Project D:
Galaxy Classification

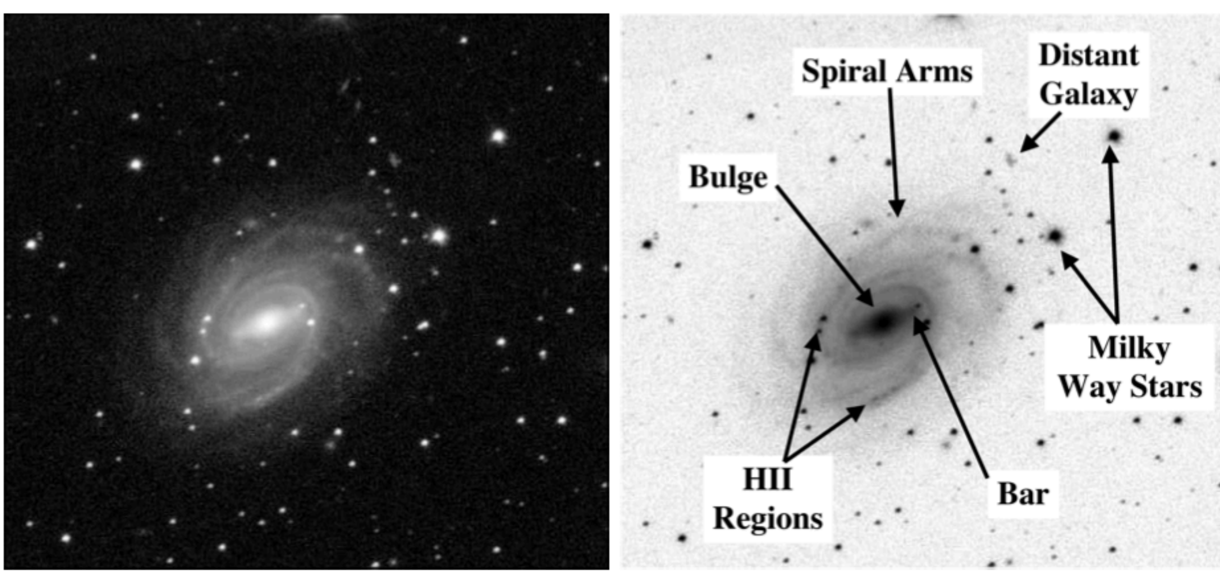
Galaxies have a wide variety of appearances. Some are smooth and some are lumpy. Some have a well-ordered symmetrical spiral pattern, while others are diffuse, patchy, and irreg- ular. For many decades, astronomers have tried to find the underlying order in the diverse properties of galaxies. This desire has led to the development of the Hubble Sequence, a system of classification that groups galaxies into a series of “types”, based only on images.

Although the Hubble Sequence is used to classify galaxies solely on the basis of images seen through a single filter (i.e. images that would appear to be black and white if printed), astronomers have found that many other properties of the galaxies, such as their colors and spectra, also correlate with their Hubble classification. In other words, galaxies that differ structurally (or “morphologically”) also tend to differ in their colors and spectral properties. The origin of this remarkable correlation is still not understood.

In this lab you will explore the Hubble sequence by classifying a number of galaxies. You will then inspect the colors and spectra of those galaxies, and interpret the trends you identify.

Understanding Galaxy Images

In the figure below are two images of the same spiral galaxy. The left panel shows the familiar image that you would see if you took a picture of the galaxy through a single filter. The image on the right shows the “negative” (or “inverse”) of the image on the left. The negative image has been altered so that dim parts of the original image are now white, and bright parts are now dark. Astronomers use these “negative” images to classify galaxies, because they typically show more detail than the more traditional “white-on-black” view.



Galaxies are assigned a Hubble type of “E”, “S0”, “Sa”, “Sb”, “Sc”, “Sd” or “Irr”. Galaxies which fall early in this sequence are sometimes called “early-type”, and galaxies near the end of the sequence are called “late-type”. A galaxy’s Hubble type is based on the prominence of many different features, some of which are labeled in the right hand image of the figure above. The most important of these features are:

1. The size of the bulge compared to the disk. Galaxies with a strong bulge but no detectable disk are classified as ellipticals (denoted as “E”). Galaxies with disks but no detectable bulges are classified as late-type spirals (“Sd”) or irregulars (“Irr”). In between these two extremes are galaxies with both disks and bulges. These are classified as “S0”, “Sa”, “Sb”, and “Sc”, with galaxies with smaller bulges appearing later in this sequence.

2. The presence or absense of spiral arms. Galaxies with spiral arms are classified as “Sa”, “Sb”, “Sc”, and “Sd”. Galaxies with smooth disks, but no spiral arms, are classified as “S0”. Galaxies with lumpy irregular disks, but without spiral arms, are classified as irregulars (“Irr”).

3. The “tightness” of the spiral arms. In “early-type” galaxies (“Sa”, “Sb”), the spiral arms are very tightly wound around the galaxy. In many cases the arms are so tightly wound that one could not count how many spiral arms are present. In “late-type” galaxies (“Sc”, “Sd”), the spiral arms are open and very loosely wound, making it easy to trace a spiral arm outwards from the center of a galaxy.

4. The lumpiness of the spiral arms. The spiral arms of “early-type” galaxies tend to be very smooth, with few lumps. The spiral arms of “late-type” galaxies (“Sc”, “Sd”) tend to be very lumpy. The lumps are actually compact regions of star formation known as “HII regions”.

5. The presence or absence of bars. Many spiral galaxies have linear arrangements of stars in their central regions that are distinct from the central bulge. These features are known as “bars”. Spiral galaxies with bars are denoted with a capital “B” after the initial “S”, so that an Sa galaxy with a bar is classified as an SBa. Note that the “B” is always capitalized for barred galaxies.

Many of the features above tend to go together. “Early-type” galaxies with large spheroidal bulges also have many tightly wound spiral arms, and few knots of star formation. “Late- type” galaxies with little or no bulges have only a few loosely wound spiral arms, if any, and many knots of star formation.

On the other hand, many galaxies do not fit cleanly into one of the classical Hubble types. Instead, they have properties that are intermediate between two adjacent Hubble classes, and are therefore labelled E/S0, S0/Sa, Sab, Sbc, Scd, Sd/Irr9. There are also some galaxies that are so unusual that they do not fit into any of these categories. Astronomers classify these simply as “peculiar”.

As you can see from the figure on the previous page, there are many other things visible in the images besides the large galaxy. The compact bright points are stars in the Milky Way that happen to intercept our view of the galaxy. Some of the smaller, fuzzier objects are other galaxies, but ones which happen to be much further away and thus appear smaller.

Understanding Galaxy Colors & Spectra

The light emitted by a galaxy comes from two different sources:

1. **Stars**: The majority of the light emitted by a galaxy comes from stars. As a result, the color and spectra of galaxies are typically not that different from those of stars. The primary difference is that the light emitted by the galaxy is not due to a single star, but to all the stars which have formed over the galaxy's lifetime.

2. **Star Forming Regions:** In addition to the continuum+absorption spectrum pro- duced by stars, most galaxies also show a characteristic pattern of emission lines. Emission lines are produced when gas is illuminated by hot thermal radiation. In galaxies, the "hot thermal radiation" comes from young massive main sequence stars. These O- and B-stars have very short lifetimes (< 0.01 Gyr), and thus the emission lines are only seen when star formation has recently occured. Star formation tends to occur in tight clusters of new stars. These regions are known as "HII regions", because much of the Hydrogen in the region is ionized[1].

The tight link to stars and HII regions, suggests that a galaxy's spectrum can be used to estimate how many stars a galaxy formed in the past, and how many stars the galaxy is forming presently.

For example, the underlying shape of a galaxy's continuum spectrum can tell you which stellar types dominate the population of bright stars. If the brightest stars are red giant stars, then the spectra will rise to the red, and may have spectral absorption line features found in G and K stars. In this case, the absence of bright blue main sequence stars indicates that star formation probably stopped more than 1Gyr ago, and that the galaxy has been relatively quiescent since. In contrast, if the brightest stars are blue main sequence stars, then the spectra will rise to the blue, and may have absorption line features due to O, B, and A stars. Since bright blue main sequence stars are short-lived, their presence indicates that stars are currently forming in the galaxy.

Similarly, the presence of emission lines in a galaxy's spectrum also is a strong indication that star formation is on-going. The HII regions that produce emission lines must contain large numbers of massive main sequence stars. Because these stars must have formed recently, the emission lines are a direct indication of recent star formation. In addition to being detectable through the presence of emission lines in the galaxies' spectra, HII regions can sometimes be detected in the images of the galaxies, where they appear as bright compact knots, usually concentrated along the spiral arms. The knots are the bright regions produced by a cluster of luminous young O and B stars.

[1] Neutral Hydrogen is frequently denoted as "HI", and ionized Hydrogen is denoted as "HII".

Procedure

Attached to the lab are images of 30 galaxies. (You will also find color images of these galaxies linked to the class web page.) Half of the galaxies have been classified according to the Hubble system. For each galaxy you will also see a spectrum of the galaxy. These spectra were generated from the light emitted in the centers of the galaxies. All of the images and spectra were taken from the Sloan Digital Sky Survey.

Classifying Galaxies

Using only the galaxies that have already been assigned to a Hubble type, lay the galaxy images out according to the Hubble sequence. Place galaxies with intermediate Hubble types between the standard Hubble classes (i.e. place Sab galaxies between Sa and Sb galaxies). For this lab,you may ignore whether galaxies are barred or not! However, notice the very high frequency of barred galaxies – probably between 1/3 to 1/2 of all spiral galaxies are barred.

Notice the ways in which the following three quantities vary along the sequence:

• The size of the bulge, compared to the disk
• The tightness with which the spiral arms wind around the galaxy.
• The lumpiness of the spiral arms.

You will find that many of the galaxies assigned to intermediate Hubble types will have properties intermediate between the galaxies assigned to adjacent types. For example, an Sab galaxy might have a bulge that is smaller than a typical Sa, but spiral arms which are smoother than a typical Sb.

1. Based on the black and white images alone, and using the three criteria listed above, decide where to place the unclassified galaxies in the sequence you've laid out (i.e. E, E/S0, S0, S0/Sa, Sa, Sab, Sb, Sbc, Sc, Scd, Sd, Sd/Irr, Irr). Assign the galaxies to the nearest Hubble type, and record your answers in the table on the following page. You will probably discover that it is not always obvious where galaxies fit in the sequence. It is often truly ambiguous how a galaxy should be classified. Three different people might classify the same galaxy as an Sab, Sb, or Sbc, even if all three people are professional astronomers. For this reason, *do not worry too much about finding the one correct type for each galaxy*, since no such thing exists. Just classify the galaxies as best you can, and try not to spend more than a minute per galaxy.

