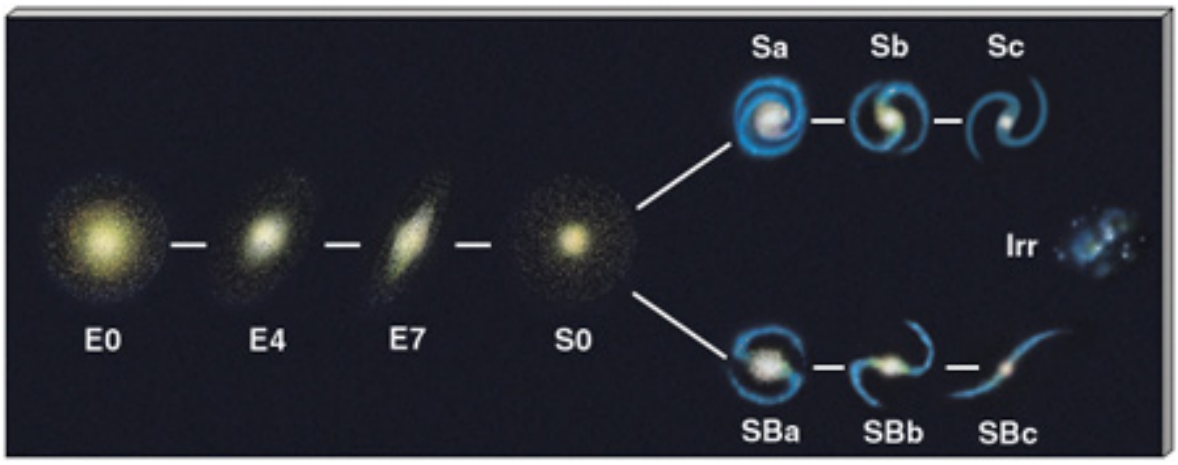
name

# Galaxy Classification and Evolution

The word “galaxy,” having been used in English since the fourteenth century, is as old as this language. Galaxy was derived from the French, Greek, and Latin words for milk. To pre-industrial people, lacking bright lights, the Milky Way, a band of diffuse light stretching across the dark sky, would have been as familiar as the planets and the Moon. This band of stars completely encircles Earth. It is the disk of our Galaxy seen from the inside (but not the center). With unaided eyes one other galaxy can be seen in the northern sky, the Andromeda nebulae, as it was called before its true nature was known. It is a faint fuzzy patch in the region of the sky containing the stars of the constellation Andromeda. Two galaxies, the Large and Small Magellanic Clouds, can be seen with unaided eyes in the southern sky from south of about 10 degrees north latitude. The Magellanic Clouds were described by sailors from Magellan's voyage, and are now known to be small irregular galaxies, that orbit the Milky Way. Our Sun and all of the individual stars that can be seen with unaided eyes from Earth are part of the Milky Way.

Immanuel Kant (1724-1804) speculated that the faint patches of light, which improved telescopes revealed in large numbers, were "...island universes - in other words, Milky Ways..." Astronomers of the eighteenth century identified celestial objects as being either stellar or non- stellar, with the second category including gaseous nebulae, planetary nebulae, hazy star clusters, and faint lens-shaped formations. If these objects were nearby, with distances comparable to those of observable stars, they would have to be luminous clouds of gas within our Galaxy. If they were very remote, far beyond the foreground stars of the Galaxy, they would be systems containing billions of stars. Kant's speculation was rejected for over 150 years. Edwin Hubble published a paper in 1929, "A Spiral Nebula as a Stellar System," which showed that the fuzzy patch in the constellation Andromeda is a system of numerous individual stars, star clusters, and dust clouds. The Andromeda galaxy, as it is now known, is 2 million light-years away, and is the nearest spiral galaxy to the Milky Way. Hubble also proposed a classification scheme based entirely on the visual appearance of a galaxy on a photographic plate. His system has three basic categories: elliptical, spiral, and irregular galaxies. The elliptical and spiral galaxies are subdivided further, as illustrated below. This is known as the “Hubble Tuning Fork.”



