Whittle : EXTRAGALACTIC ASTRONOMY

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2. MORPHOLOGICAL CLASSIFICATION

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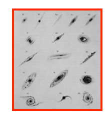
(1) Motivation & Aims

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

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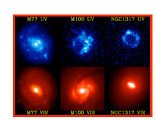
(2) Caveats with Standard System

- 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.
    E.g. 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).

- Many kinds of galaxies don't fit easily into the standard Hubble scheme:
  - Disturbed or interacting galaxies
  - Galaxies at high-z (eg ~30% @ z~1 don't fit :- "peculiar")
  - Low Surface Brightness (LSB) galaxies

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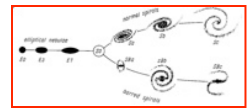
(3) Brief History of Hubble Sequence

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*).
  Hubble's original tuning fork diagram: [image]



(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: [o-link]
  A more modern collection of CCD images is given here: [o-link]
- The system explicitly introduces continuity along **three** axes:
  stage, (**early-late**); family (**bar**); variety (**inner ring**) [see below]
- 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

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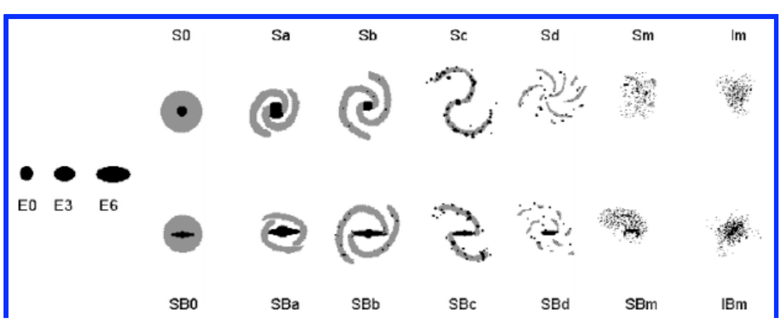
(4) Description and Illustration of Types

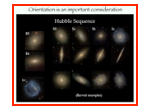
(a) Overview:

- Four Basic Components : **Spheroid**; **disk**; **bar**; **arms**.
  Presence/absence & relative strength of these components defines class

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



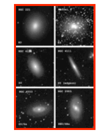
Real examples, including edge-on examples: [image].



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

(b) Ellipticals : E

Examples of Ellipticals and S0 galaxies: [image]



(i) Intermediate and High Luminosity

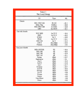
- Smooth & structureless (weak nuclear dust lanes sometimes present)
- Many appear flattened: E<u>m</u> where m = 10×(1-b/a) (e.g. E5 has b/a=1/2, range E0 - E7)
  Note: n is not fully intrinsic, partly projection (eg typical intrinsic is E4)
- Steep fall-off in light: SB(mag/ss) $\propto r^{1/n}$ n = 2 - 10 (n = 4 is the **de Vaucouleur's profile**)

- Systematic differences between **Intermediate** and **High** luminosity Es (boundary $M_V \sim -20.5$)
  For example: (see Topics 7.2 & 7.3)
  Intermediate L: lower n; oblate spheroids; disky isophotes; steep nuclear profiles; isotropic velocities
  High L: high n; triaxial ellipsoids; boxy isophotes; flatter nuclear profiles; anisotropic velocities
  Probably reflect different formation mechanism (Topic 7.9)

(ii) Low Luminosity (Dwarf) Ellipticals/Spheroidals:

Smooth light distribution & no disk: so superficially like small ellipticals [image]
However, there are **significantly differences** from normal Ellipticals.

- They have exponential light profiles (like disks).
- They do **not** follow 2 & 3 parameter correlations for ellipticals (Topic 7.4)
  → probably different origin to Ellipticals (maybe gas stripped dIrr?)



Some confusion over naming all these:

Previously, dE with dSph for lowest luminosity (Local Group) examples
Kormendy suggests they are **all** called **Spheroidals**

Note: there are still true low luminosity true ellipticals (e.g. M32, cE = compact E).