Galaxy Name	Classification
1	S0/Sa
2	
3	E/S0
4	
5	
6	Sc
7	
8	S0
9	E
10	Irr
11	Scd
12	Sc
13	
14	
15	
16	Sab/Peculiar
17	Sb
18	
19	
20	
21	Sd/Irr
22	
23	
24	Sbc
25	E
26	
27	
28	
29	Sb
30	Sa

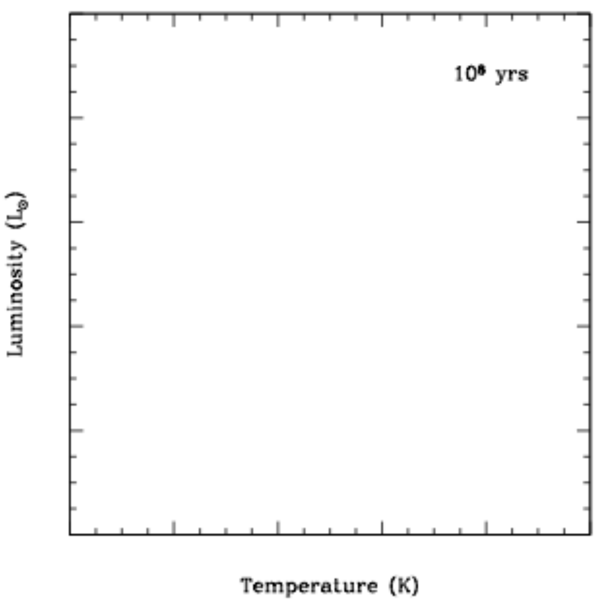
Interpreting Colors of Galaxies

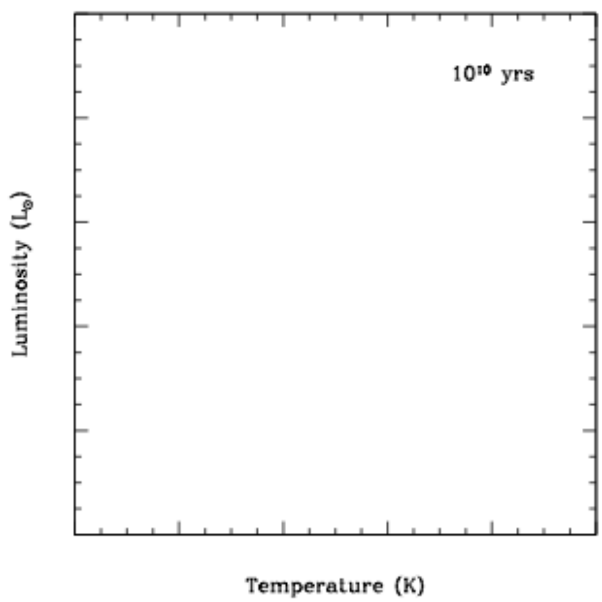
The color of the galaxy is largely determined by the types of stars found in the galaxy. As discussed in the introduction, the colors of the brightest stars will determine the color you perceive with your eye. Thus, the color gives you a hint as to what the “stellar popula- tion” of the galaxy might look like on an H-R diagram, even though you can’t measure the luminosities and colors of the individual stars in the galaxy.

2. Based on the *color* images, how do the typical colors of galaxies vary along the Hubble Sequence, going from early-type elliptical galaxies to late-type disk galaxies? Pay attention to the entire color of the galaxy, not just the central region.

   Early-type galaxies are typically ____________ [redder/bluer] than late-type galaxies.

3. Draw two H-R diagrams in the boxes below, one for a group of stars that all formed recently ($< 10^8$ years ago), and one for a group of stars that all formed long ago ($> 10^{10}$ years). *Please label your axes and a few tick marks,* referring to your textbook if needed.





4. On each H-R diagram, circle the stars that are likely to dominate the *total* light emitted by the entire collection of stars in the H-R diagram.

5. Which H-R diagram will appear bluer when you observe *all* the stars at once (i.e. when you detect the light from all the stars simultaneously, without being able to tell which photons came from which star).

_______________ [older/younger] stellar populations would appear bluer if all the stars were observed at once.

6. Based on your H-R diagrams, which will appear bluer: a galaxy with recent star forma- tion, or one where star formation ended long ago? Explain your reasoning.

7. Based on your answers for Questions 2 & 6, how does the star formation history of early-type galaxies differ from late-type galaxies?

   Early-type galaxies are typically _______________ [younger/older] than late-type galaxies.

8. If you examine the color images of the late-type spiral galaxies (Sb,Sc,Sd), you will find that in general the inner regions of the disk and bulge are typically redder than the bluer outskirts. What might you conclude about the difference in age between the inner and outer regions, and why? (Note, these color variations might be most visible in the web version of this lab, rather than the printed copies!)

Interpreting Spectra of Galaxies

Now examine the spectra of the galaxies you have classified. For reference, the vertical line on each spectrum shows the approximate location of the Hα line produced by ionized Hydrogen. You have seen this same Balmer line in the spectra of stars, but in absorption, not emission. This emission line is almost always present when star formation is taking place. However, remember that the spectra were taken only at the centers of the galaxies, so sometimes a galaxy can have HII regions visible in its spiral arms, but no strong emission lines in its spectrum.

9. Based on the spectra and images of the galaxies, how does the prominence of HII regions vary along the Hubble sequence?

Early-type elliptical galaxies have _______________ [more/less] prominent emission lines than late-type disk galaxies.

10. Given your analysis of the spectra above, how does the current rate of star formation vary along the Hubble sequence?

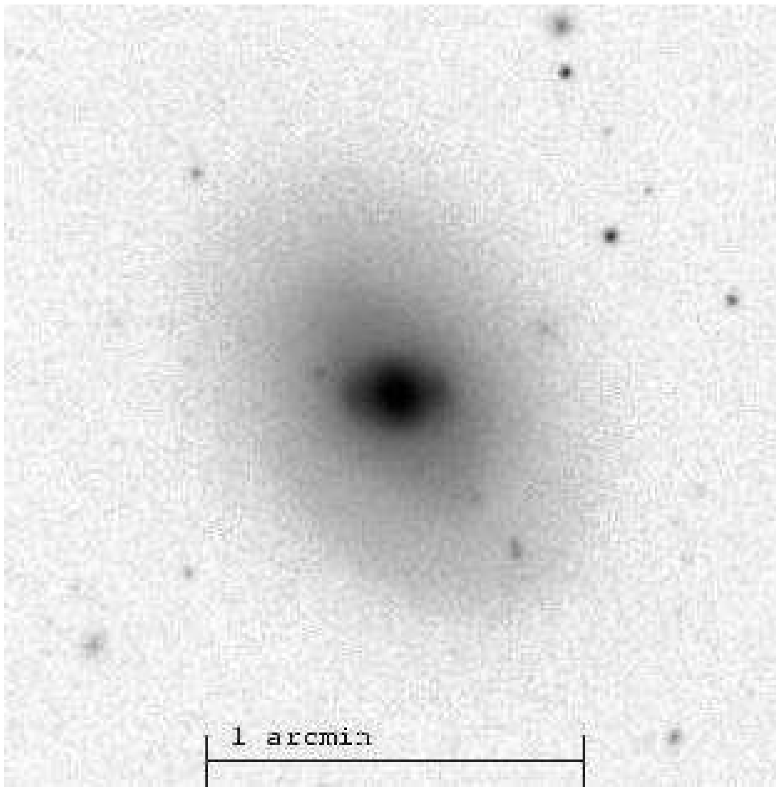
The star formation rate in early-type spirals is _________[lower/higher] than in late-type spirals.

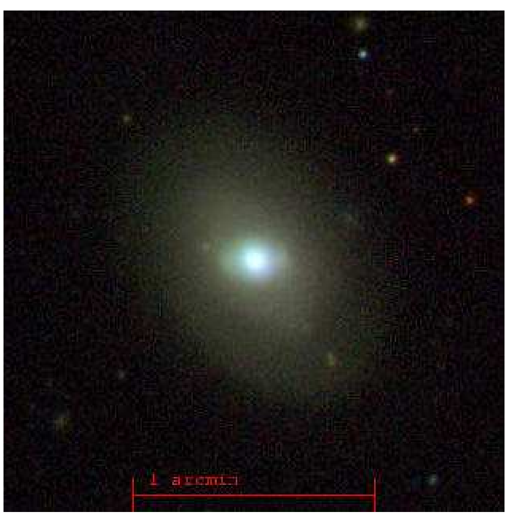
11. Is your answer for Question 7 above consistent with your answer for Questions 10? Explain your reasoning.

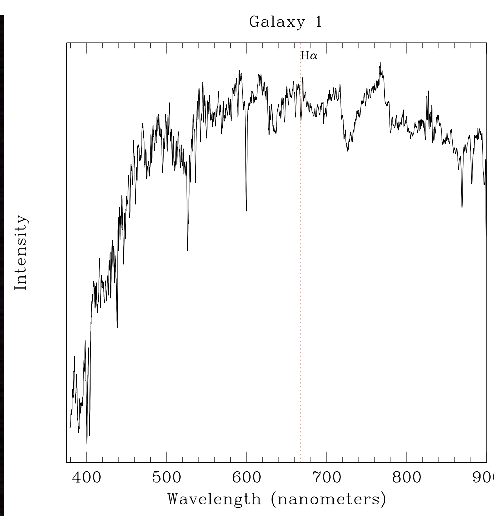
12. Galaxy #22 has an unusual spectrum. It has reasonably strong emission lines, indicating the presence of recent star formation. On the other hand, the underlying continuum appears to be quite red, not blue. Looking at the image of the galaxy, can you speculate about the reason for this discrepancy?

13. Galaxy #10 also has an unusual spectrum. It has blue colors, strong Balmer lines, but no emission lines. Spectra with these characteristics are often called “post-starburst” spectra. Why do you think this nomenclature is applied to spectra like the one seen for Galaxy #10? (Hint: What sort of main sequence stars must be dominating the stellar spectrum? What is the lifetime of such stars, and how does it compare to the main sequence stars that are responsible for producing HII regions?)