# Describing Galaxy Morphologies

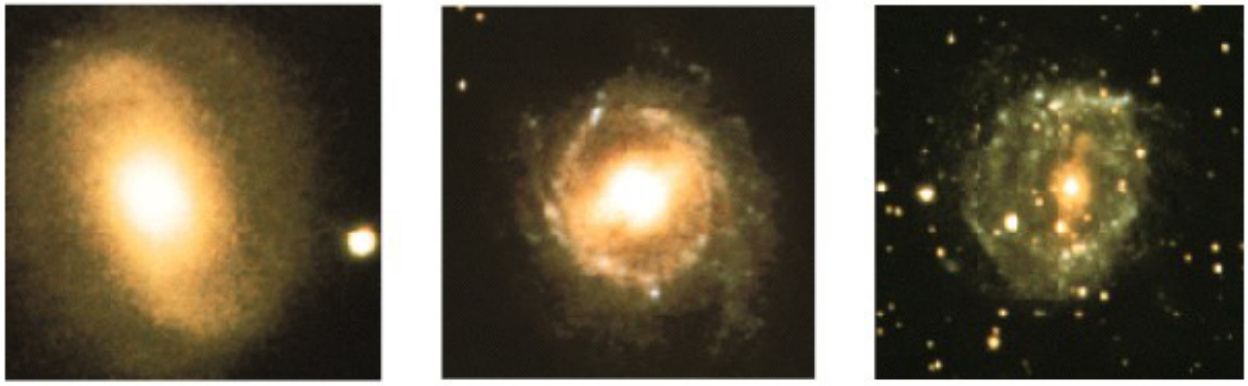
## (a) Spiral Galaxies

Spiral galaxies are associated in the public's mind with galaxies because their curving arms and dust clouds make spectacular pictures. Photographs of the Andromeda, the Whirlpool, and the Sombrero galaxies are often reproduced because of their beauty. The arms form a disk that extends out from a central or nuclear bulge of stars, often called the nucleus, which is brightest at its center. The arms require longer exposures as seen in astrophotography, which usually causes the nucleus to be overexposed. In spiral galaxies, the disk and central nucleus of a spiral galaxy is enclosed in a larger spherical halo, which includes many globular clusters of stars. The halo is surrounded by a dark corona with a radius of several times the radius of the disk. The corona is the location of the hypothetical dark mass. The disks of spiral galaxies are filled with clouds of dust and gas.

Spiral galaxies are classified by the shape of their nuclei and their arms. Spirals with arms that appear tightly wound are classified as Sa galaxies, while those with more loosely wound arms are Sc galaxies. Sb's are between these classes. Spirals with loosely wound arms also have smaller central bulges.

Sa Sb Sc

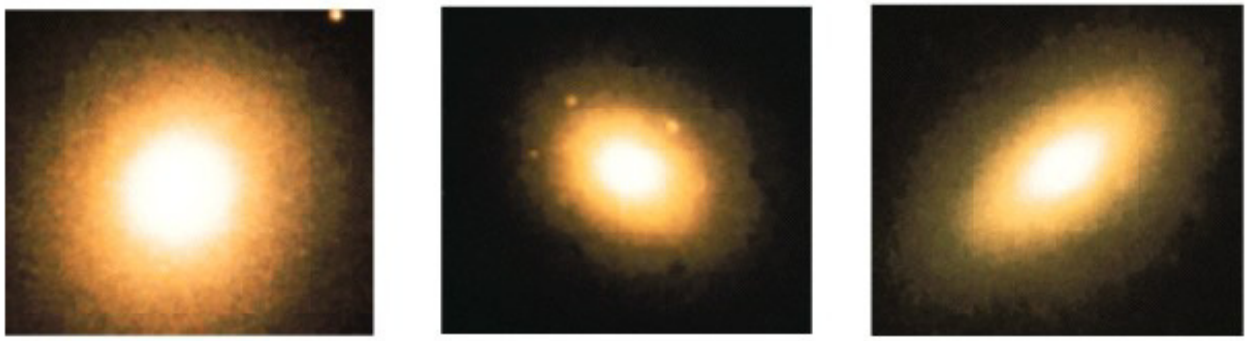
The arms in barred spirals originate at the ends of a bar running through the galaxy's nucleus. Some barred spirals have tightly wound arms, while other barred spirals have loosely wound arms, which are classified into SBa, SBb, and SBc categories.



Sa Sb Sc

## (b) Elliptical Galaxies

Ellipticals are galaxies whose images have elliptical outlines, without spiral arms, and often appear rather smooth and featureless. Ellipticals vary in shape from spherical to flat, lens-shaped formations. Hubble identified these galaxies with the letter E and classified them according to their elliptical shape using numbers from zero through seven. Spherical galaxies are classified as EO, almost spherical as E1, and galaxies with maximum elongation as E7. Elliptical galaxies contain relatively little dust and gas. Some giant ellipticals contain as many as a hundred times more stars than our Galaxy. M87 is an example of such a giant galaxy. Dwarf ellipticals are the most numerous type of galaxy, and typically contain only a few million stars. Since the formation of new stars occurs in regions which contain dust and gas, elliptical galaxies are composed primarily of old stars.



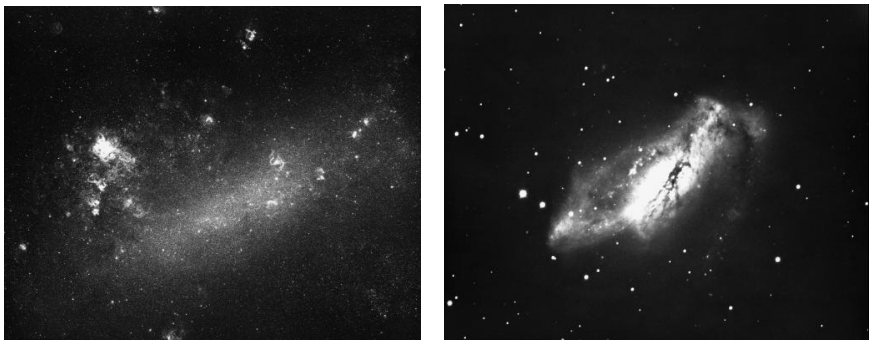
E0 E3 E6

## (c) Lenticular Galaxies

Still another class of galaxies intermediate between the elliptical and spiral galaxies are the SO galaxies. Superficially, they appear like ellipticals, but they contain too much dust to be ellipticals, yet are too smooth to be spirals. Some show faint disks. The range of galaxies that exist seem to form a continuous sequence of galaxy types between the ellipticals and the spirals.

## (d) Irregular and Peculiar Galaxies

Irregular galaxies lack the organized appearance found in ellipticals and spirals.



