347 : SBb(r)I)
  II ...... (eg NGC 4725 : SABb(r)II)
  III = "giant" : intermediate (eg NGC 5055 : Sbc(s)II-III)
  IV ...... (eg NGC 5204 : SdIV)
  V = "dwarf" : weak/no arms; (eg Sextans A : ImV)

- In practice, LC I-III are usually found in Sa-Sc while LC IV-V are usually Sd-Sm
  This is because late type galaxies are often lower-luminosity galaxies,
  indeed, Sc → Im is basically a luminosity sequence: [image]
  → very low luminosity spirals dont exist; instead only Sm/Im (always LC IV & V)
  → surface brightness very low below M_B~-18
  → ~ no morphological features as $M_B \rightarrow -10$

- Original Luminosity Classes showed r.m.s. scatter of ~0.6 mag in M_B → used in H_o studies
  Later clear that this was underestimate (~ 3 mag spread; Tammann, Yahil & Sandage 1979)
  Kennicutt (1982) looks deeper into what correlates best with luminosity :
  → finds arm length & arm width/disk size **don't** correlate well (van den Bergh's main criteria)
  → but **physical arm width** (in pc) correlates well
  → arises directly from Tully-Fisher relation & increase of V_{rot} - $V_{pattern}$ with V_{rot}
  → ultimately, yields r.m.s. ~1 mag, so of marginal/no use in distance estimates.

(b) Elmegreen & Elmegreen (1982, 1987) Arm Classes

- Similar to DDO luminosity classes
  AC 1 = chaotic, fragmented, unsymmetrical arms (Flocculent) (example)
  .... etc ....
  Intermediate : "Multiple Arm" -- strong inner arms, outer ratty appearance
  .... etc ....
  AC 12 = two long strong spiral arms dominating the disk (Grand Design) (example)

- Grand Design are 32% of isolated galaxies and 67% of binary galaxies
  Suggests : Grand Design related to m=2 density wave, while
  Flocculent may not be (possibly local instabilities or self-propagating star formation).
  See Topics 5 & 6 for further discussion : (T5.6 T6.4 T6.5)

(c) van den Bergh's "Trifork" Diagram

van den Bergh (1976) introduces disk gas/arm prominance as secondary parameter

- **Two** important realizations :
  - S0 galaxies parallel Sa - Sc in their bulge/disk ratio : hence S0a, S0b, S0c
    eg some S0s structurally closer to Sbc than E (but none later than Sc)
  - Many spirals have weaker arms with reduced star formation (**"Anemic Spirals"** : Aa, Ab, Ac)
    They are common in clusters, suggesting some form of gas stripping.

- This suggests three parallel sequences, each with decreasing bulge/disk ratio : S0s; As; Spirals
  The revised Hubble tuning fork becomes a **"trifork"** (image/viewgraph)
  The physical basis, it is suggested, is of progressive transformation, eg : Sb ⟶ Ab ⟶ S0b
  gas is removed so star formation & arm prominence decreased in the cluster environment.

- Kormendy suggests that dwarf spheroidals (dSph) extend the S0 sequence into the Sm/Im region
  they have exponential (not $r^{1/4}$) profiles, and are likely Sm/Im/dIrr galaxies which have lost their gas
  the combined luminosity function of S0 + dSph now matches the combined luminosity function Spirals + Im

(d) Yerkes Concentration Classes

Morgan (1957-62) working at Chicago

- Based on correlation between **spectra** of galaxies and their central concentration
  More concentrated have K type spectra
  Less concentrated have A type spectra
  Use morphology **alone** to assign concentration types a,f,g,k (with intermediates)
  Think of as a pure Bulge/Disk criteria
  Correlates quite well with Hubble stage (viewgraph)

- In addition to these classes, we inherit several other 'oddball' classes :
  - cD galaxies : "extra (c) large and diffuse (D) galaxies with extended envelopes
    often found at the centers of rich clusters, with multiple nuclei (picture).
  - db galaxies : "dumbell" or double elliptical galaxies; also found in cluster cores;
    Both cD and db galaxies are now thought to result from mergers/cannibalism.
  - N galaxies : small bright nucleus on a faint smooth background
    a number of active radio galaxies are N galaxies

Next Prev Top

(9) Variation along the Hubble Sequence

We expect **some** properties to vary systematically along the Hubble sequence (E ⟶ Sa ⟶ Sc ⟶ Im)
A detailed discussion is given by Roberts and Haynes : 1994, ARAA [o-link]
from which these plots have been taken [image] , [image] , [image] .