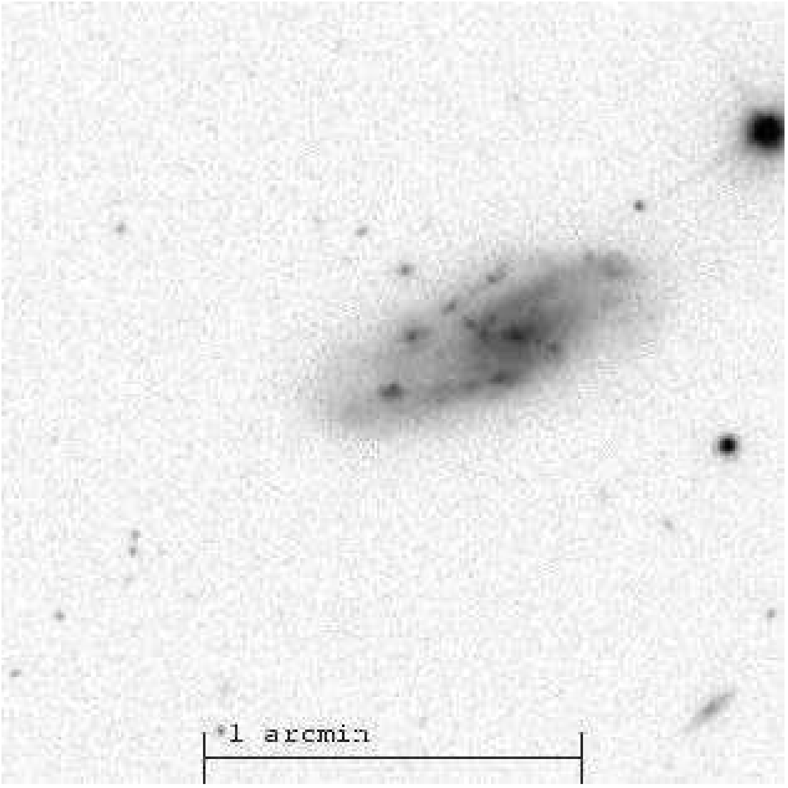
Galaxy #1 Classification: S0/Sa

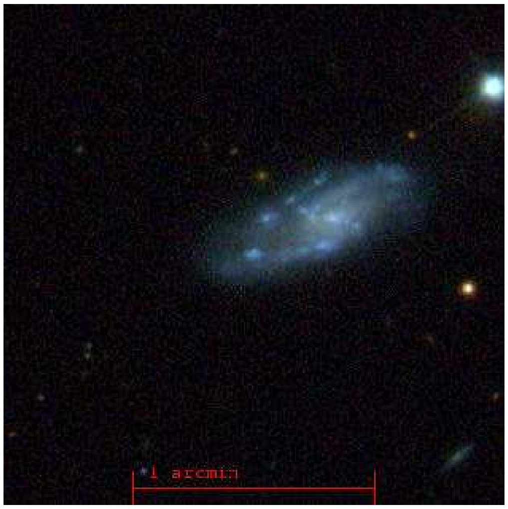


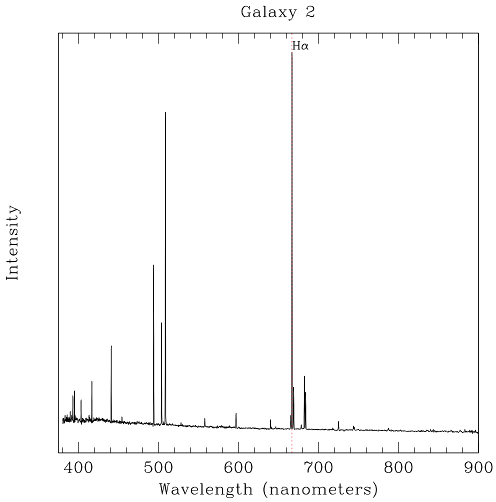




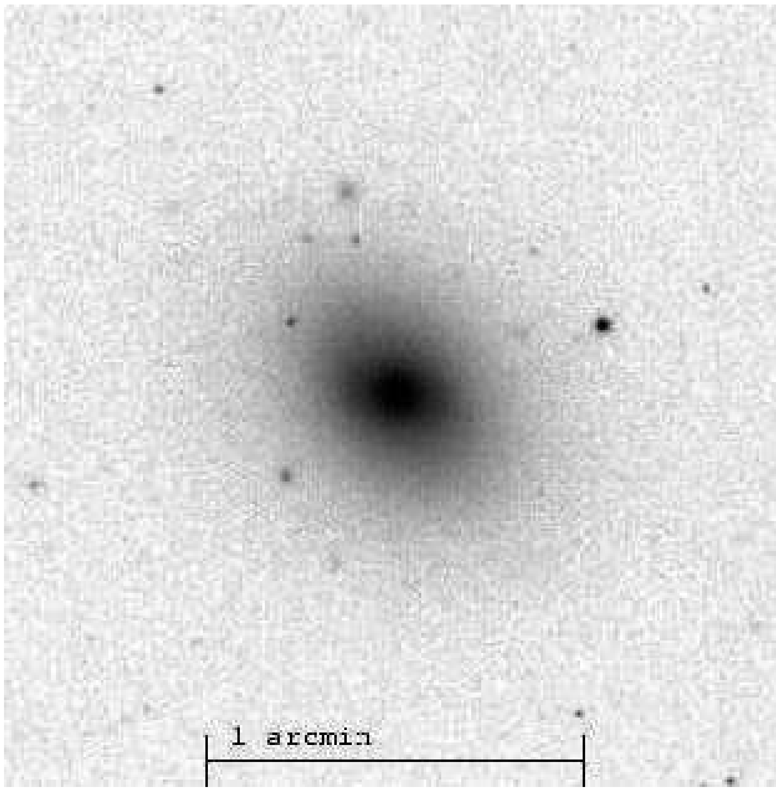
Galaxy #2 Classification:______________

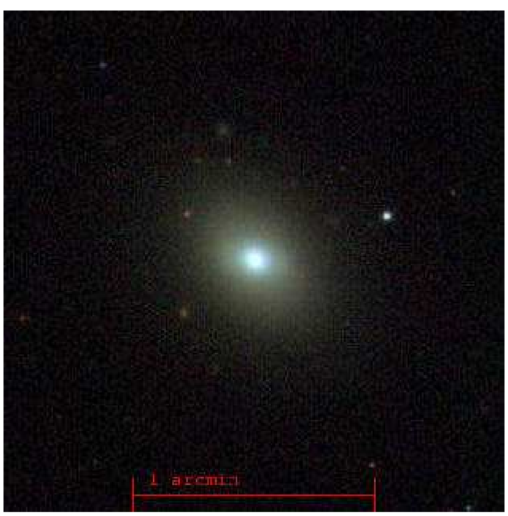


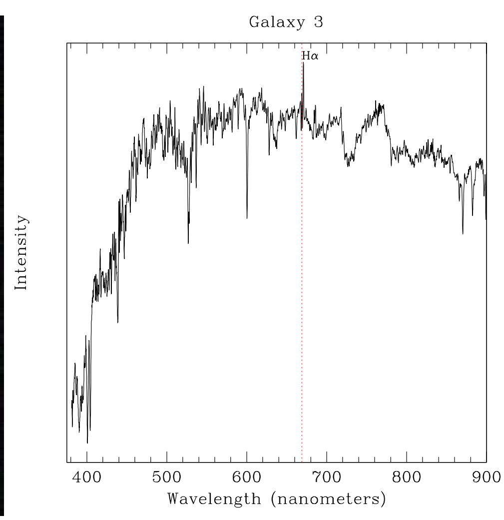




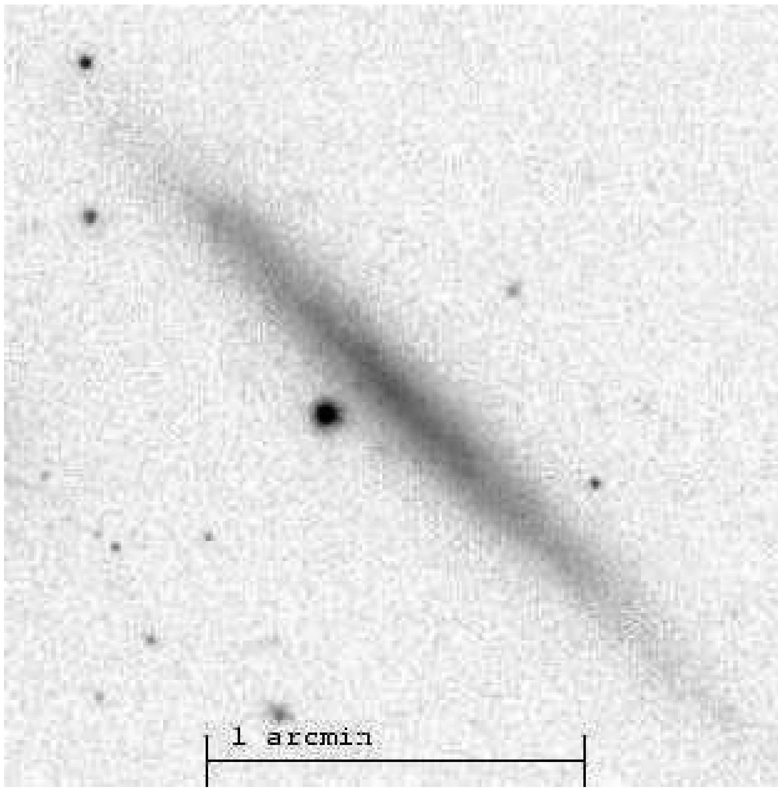
Galaxy #3 Classification: E/S0

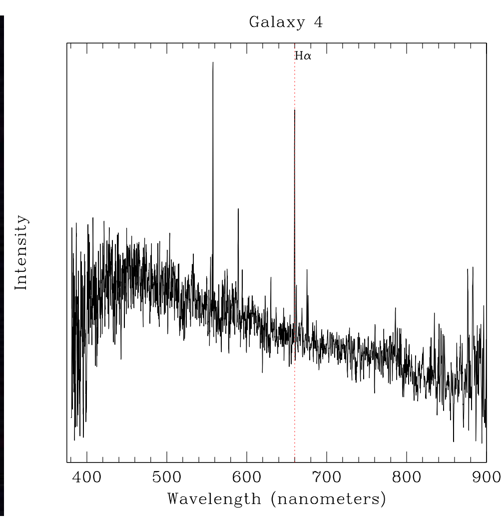




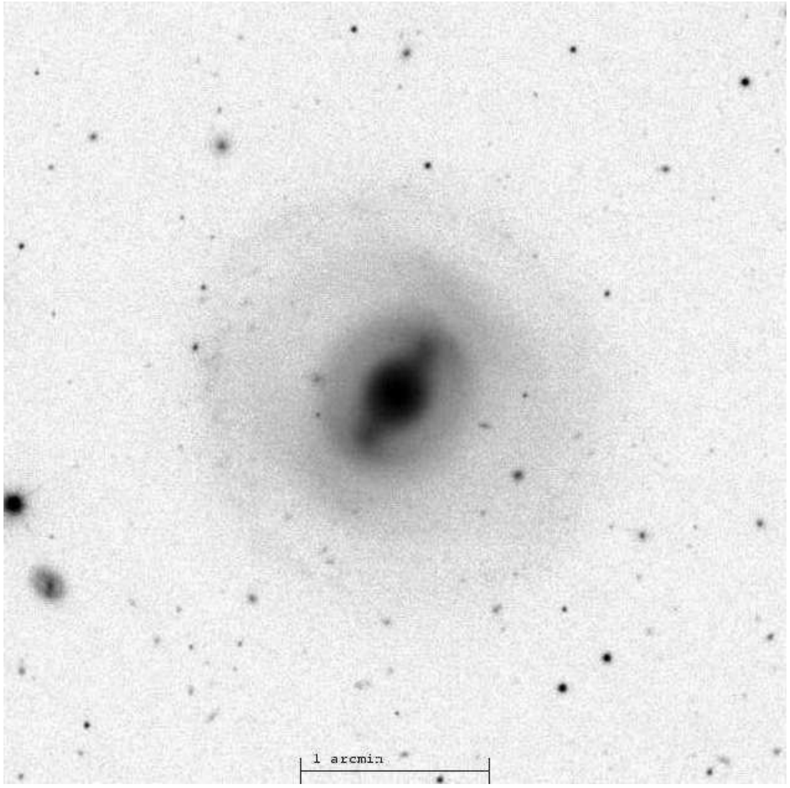


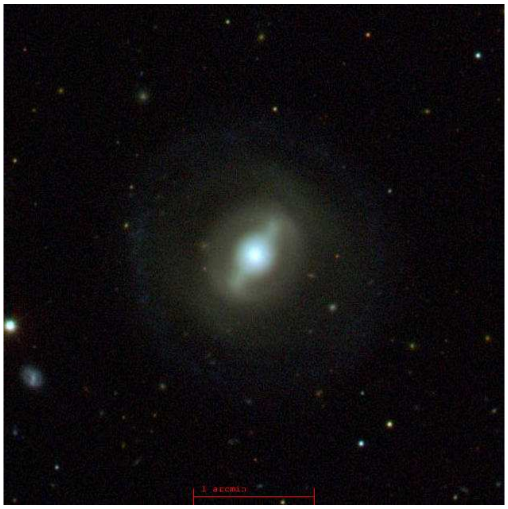
GALAXY #4 CLASSIFICATION:____________