# Part I — Classification

Please click on
http://cosmos.phy.tufts.edu/~zirbel/laboratories/galaxyimages/

The first step prior to studying galaxies and their evolution is to categorize them by some method. A classification scheme generally must satisfy two criteria to be successful: It should act as a shorthand means of identification of the object, and it should provide some insight to understanding the object. We still use the classification scheme proposed by Edwin Hubble in 1926. His classification is based on the visual appearance of a galaxy on a photographic plate.

a) On the next page you will see some galaxies that have been classified according this scheme.

b) Classify all galaxies (e.g. S0, Sc, SBa, E0, E4 etc; just Elliptical or Spiral in not enough). Write the classification into Table 1. Please look at the pictures on the computer (to see sufficient detail); the thumbnails on the next pages are for orientation only. Write a short comment of how you arrived at each classification.

Note: You can try to do a fast job and classify the galaxy thumbnails on the photocopies – but please do look at the larger galaxy images on your computer. You will find that the additional detail does often result in different classifications.

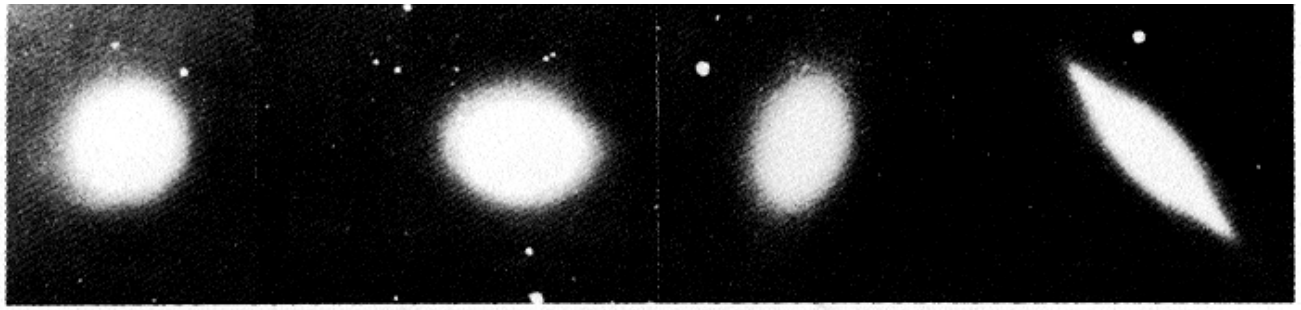
## The Classification Scheme in Brief

- **Spirals** have a bulge and a disk with a spiral structure. A big bulge with tightly wound arms corresponds to a Sa; a small bulge with loosely wound arms is an Sc – pay attention to the length and tightness of the spiral arms and to the relative size of the bulge. Sometimes you might even be able to determine intermediate cases; for example an Sbc is intermediate between an Sb and Sc. If there is a bar, you might have an SBb, or an SBc. Do not confuse spiral arms with tidal arms (a gravitational influence of a close neighbor)

- **Elliptical** galaxies tend to be smooth and regular. Ellipticals do not have a disk or a bulge, only a spheroidal component. Their shape somewhat resemble that of a "fuzzy football". The flattest Ellipticals are classified as E7, round ones as E0. In some cases you might see a rather broad dust patch orbiting the galaxy (as in the case of Cygnus A). These dust patches look very different from signatures of dust seen in the arms of spiral galaxies.

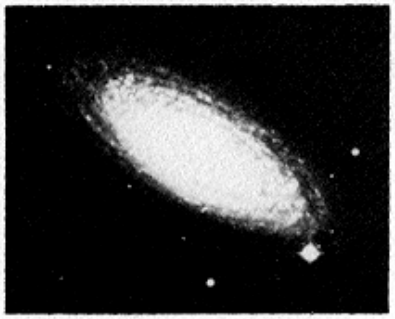
- **Lenticular** galaxies (denoted S0) are often confused with elliptical galaxies, however they are rather different. They look as smooth and regular as Ellipticals, however they have a disk and a bulge (Ellipticals do not have a disk). They are basically spiral galaxies with NO arms.

- **Irregular** galaxies do not have a well-defined shape and are not as symmetrical or regular like Ellipticals or Spirals. Some galaxies may have a rather weird structure – these can be classified as "peculiar" or Irr II.

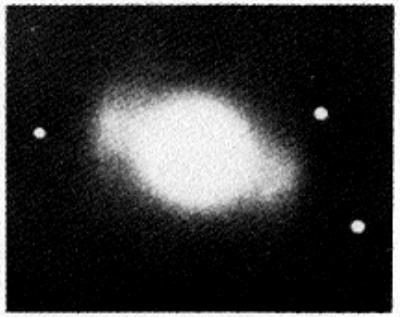


EO NGC 3379 E2 NGC 221 (M32) E5 NGC 4621 (M59) E7 NGC 3115

NGC 1201 Type SO



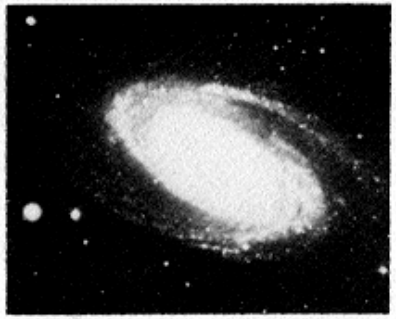
NGC 2841 Type Sb



NGC 2859 Type SBO

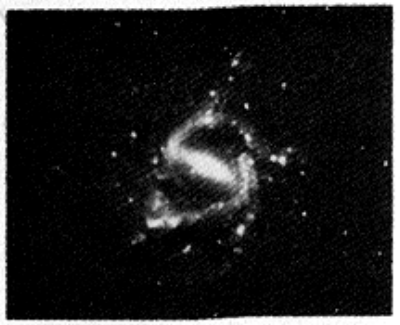
NGC 2523 Type SBb(r)