- **Selection effects** are very important, with different results for flux & volume limited samples.
  Robers & Haynes use a sample of ~5000 RC3 galaxies with cz < 3000 km/s (Local Supercluster).
- **Three** basic groups : Ellipticals, Spirals (Sa - Scd), Dwarfs (Sd - Im) [S0 nature still debated]

- **Surface mass density** decreases E ⟶ Im;
  ⟶ reflects decreasing bulge contribution (Sm-Im no bulge)
- Median **size, luminosity**, or **mass** ~constant for E ⟶ Sc;
  however, significant decrease Scd ⟶ Im
  ⟶ there are essentially **no** small low-luminosity Sa - Sb galaxies;

→ likewise no large high-luminosity Sm-Im.

- **Gas content** (particularly HI) increases along sequence :
  HI surface density; M_{HI}/L_B; M_{HI}/M_{tot} : however :
  including molecular gas (H_2 measured using CO) reduces this trend
  as does including the hot (X-ray) coronae in Ellipticals
- **Star formation** increases along the sequence : [image]
  bluer color (eg U-B; B-V : [image])
  more Hα emission (equivalent width) : [image]
  more radio continuum emission (relative to R or I band light)
  higher gas content (see above)
  [FIR does **not** follow : several heating sources besides SF in normal galaxies]
  Caution, the story is more complex : nuclear vs disk SF differ (see Topic 11.5)
- **M/L_B ratio** decrease slightly S0 → Scd (8 → 6), (but ~7 for Sm - Im);
  however, large range; not as clean as expected (Sm-Im have significant HI).
- **Metallicity** decreases Sc → Im;
  but primary correlation with luminosity/mass (deep potentials retain metals)

Next Prev Top

(10) Physical Morphology

- Classical morphology focusses only on apparent form
  it is usually a mistake to include theoretical prejudice, particularly early on
  as understanding builds, it becomes reasonable to use theory to inform classification
  one can view classification as identifying groups of stars with different dynamics/histories.
  Kormendy (1982, 12th Saas Fee) has emphasized this approach.

- Here is his description of the physical origin of the major classified components :

Component	Formation Mechanism
Halo	Dissipationless collapse of ?? during early phase of galaxy formation
Spheroidal : Elliptical	Dissipationless collapse + mergers; (stars form before/during collapse)
Spheroidal : Bulge	Ditto above but less so
Disk : Thick	Ditto below but more so
Disk : Thin	Dissipational collapse; (stars form after collapse)
Bar	Dynamical instability during collapse + secular growth
Lens	Made from bar by destruction of resonance
Inner ring (r)	Disk material rearranged by bar
Outer ring (R)	Disk material rearranged by bar

- One can think of a galaxy as the **sum** of these components
  their relative strength defines (in large part) the type class

- Implicit in this table is **evolution** : both initial and secular
  birth process important in defining bulge/disk
  ongoing interactions/resonances can generate bars/lenses/rings

- There has also been an attempt using Principal Component Analysis (PCA) to find the underlying physical variables.
  For a large sample, many parameters gathered.
  PCA finds those linear combination of parameters for which the data span the largest range
  these new composite-parameters are considered to be more "fundamental"
  Whitmore (1984) applied PCA to 60 spirals Sa - Sc and finds **two** principal axes :
    - the "form" : a combination of bulge/total ratio and B-H color
    - the "scale" : a combination of isophotal diameter and blue luminosity

  this is perhaps not surprising, it tells us that a galaxy's properties depend mainly on :
    - the relative dominance of the bulge
    - the basic size/mass of the galaxy

  Future topics will, of course, explore these components in more detail.

Prev Top

Home Main Index Toolbox PDFs