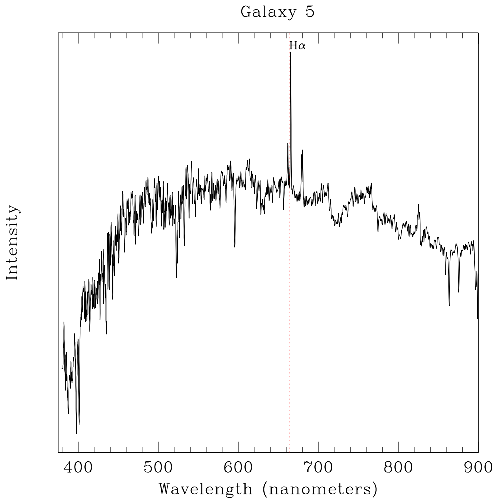




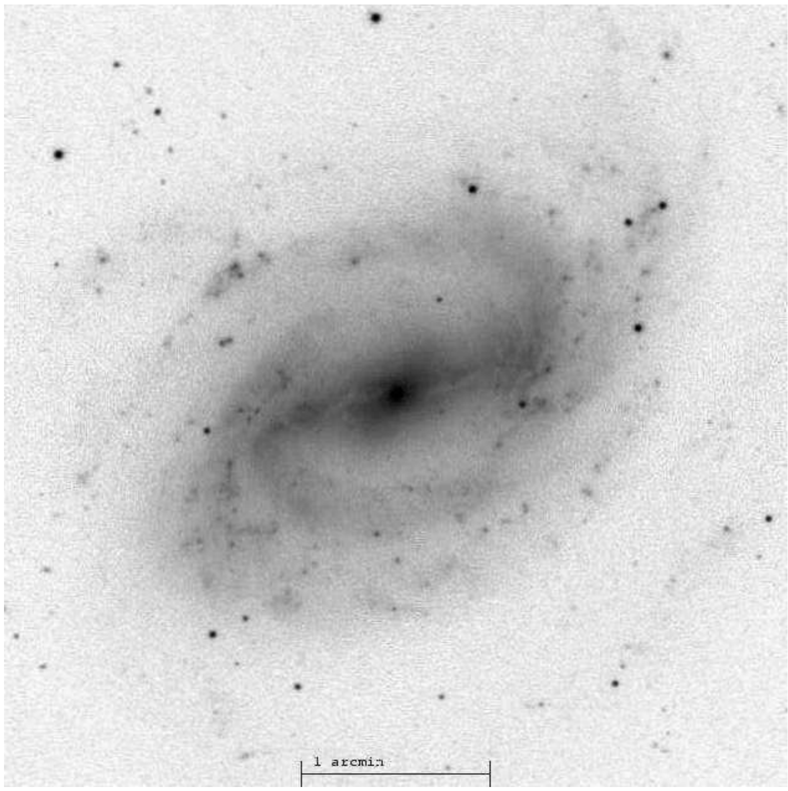
Galaxy #5 Classification:________

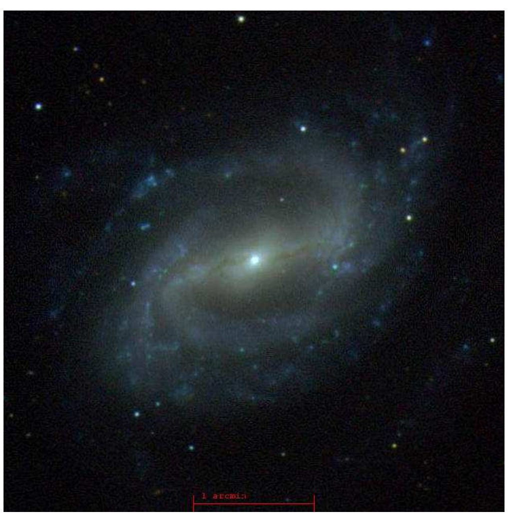


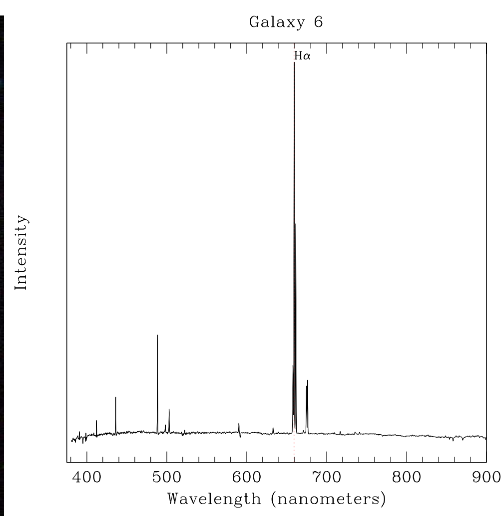




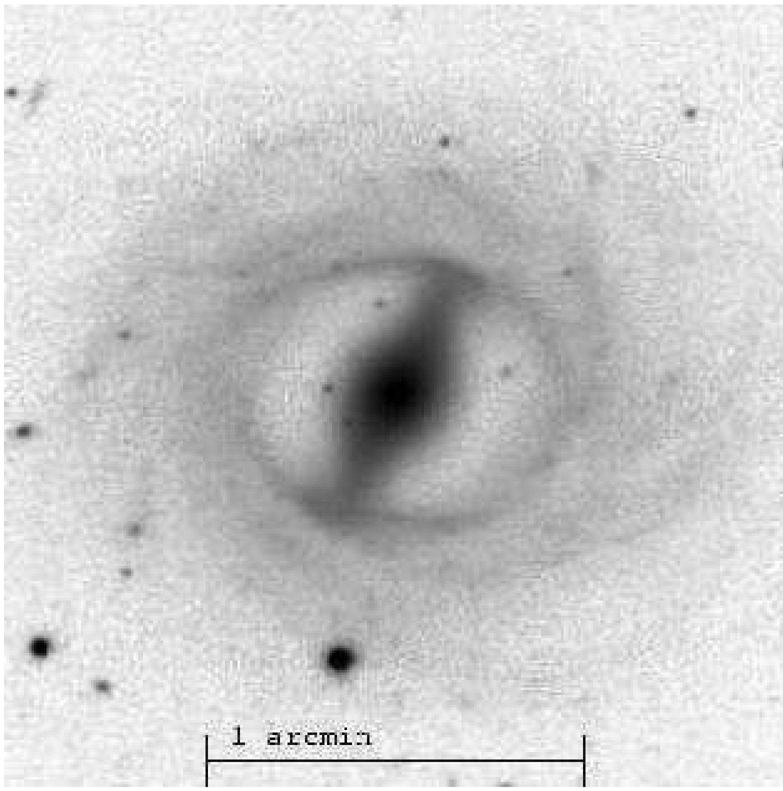
Galaxy #6 — Classification: Sc

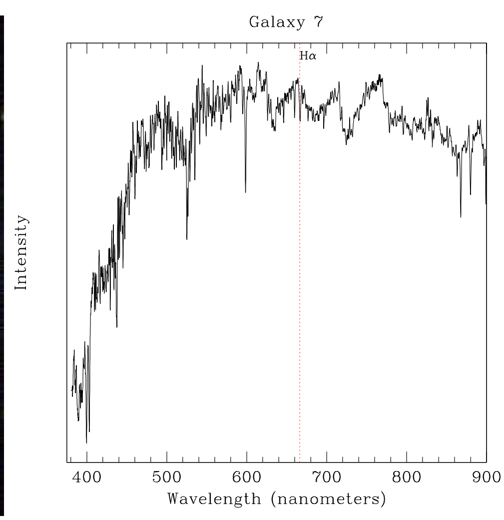




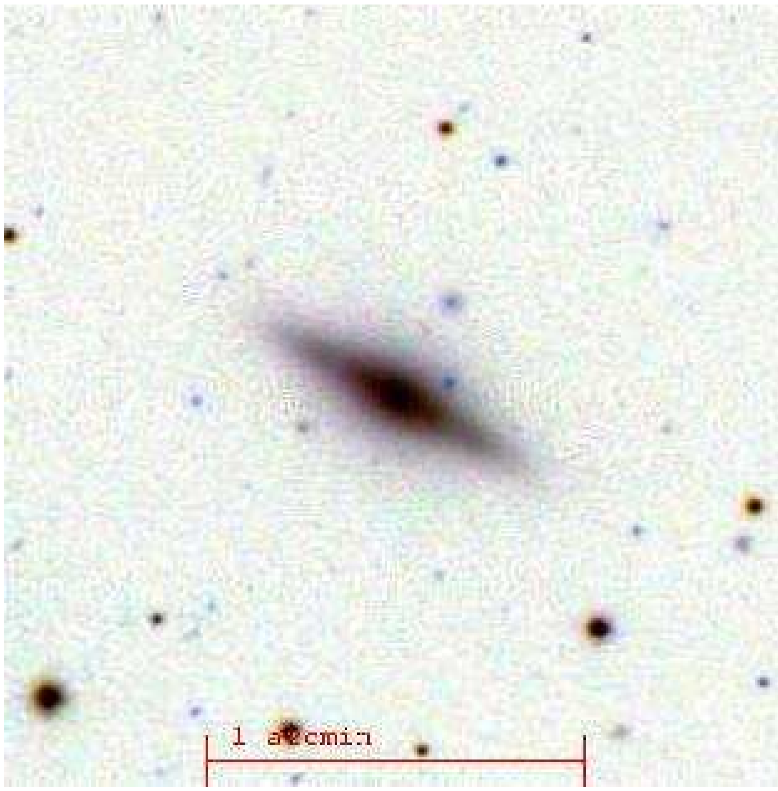


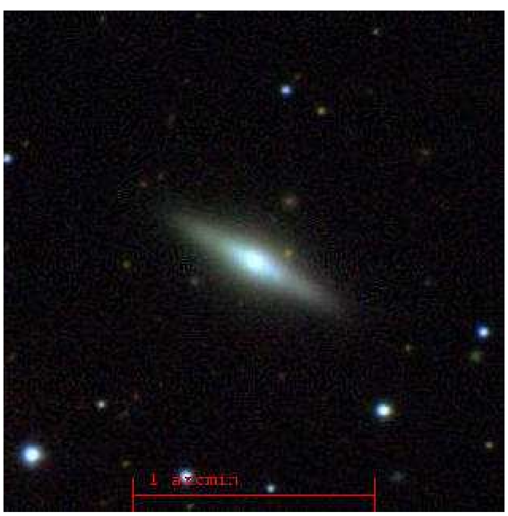
Galaxy #7 Classification:______________

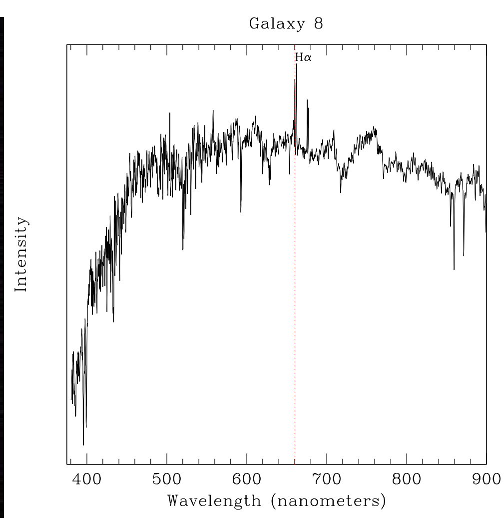




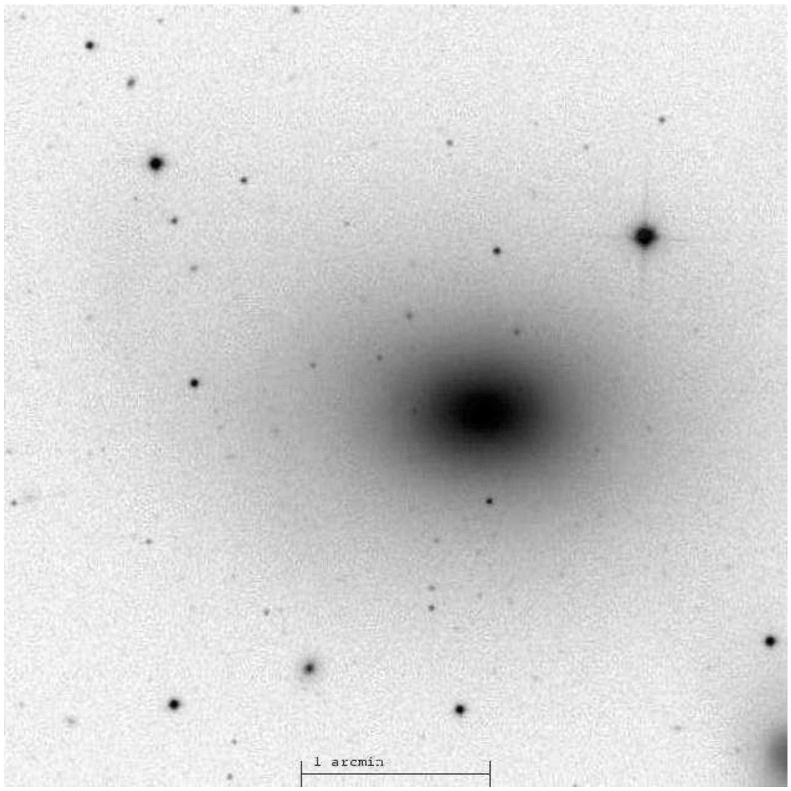