NGC 2811 Type Sa

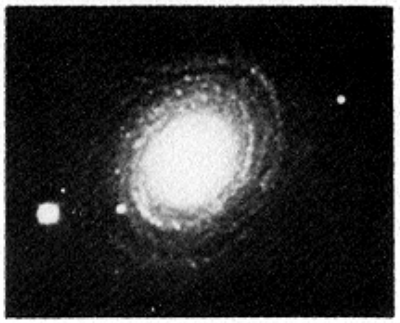


NGC 3031 M81 Type Sb

NGC 175 Type SBab(s)

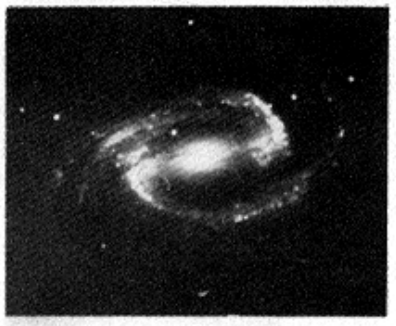


NGC 1073 Type SBc(sr)

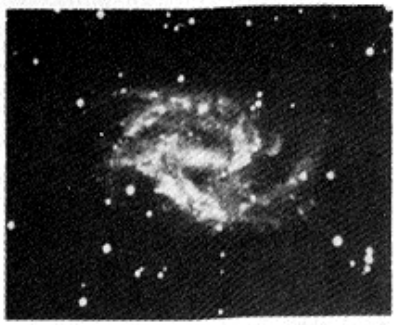


NGC 488 Type Sab

NGC 628 M74 Type Sc



NGC 1300 Type SBb(s)

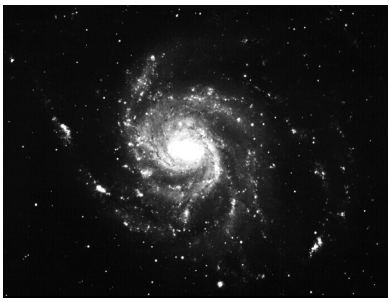


NGC 2525 Type SBc(s)

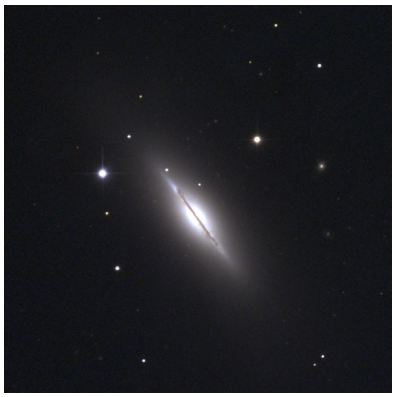
# Table 1: Galaxies to be classified

| Name | Type | Comments of unusual morphologies; e.g., E3, but with dust ring |
|---|---|---|
| M101 | | |
| M102 | | |
| M104 | | |
| M110 | | |
| M32 | | |
| M33 | | |
| M49 | | |
| M51 | | |
| M59 | | |
| M61 | | |
| M64 | | |
| M74 | | |
| M77 | | |
| M104 | | |
| LMC | | |
| M81 | | |
| M84 | | |
| M85 | | |
| M87 | | |
| M95 | | |
| M88 | | |
| M89 | | |
| M94 | | |
| NGC2147 | | |
| NGC2644 | | |
| NGC2685 | | |
| NGC3077 | | |
| NGC3718 | | |
| NGC4565 | | |
| NGC4651 | | |
| NGC470 | | |
| NGC5364 | | |
| NGC5383 | | |
| NGC55 | | |
| NGC6946 | | |