(c) Lenticulars : S0

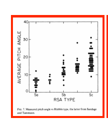
- Like ellipticals, S0s have smooth structureless light distributions [image]
- Central concentration (**bulge**) + envelope (**disk**) of less steep gradient
- Can sometimes have a **bar**: SB0
- **deVaucouleurs** subdivides early types: E^+, $S0^-$, $S0^o$, $S0^+$, S0/a

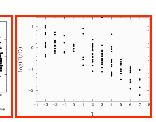
- Difficult to classify (unless edge on), easy to confuse with Ellipticals
  S0s have a flatter light distribution then Es
  In uncertain cases, the designation E/S0 is commonly used

(d) Spirals

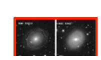
- Comprise: Bulge + (bar) + (ring) + disk + arms

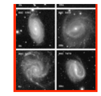
- **<u>Stage</u>**
  - a,b,c,d,m, with intermediates (eg Sab, Sdm) defined principally by [image]
    - Bulge/disk (B/D) ratio
    - Pitch angle (ψ): e.g. "tightly wound," or "open"
    - Resolution of arms into HII regions





  Examples (with unbarred down LHS): [image]

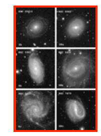




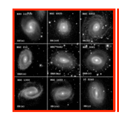
- **Sandage** emphasises ψ over B/D ratio (eg Hubble atlas explicitly ignores B/D)
  deVaucouleurs emphasises B/D ratio over ψ
  Since B/D and ψ don't correlate perfectly, Sandage and deVaucouleur types can sometimes **differ** (e.g. RSA and RC3 types may differ)
- Edge-on systems have postfix (sp) for "spindle" (and stage estimated from B/D ratio)
- **deVaucouleurs** introduces T integer (-5 to +10) which tracks the stage (E to Im)

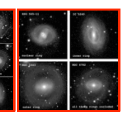
Type	E	E+	$S0^-$	$S0^o$	$S0^+$	S0/a	Sa	Sab	Sb	Sbc	Sc	Scd	Sd	Sdm	Sm	Im
T	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10

- **Bars**
  - Linear feature of stars: examples (with barred down RHS): [image]
    If bar present then arms usually start at end of bar

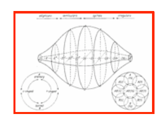


  - **deVaucouleurs** explicitly notes **non-barred** galaxies (SA)
    and also introduces intermediate bars (SAB) : eg SAcd, SABa, SBb
  - **Sandage** keeps original Hubble notation, eg Scd SBb
    He has no intermediates
- **Rings**
  - Nuclear rings, usually associated with star formation (not coded)
  - 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 are closely associated: both linked to **resonances**
    Examples of all kinds of rings (Nuclear, Inner, Outer): [image]
    Examples of all combinations of SA,SAB,SB with (s),(rs),(r) : [image]



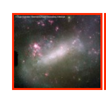


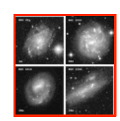
- **The deVaucouleurs System**:
  - Is really a 3-D classification system, illustrated here: [image]
  - Here's the whole system laid out as a [table]
  - One virtue of this system : you can omit what is not possible to discern
    e.g. SB(r)cd ..... SBcd ..... Scd ..... S... for progressive loss of detail.



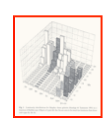
(e) Very Late Spirals and Irregulars

- DeVaucouleurs and Sandage both extended Hubble's system to "later" stages: Sd, Sm, Im
  S is used if a (weak) spiral is present, and I if not (I for "Irregular").
  Sd used if nucleus present, Sm if not
  "m" is for "Magellanic" e.g. LMC is SBm and SMC is Im: [image]
  Some examples of Late Spirals and Magellanic Irregulars: [image]

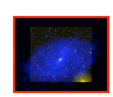




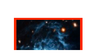
- These late type galaxies are often lower-luminosity galaxies,
  indeed, Sc → Im is basically a luminosity sequence: [image]
  → Very low luminosity spirals dont exist; instead only Sm/Im
  → Surface brightness very low below M_B~-18
  → ~ no morphological features as $M_B \rightarrow -10$



- At lowest luminosities we have Dwarf Irregulars: dIrr
  No clear disk or spiral or nucleus
  Patchy star formation on fainter old population
  Often HI rich (or even dominated) [image]



  Extreme examples are BCD (Blue Compact Dwarfs): [image]



These have strong star formation → HII bubbles
May be local analogs of high-z infant galaxies.

(f) Peculiars

5%-10% galaxies are classified as "peculiar"
These don't fit easily into E, S0, S, I or dwarf categories
Nor are they mildly unusual, with postfix "pec", which is common (e.g. M87 is E0pec)
Catalogues : Vorontsov-Vel'yaminov (1956) and Arp (1963) [o-link].
Most are the result of interactions [images] (see Topic 13)
Induced star formation (and associated dust) leads to a large spread in color.