Galaxy #8 Classification: S0

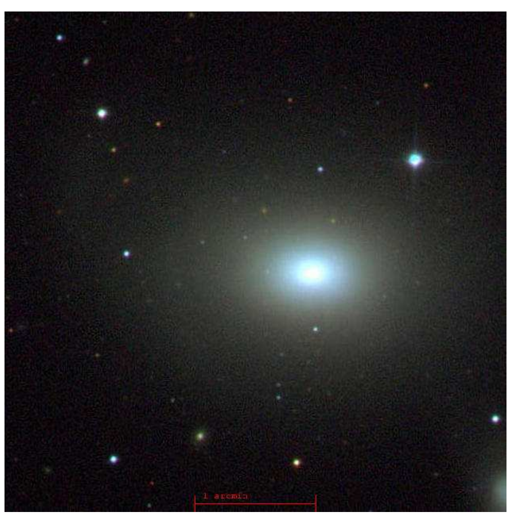


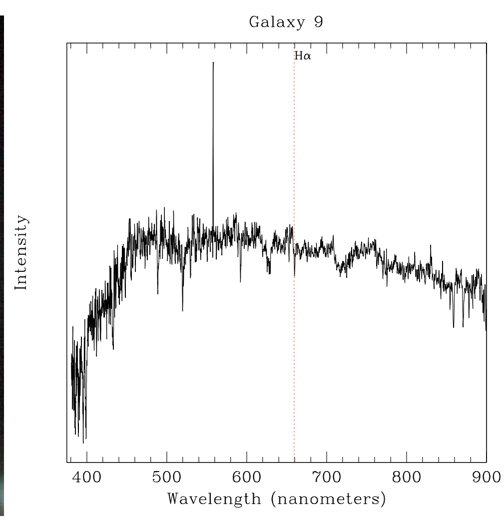




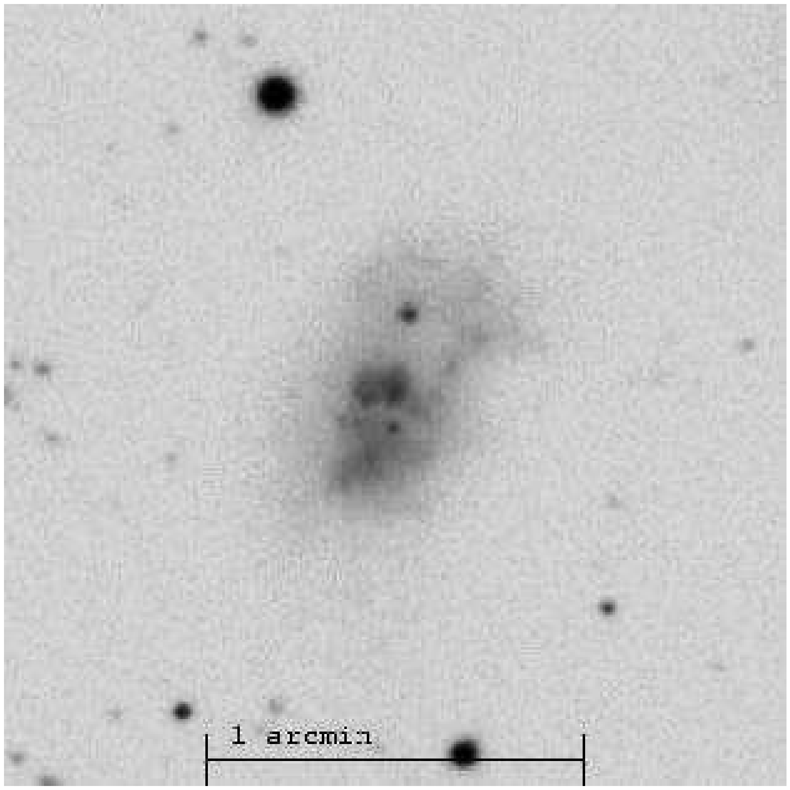
Galaxy #9 Classification: E

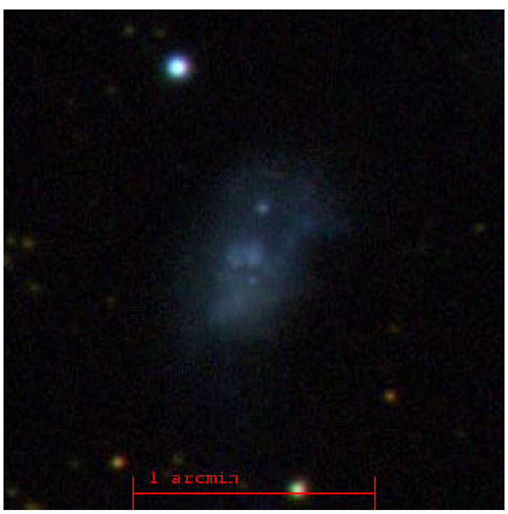


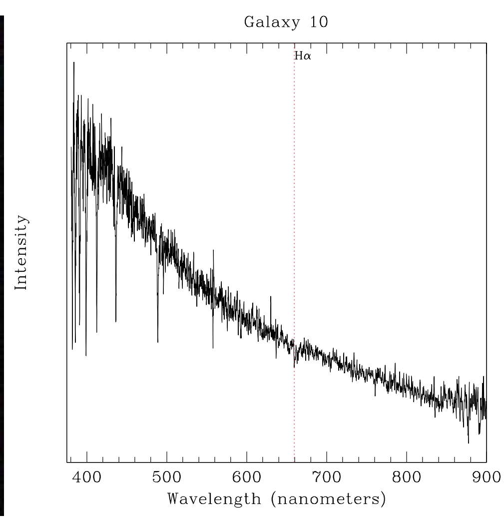




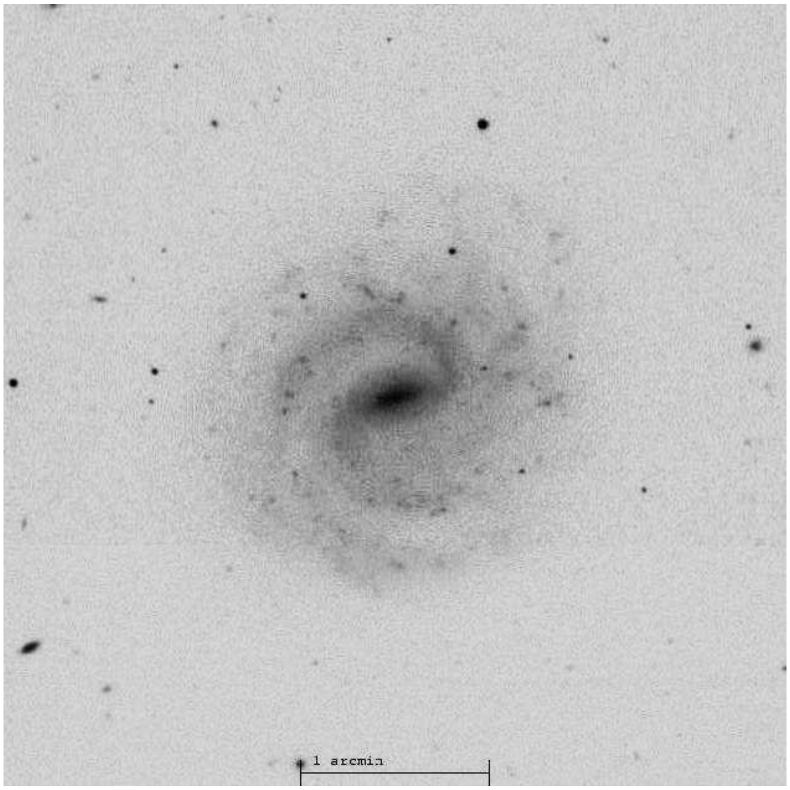
Galaxy #10 Classification: Irr

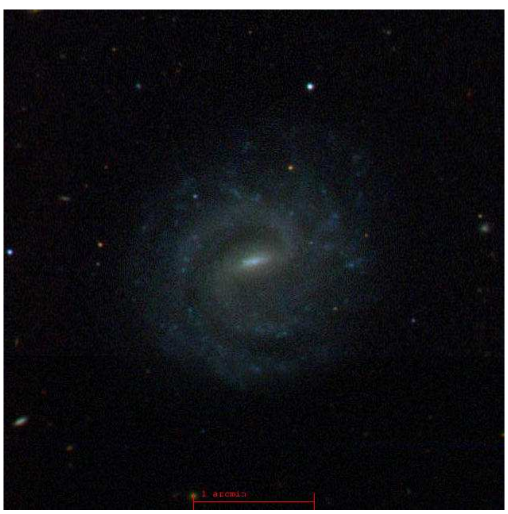


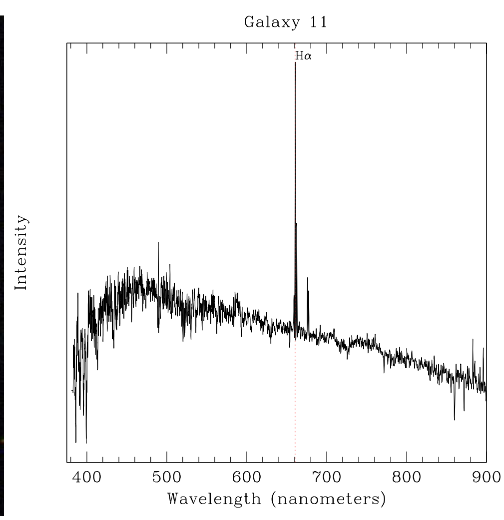




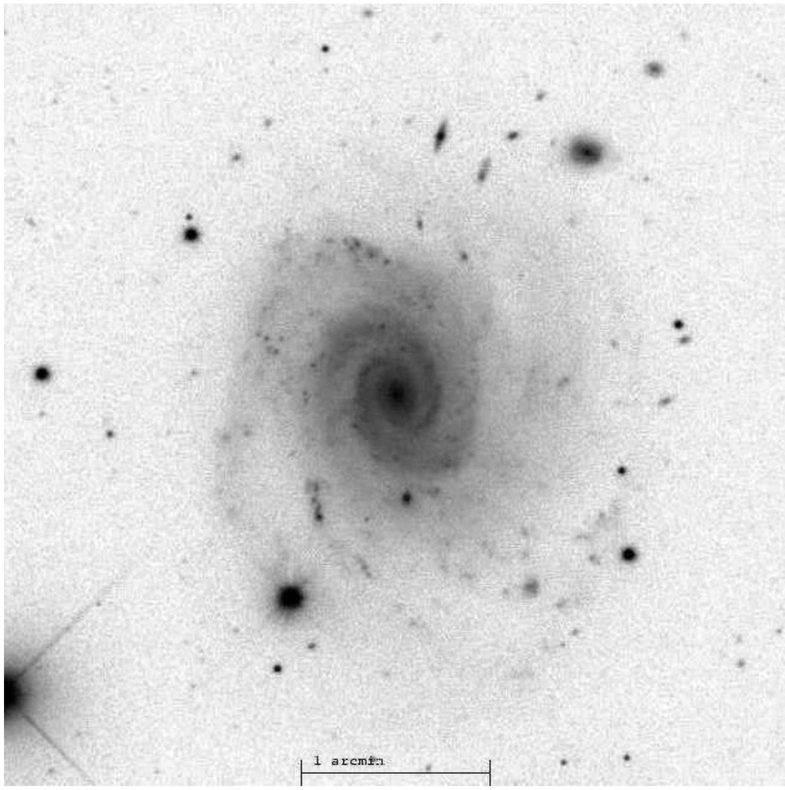
GALAXY #11 CLASSIFICATION: Scd

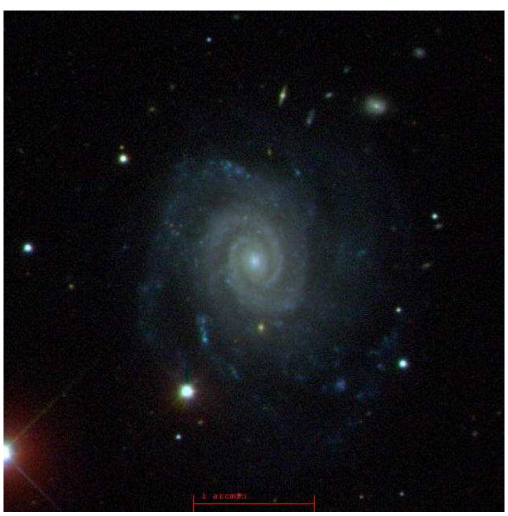