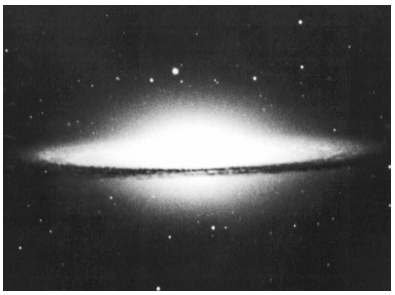
# Galaxies to be classified



M101



M102



M104

M110

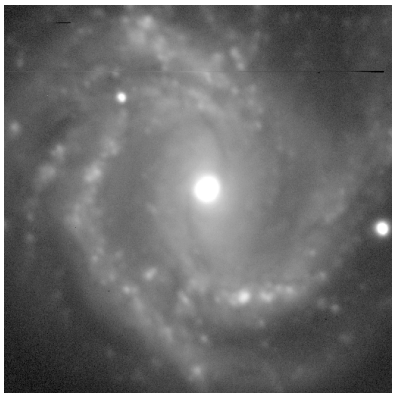
M32

M33

M49

M51

M59

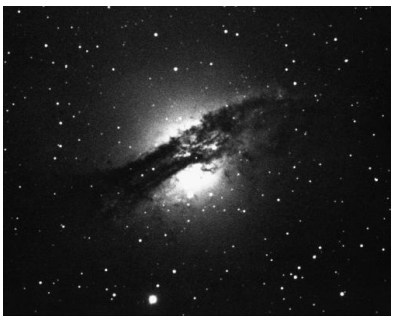


M61

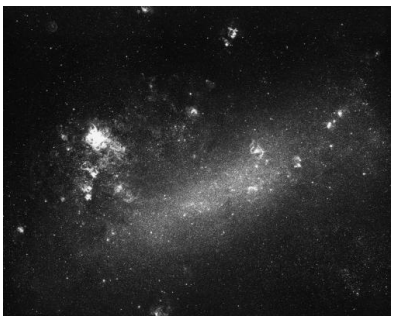
M64 / Black-Eye Galaxy

M74

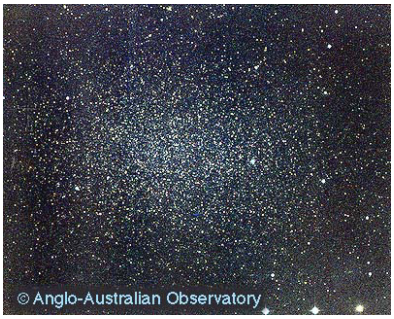
M77



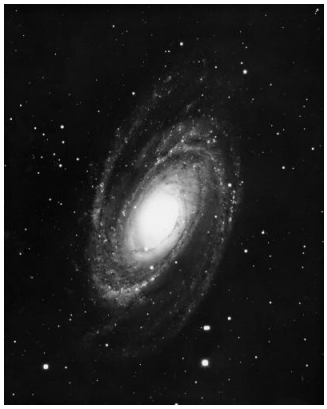
M104 / Cygnus A



LMC



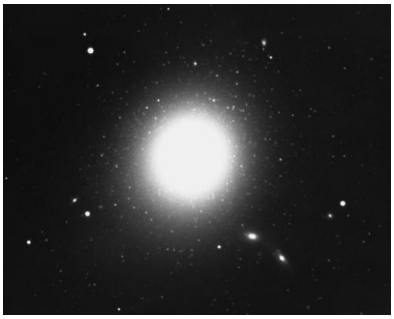

Local Group Galaxy



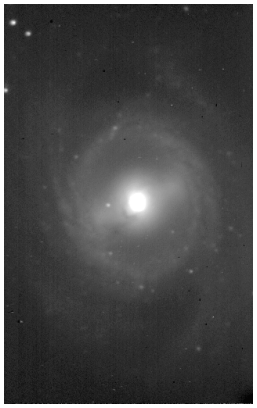
M81

M84

M85



M87



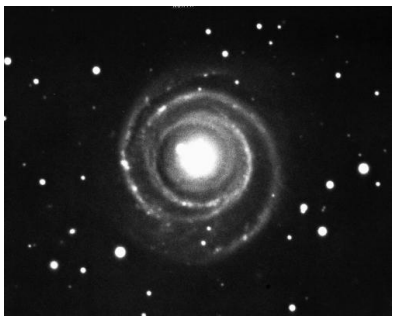
M95

M88

M89

M94

NGC2147



NGC2644

NGC2685

NGC3077

NGC3718

NGC4565

NGC4651

NGC470

NGC5364

NGC5383

NGC55

NGC6946

# Part II: The Colors of Galaxies

Look at the Pictures on the next page AND at the pictures in color on the Computer!

a) Do the colors of galaxies seem related to their shapes? Explain.

b) Suggest an explanation for the colors of Spiral, Elliptical and Irregular galaxies. In particular, comment on the amount of gas and dust and the stellar populations of those galaxies.

c) Compare the bulge of Spiral galaxies to elliptical galaxies. In what sense are they similar?

d) Look at M101, NGC2997 and M100. Why are the colors of the bulge and the colors of the spiral arms so different? Suggest an explanation.

e) Look at NGC55: Some parts of the spiral arms have a reddish glow. What is that? NGC2997 is also a spiral galaxy, but not much of this pink light is visible. Why not?

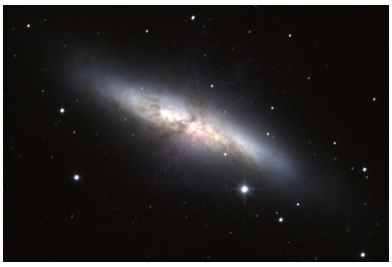
f) NGC6745 is interacting with another galaxy that is located at the bottom right of that picture. Comment on the overall colors of NGC6745. How much gas and dust do you think this galaxy has relative to NGC22? What are the blue patches? Why aren't any other parts of that galaxy so blue?