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

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(5) Relative Frequency of Types

A detailed discussion requires analysis of catalogue selection effects:

e.g. 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 catalog.
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

- 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

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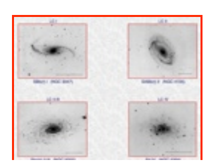
(6) Other Classification Systems/Extensions

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

- Although called "Luminosity Class" this is really a classification of **arm definition**
  (Later work showed arm definition and luminosity only weakly correlated).
  See RSA for pictures illustrating the luminosity classes : [o-link]
  Classes I,II,III,IV,V (with intermediates) [examples]



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

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

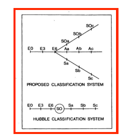
- Grand Design spirals are 32% isolated galaxies and 67% binary galaxies, suggesting:
  Grand Design are related to m=2 density wave, while
  Flocculent may not be, but probably arise from local disk instabilities
  (see Topics: 5.6 6.4 6.5)

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

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

- **Two** important realizations :
  - S0 galaxies parallel Sa - Sc in their bulge/disk ratio: hence S0a, S0b, S0c
  - 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 [image].

- This suggests three <u>parallel</u> sequences, each with decreasing bulge/disk ratio: Spirals; As; SOs
  The revised Hubble tuning fork becomes a "**trifork**" [image]
  The physical basis is of progressive transformation, eg : Sb → Ab → S0b
  As gas is removed in a cluster, star formation & arm prominence decreased.



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(7) Automated Galaxy Classification

Modern CCD imaging surveys generate vast numbers of galaxy images
There is a need for fast, objective, robust classification.
Several approaches:

(a) Brute Force Approach

(i) Galaxy Zoo Project o-link

Members of the public learn simple classification and classify SDSS galaxy images.
In first year: 150,000 people made 50 million classifications!
Cross-comparisons self-calibrate and reduce "noise".
Second phase: more detailed classification of SDSS galaxies in "stripe-82" & HST images
Data successfully used for a number of projects.

(ii) Neural Nets

Images of a sample of well-classified galaxies are analyzed using many parameters.
Computer uses "Neural Net Algorithms" to find associations between classes and parameters.
Basically, it "learns" how to classify, and so can then classify other images.
Ultimately, about as good as people, as long as galaxies conform to classification scheme. (ref)

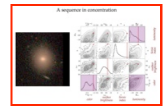
(b) Automated Approach

Often, surveys yield distant galaxy images that are too small for detailed classification
But it is still crucial to know basically what type of galaxy they are.
A number of simple parameters have been found to be very useful:

(i) Simple Image Parameters

After some experimentation, it seems a good system uses three (CAS) parameters: concentration, asymmetry and smoothness. Modern CCD surveys also yield reliable color information, so this is also used.

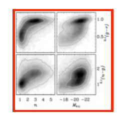
- **Concentration**: tends to track the stage (elliptical → spiral) since it correlates with bulge/disk ratio, and bulges are denser than disks.
  There are several parameters that track concentration:
  - **R90/R50** where R90, R50 are the radii enclosing 90% & 50% of the flux.
  - **Sersic n**: fit Sersic profile, $I(R) = I_e \exp(-b [(R/R_e)^{1/n} - 1])$
    R_e = effective (half-light) radius; I_e = surface brightness at R_e
    Solve for n: e.g. n = 1 (exponential), n = 4 (deVaucouleurs) [examples]



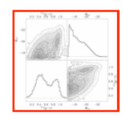
  - χ^2 **goodness of fit**: to model brightness profiles
    e.g. try deVaucouleurs; exponential; or PSF fits, and see what the χ^2 value is.
- **Asymmetry**: This correlates well with distortions and interactions
  One can cast an image as odd + even functions, the odd functions give the asymmetry
  Another approach subtracts a reflected version and looks at the residual.
- **Smoothness**: This traces star formation rates, or multiple components in a merging system.
  This can be estimated several ways (e.g. M20 and GINI parameters):
  e.g. comparing 2nd moments of the entire image, and the brightest 20% of the pixels
- **Color**: This tracks the mean age of the stellar population in the galaxy.
  This turns out to be usefully different from the stage (elliptical/spiral) parameters.

(ii) Example Results from SDSS

The Sloan Digital Sky Survey (SDSS) provides image parameters (and images) for a million galaxies.
Although explicit Hubble types are not given, several parameters effectively trace this
Some examples are shown here: [image]



These tend to show two primary classes of galaxy
On a galaxy **color-magnitude** plot they appear as "blue and red sequences" [image]



- younger population (blue star forming) spiral disks
- older population ("red" "dead) elliptical-like bulge dominated galaxies

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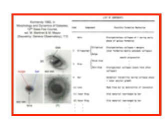
(8) Physical Morphology

- 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.



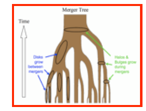
- Here is his description of the physical origin of the major classified components :

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



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