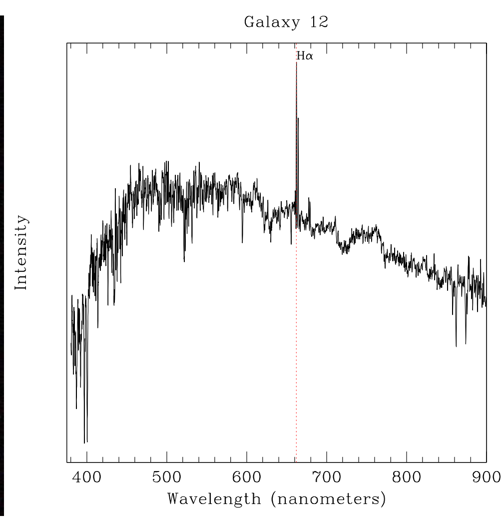




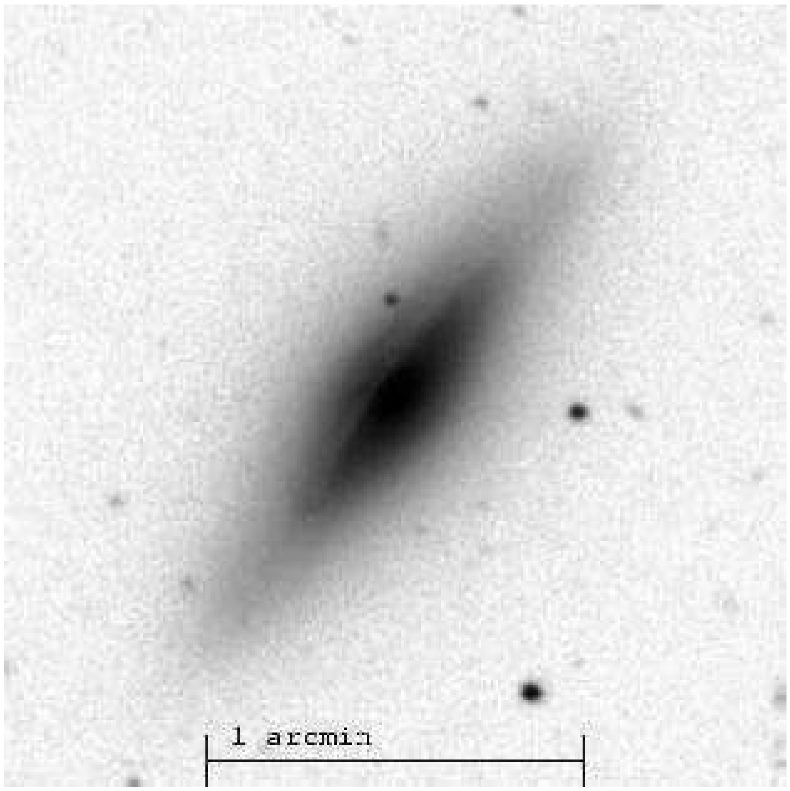
GALAXY #12 CLASSIFICATION: Sc

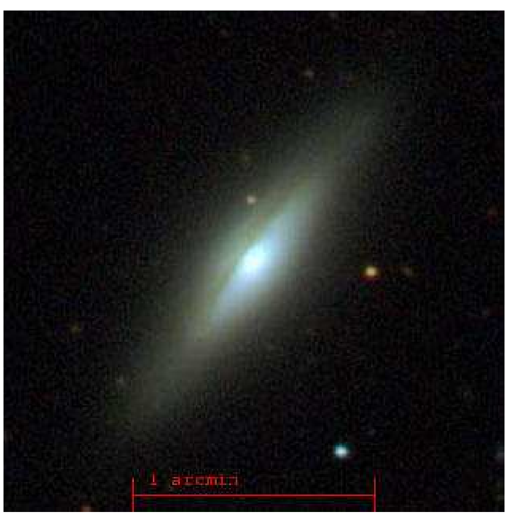


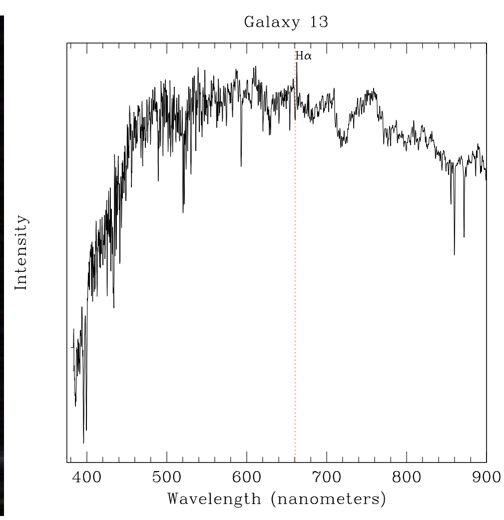




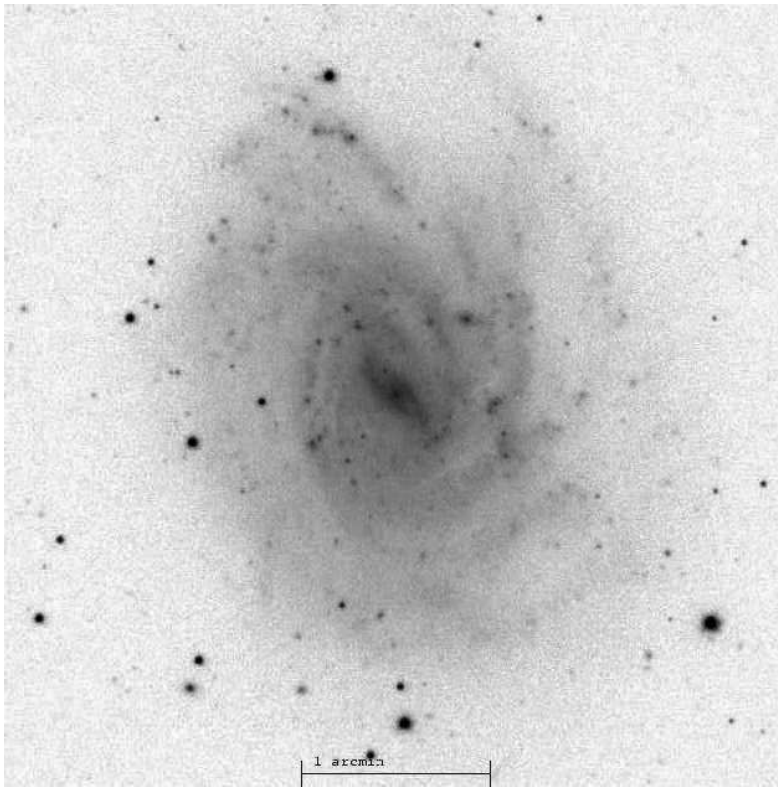
Galaxy #13 Classification:____________

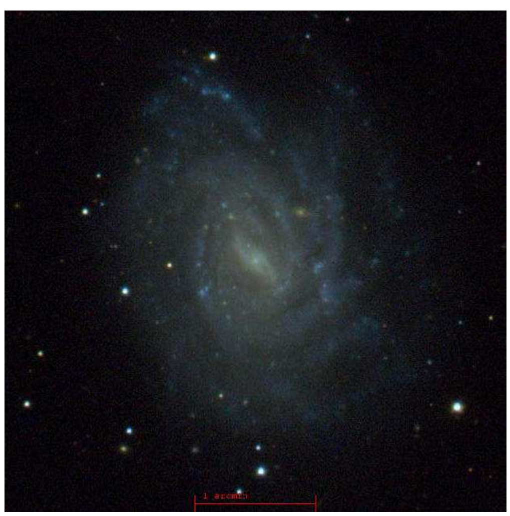


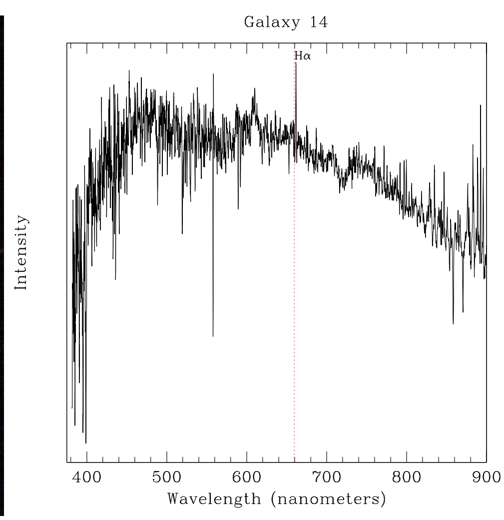




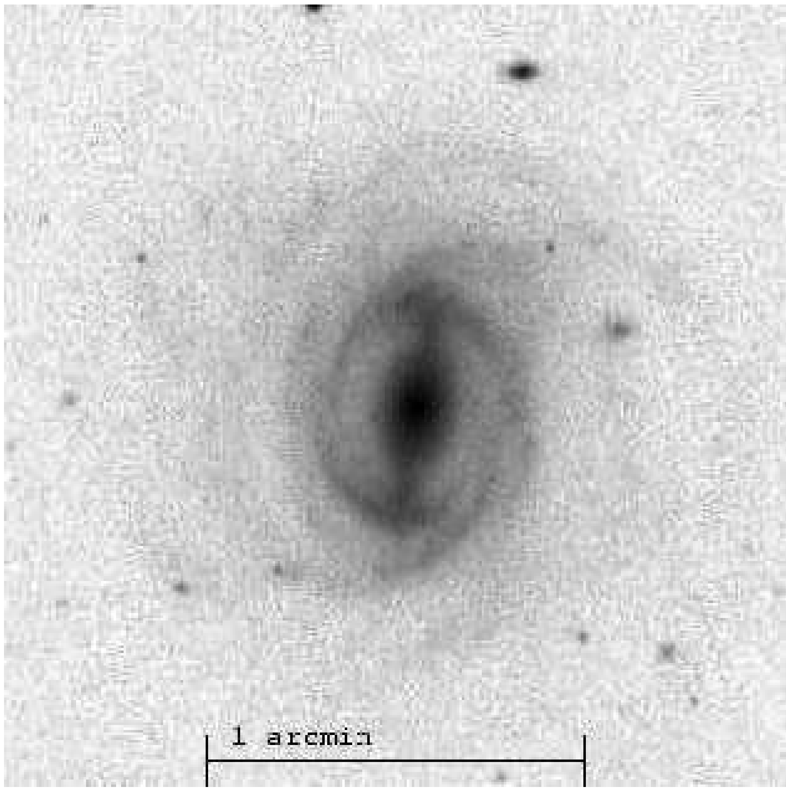
Galaxy #14 Classification:__________

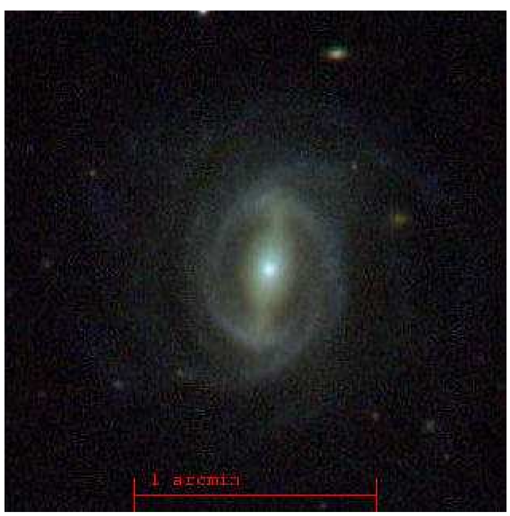


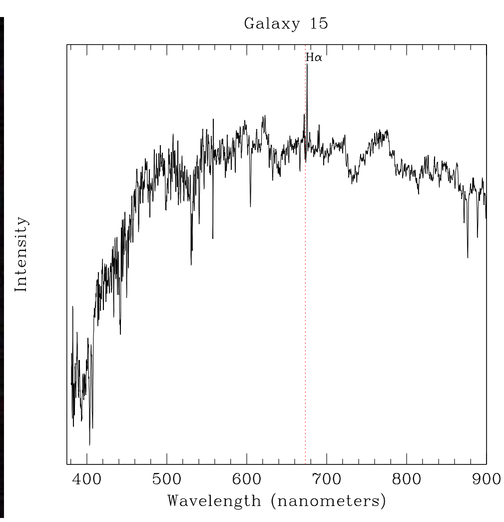




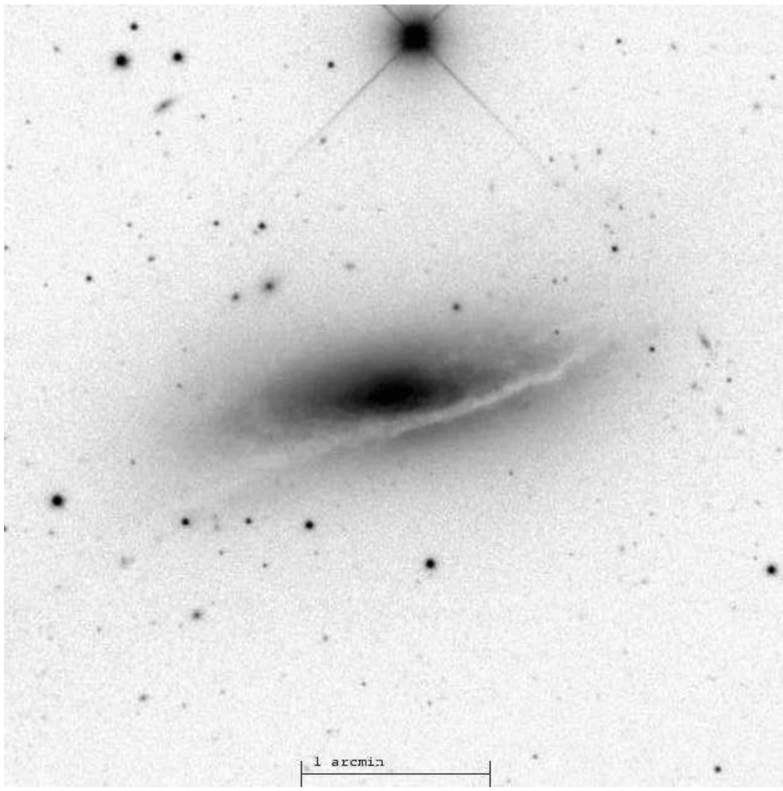