# Galaxies in Color (look at the **COLOR** pictures!)


NGC2997

M101


NGC1313



M82

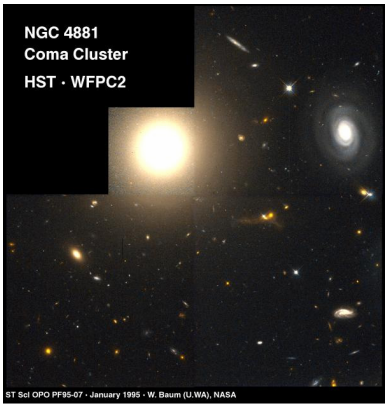

M87

NGC4565

NGC22

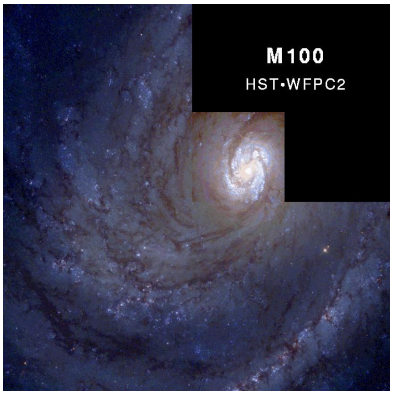

NGC6745


NGC5364




NGC4881


NGC55




M100

# Part III — Analyzing the Hubble Tuning Fork

a) Describe how the properties of galaxies change along the Hubble sequence (**from left to right**).

(i) For spirals: disk/bulge ratio

(ii) For ellipticals: the ellipticity

(iii) For spirals: tightness and length of the arms

(iv) Amount dust (as inferred from the presence of dark clouds and/or reddening and extinction)

(v) Amount gas (as inferred from the presence of HII regions)

(vi) Overall galaxy colors

(vii) Dominant spectral types

(viii) Time since the last star formation episode

b) ***Explain*** how (iv) to (viii) are correlated.

c) Originally, when Hubble proposed this classification, he had hoped that it might yield deep insights – just as in the case for classifying stars. He hoped this scheme would represent an evolutionary scheme, where galaxies start off as elliptical galaxies, then rotate, flatten and spread out as they age.

***Critically*** comment on Hubble's proposal that his classification represents and evolutionary scheme.

d) Invent an **alternate** classification scheme. In what sense does your scheme do a better job than the Hubble scheme? **Explain**.

# Part IV — Galaxy Environments

Galaxies, like stars, exist in clusters. It is now known that the Milky Way is part of a local cluster of about 30 galaxies called the Local Group. The Local Group lies on the outskirts of a much larger cluster called the Local Supercluster. A nearby cluster, the Virgo cluster of galaxies, is prominent in the sky because of its relative nearness. It lies in the Virgo and Coma Berenices constellations, at a distance of about 65 million light-years, and contains many bright objects, some with Messier numbers and hundreds with NGC (New General Catalogue) numbers. High quality astro-photographs of this Virgo Cluster show thousands of individual galaxies that are ideal for studying the various types of galaxies. There are several advantages of studying clusters of galaxies; the members of clusters are all at about the same distance, so relative luminosities and diameters can be easily compared for the cluster members. Examples of galaxies in collision can also often be found in galaxy clusters.

There are differences among clusters, and the proportion of Spiral and Elliptical galaxies depends on the galaxy environment. The Morphologies of the Galaxies turns out to depend on the environment of galaxies. This suggests that the neighbors of galaxies are somehow responsible for the final shapes of the galaxies. If we can understand exactly "how" the environment affects the evolution of galaxies, we might be able to figure out how galaxies have formed during the early stages of the universe.

# Galaxies in Different Environments

Look at the Hercules and Coma Clusters and classify the galaxies roughly according to Elliptical, Spiral, and Irregular. Let's do a rough classification first. Put the pictures of the Coma and the Hercules cluster in front of you (even the bad photocopies might be good enough for this). The scales and the exposure times of those pictures are slightly different, but that's not so important for now.

a) What are the dominant types of galaxies in the Coma Cluster? _____

b) What are the dominant types of galaxies in the Hercules Cluster? _____

c) Using the magnified pictures on the computer, please classify ~30 galaxies and count the number of galaxies in each category. (You might like to use color pens marking the galaxies you already classified as E, S, or Irr). Fill out the table below.

| | Elliptical | Spiral | Irregular | Total Number |
|---|---|---|---|---|
| Coma | | | | |
| Hercules | | | | |

d) Determine the percentage fractions of Elliptical, Spiral, and Irregular.