GALAXY #15 CLASSIFICATION:__________

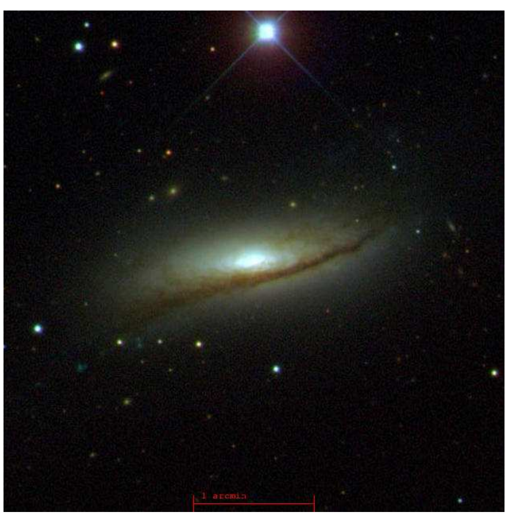


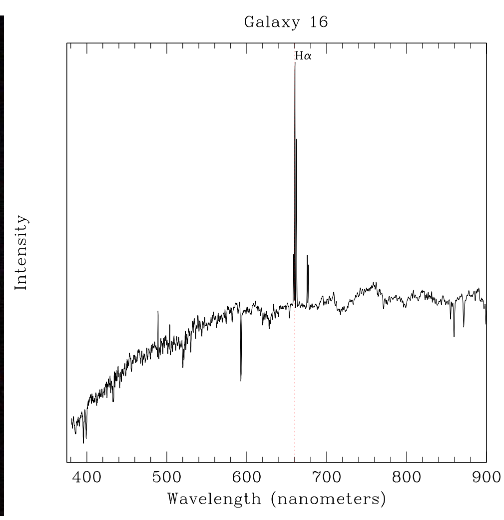




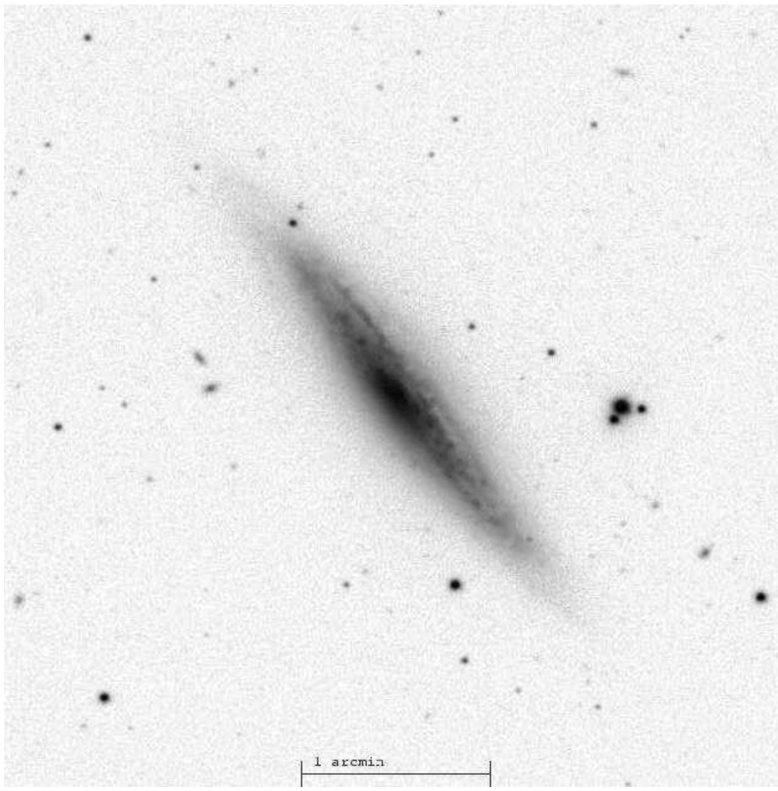
GALAXY #16 CLASSIFICATION: Sab/Peculiar

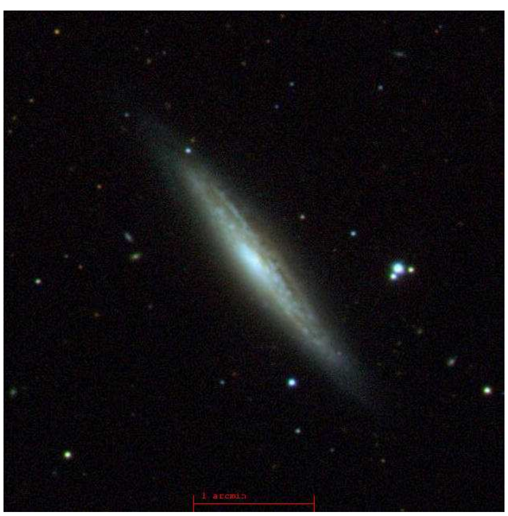


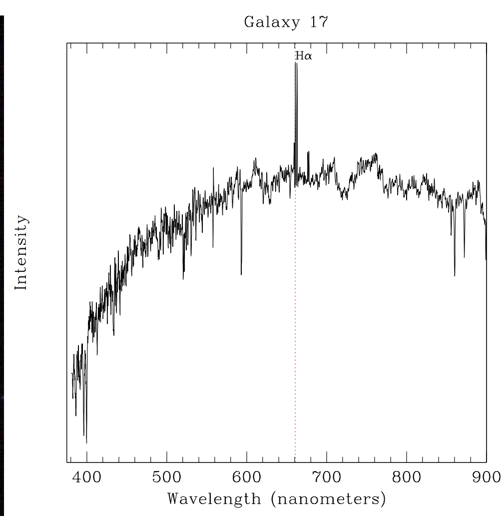




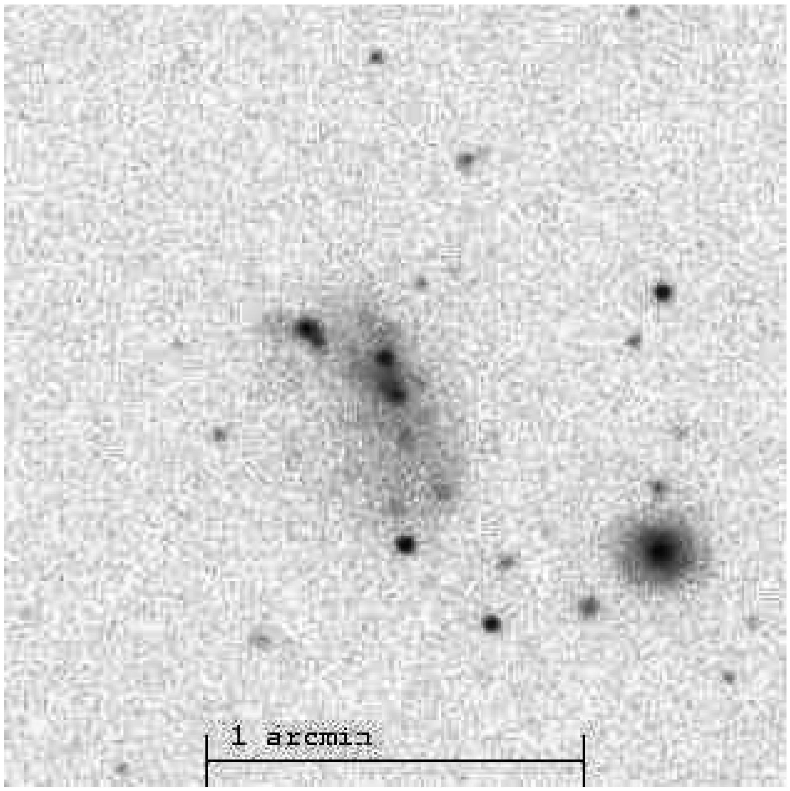
GALAXY #17 CLASSIFICATION: Sb

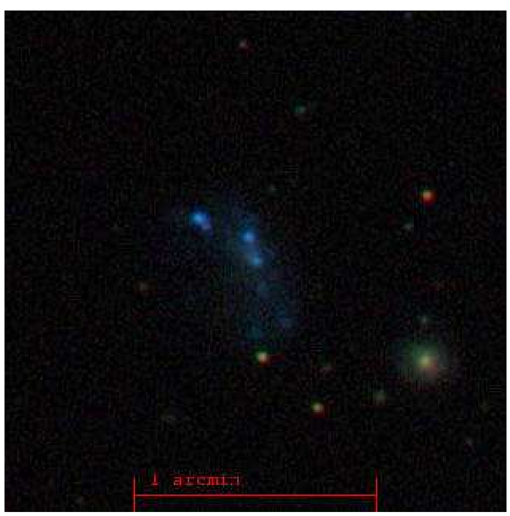


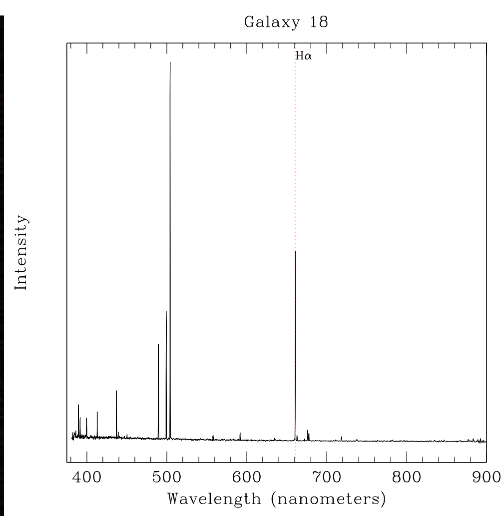




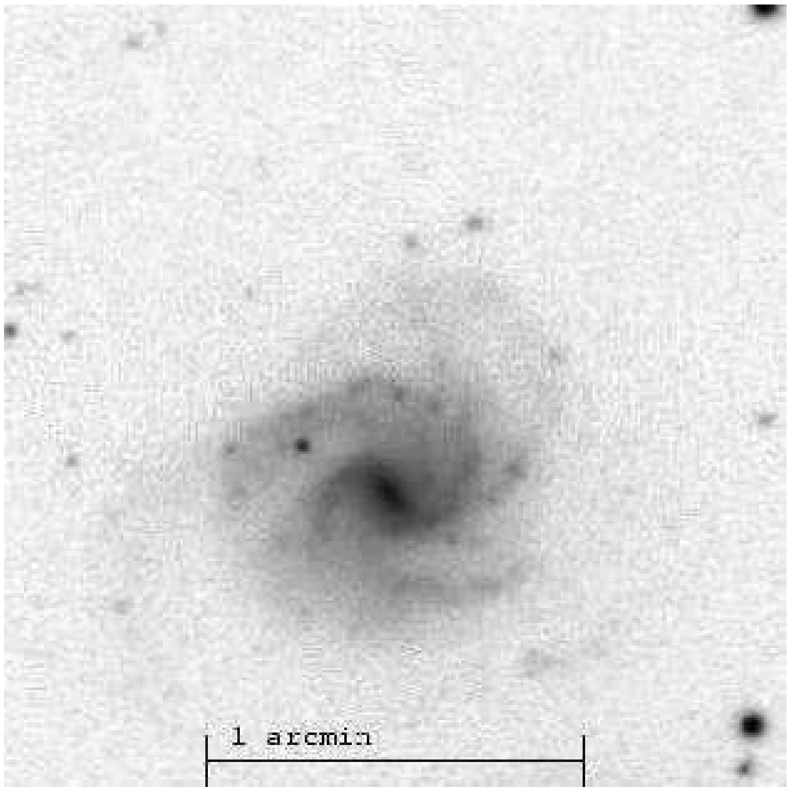
GALAXY #18 CLASSIFICATION:______________