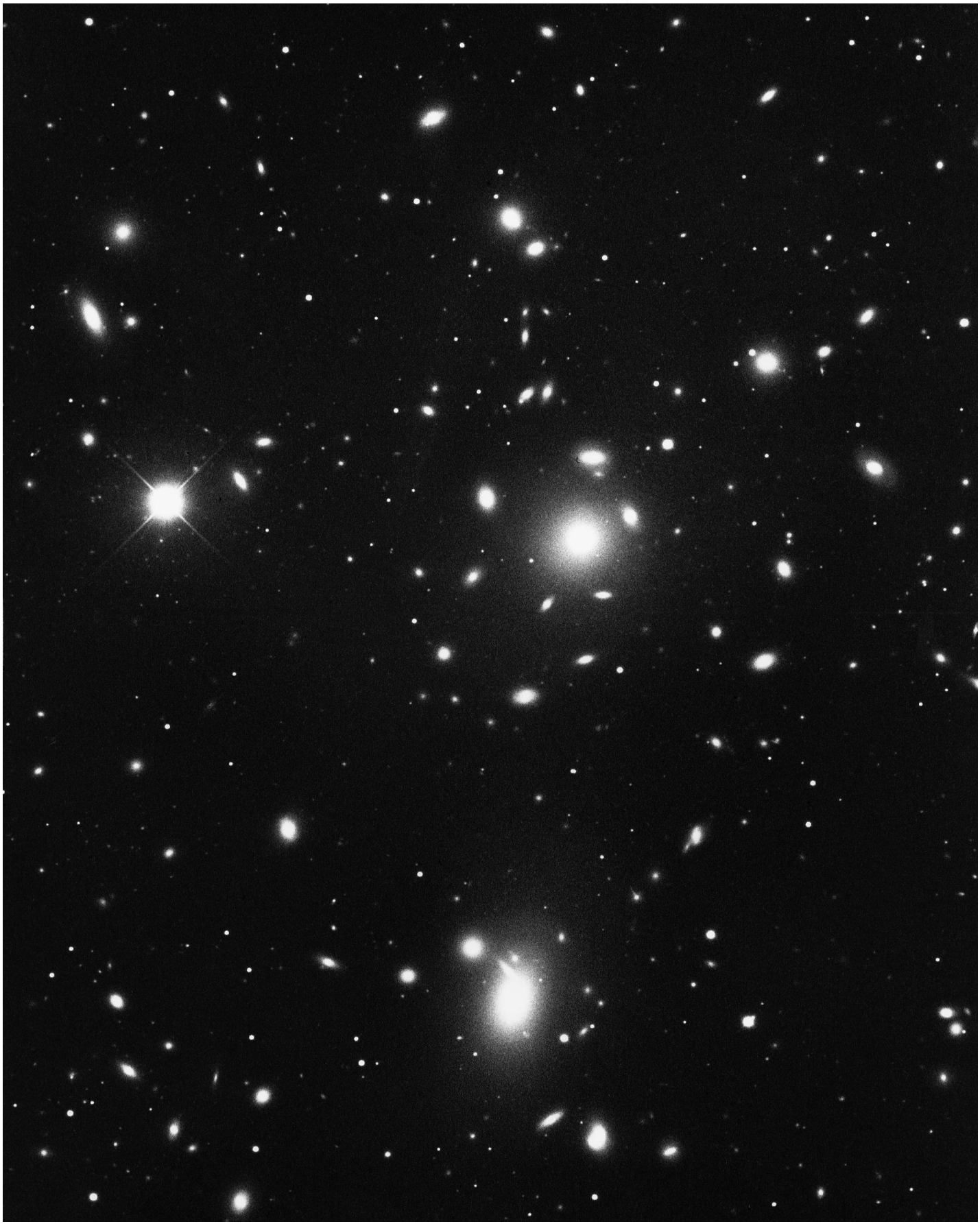
$$percentage\ \ fraction = \frac{\#\ of\ \ ellipticals}{total\ \#\ of\ \ galaxies} \times 100$$

| | Density | Elliptical | Spiral | Irregular |
|---|---|---|---|---|
| Coma | very dense | | | |
| Hercules | not so dense | | | |
| Poor groups | few galaxies | 25% | 70% | 5% |

e) How does the proportion of Elliptical and Spiral Galaxies depend on the density of the Environment?

f) As the universe ages, galaxies gravitate toward each other, in other words, clusters tend to get denser. What impact could such an evolution have on the morphologies of the galaxies?

# Coma Cluster



# Hercules Cluster

# Part V — Galaxy Evolution

a) Look at the Hubble Deep Field. These are galaxies at the edge of the universe. Since light from them takes a long time to reach us, most of those galaxies are intrinsically young. Take a part of that picture and count the number of Elliptical, Spiral, and Irregular galaxies. Determine the PERCENTAGES of Elliptical, Spiral, and Irregular galaxies and complete the table below.

| | | % Elliptical | % Spiral | % Irregular |
|---|---|---|---|---|
| Nearby Galaxies; Observed Today | Coma | | | |
| | Hercules | | | |
| | Poor Groups | 25% | 70% | 5% |
| Distant Galaxies | Field Galaxies in the HDF | | | |

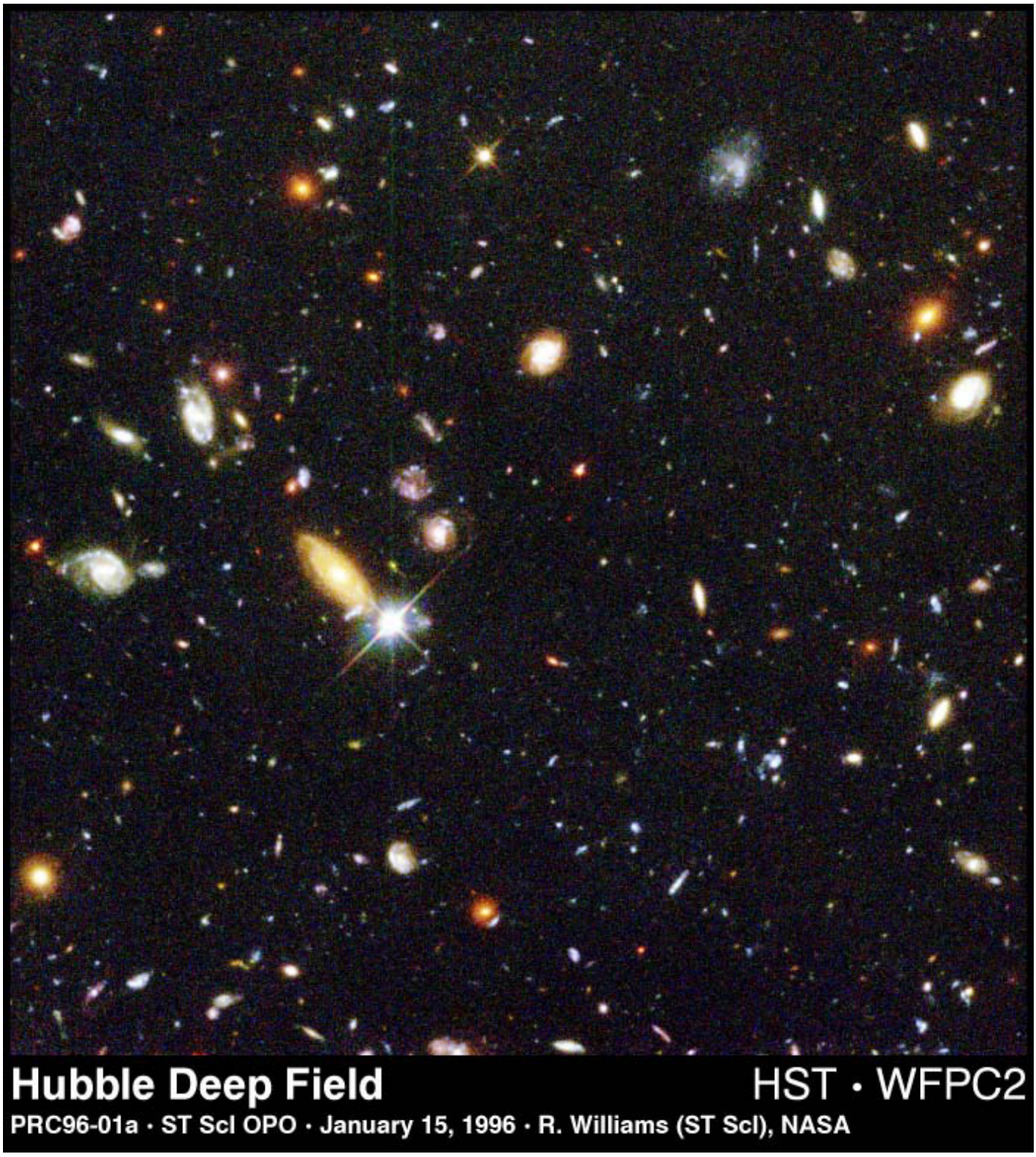
b) How are today's "field galaxies and galaxies in poor groups" different from distant ones?

c) Look at the elliptical galaxies in the HDF. Do those Ellipticals look any different from elliptical galaxies seen today? What can you infer about the ages of those galaxies?

d) Which types of galaxies have evolved most? Justify your argument.

e) Comment on the overall evolution of galaxies in the universe, and the role of the environment.

# The Hubble Deep Field




This is a Picture of the Hubble Deep Field (HDF). It was taken with the Hubble Space Telescope for 15 consecutive days. It is the deepest image taken of the sky (apart from the Hubble Deep Field South). You virtually see galaxies at the edge of the universe (and everything else in between). This is a picture of the most distant galaxies we have ever seen.

# Lab Report

1) Objective of the Lab (be brief and ***concise*** – mention methodology and objective of *entire* lab)

2) Summarize the results from Part II & III. **Critically** discuss this ***Classification*** Scheme. Is it a useful scheme? Why / why not? To ***what degree*** does this scheme depend on the quality of the pictures?

3) **SUMMARIZE** the results from Part III and IV Table. Copy the numbers from the first and second tables in part III into the table below. Copy the numbers from the first table in Part IV into the bottom row.

| | Ellipticals | | Spirals | | Irregulars | |
|---|---|---|---|---|---|---|
| | # | % | # | % | # | % |
| Coma | | | | | | |
| Hercules | | | | | | |
| Poor Groups | --- | 25% | --- | 70% | --- | 5% |
| HDF | | | | | | |

Use Words to summarize the results from the above Table.

4) **ANALYZE** your results and think about the significance of the numbers you just summarized. Now let's assume you misclassified some galaxies. Two of the elliptical galaxies in Coma are in fact Spirals, two of the Spirals in Hercules are Ellipticals, and two of the Irregulars in the HDF are spirals. Insert the new numbers into the table below and calculate the percentages.

| | Ellipticals | | Spirals | | Irregulars | |
|---|---|---|---|---|---|---|
| | # | % | # | % | # | % |
| Coma | | | | | | |
| Hercules | | | | | | |
| Poor Groups | --- | 25% | --- | 70% | --- | 5% |
| HDF | | | | | | |

Compare the results from the two above tables. How different are the numbers in the second table? How do they affect what you said in the previous point?

5) **EXPLAIN** what the results from points 4 and 5 tell you about how galaxies evolve and how this evolution depends of the environments of galaxies.

6) Because Lenticular Galaxies (the S0's) are often misclassified as Ellipticals, they were not included in Parts III and IV. Below is a Table including these Galaxies. Comment on how this would refine the conclusions you reached in point 6.

| | Elliptical | Lenticular | Spiral | Irregular |
|---|---|---|---|---|
| Coma | 40 % | 48 % | 10 % | 2 % |
| Hercules | 20 % | 44 % | 32 % | 4 % |
| Poor Groups | 10 % | 30 % | 55 % | 5 % |
| Galaxies in HDF | 30 % | 20 % | 30 % | 20 % |

7) Suggest **several** mechanisms that may make galaxies evolve. Mention how these mechanisms might change the galaxy morphologies (for example, galaxies may collide and merge, but there are also many other ways in which galaxies may change).