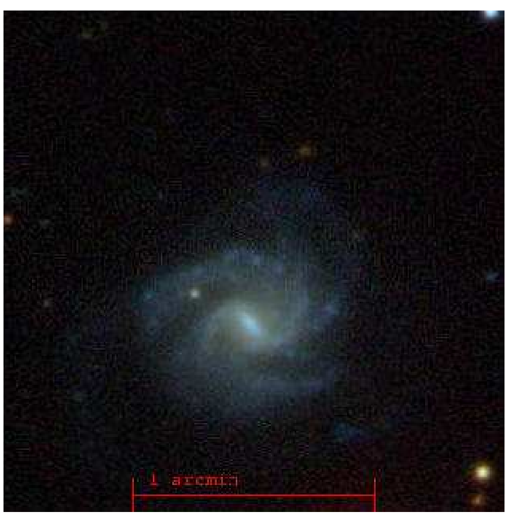


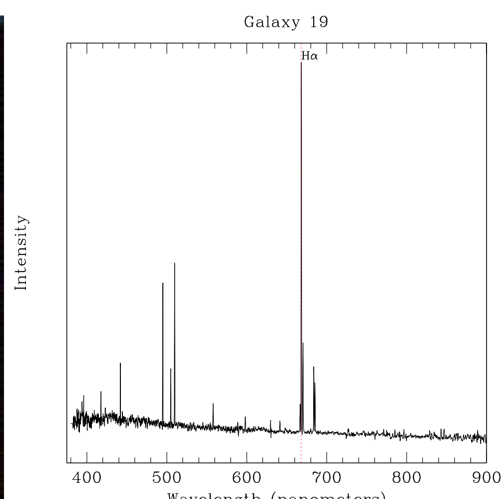




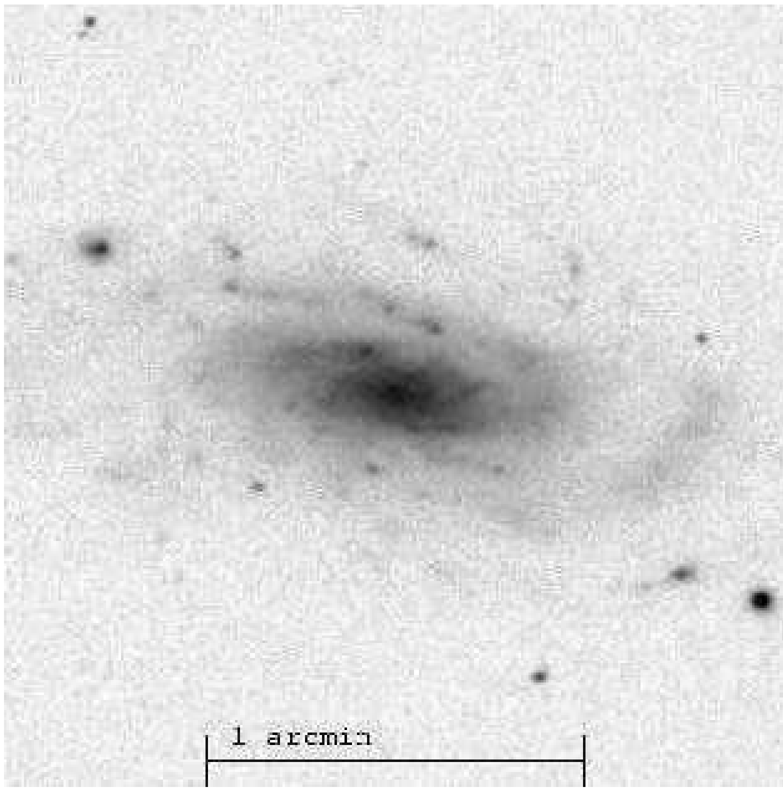
Galaxy #19 Classification:____________

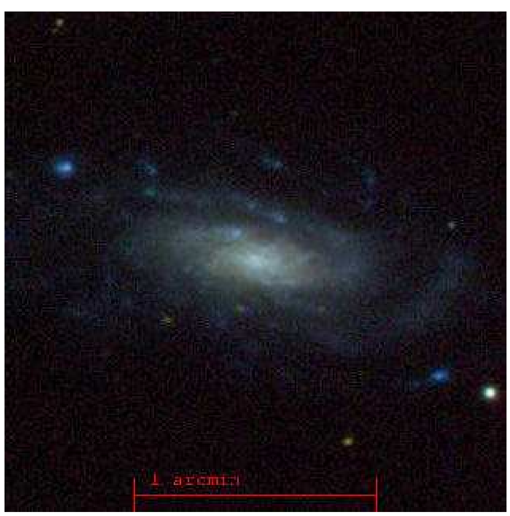


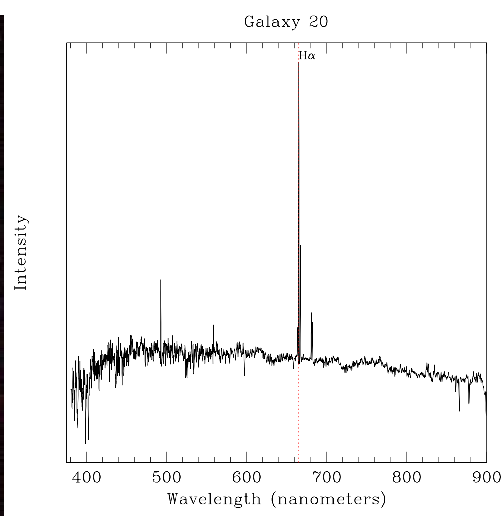




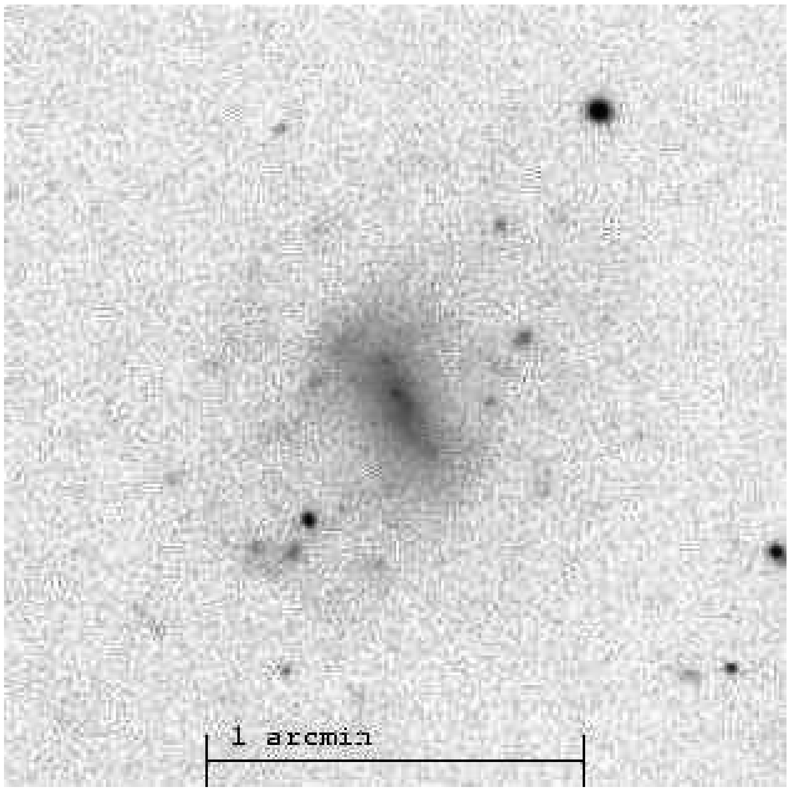
Galaxy #20 Classification:______________

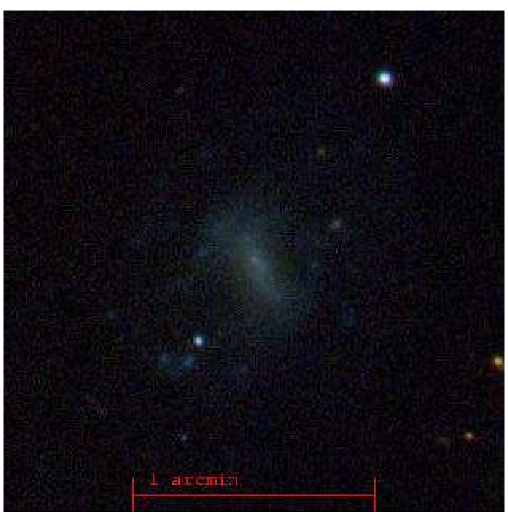


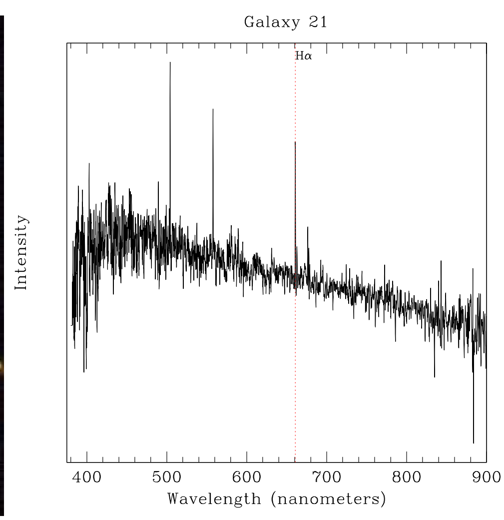




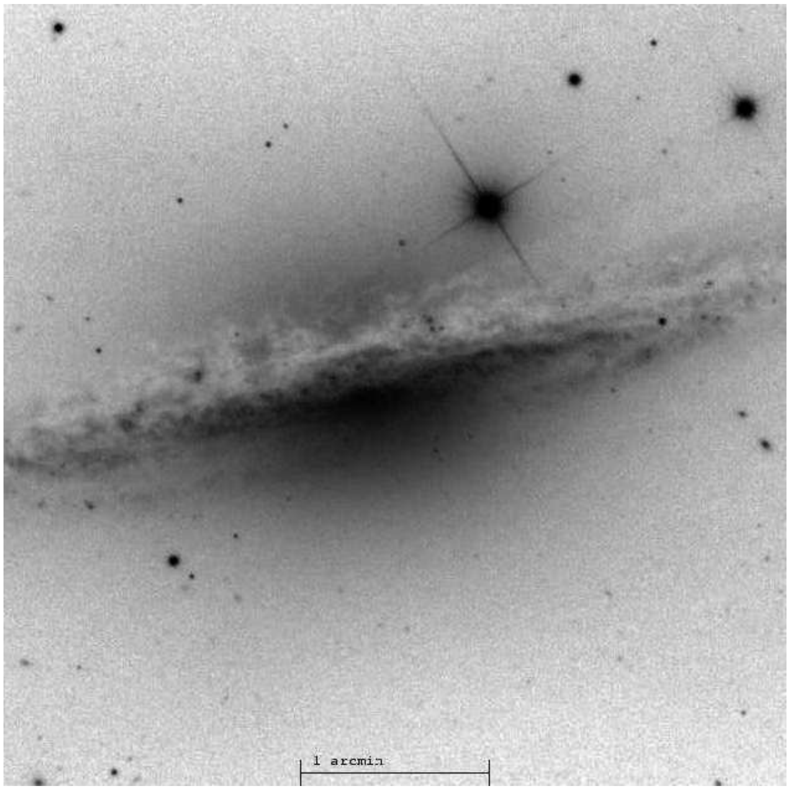
Galaxy #21 Classification: Sd/Irr

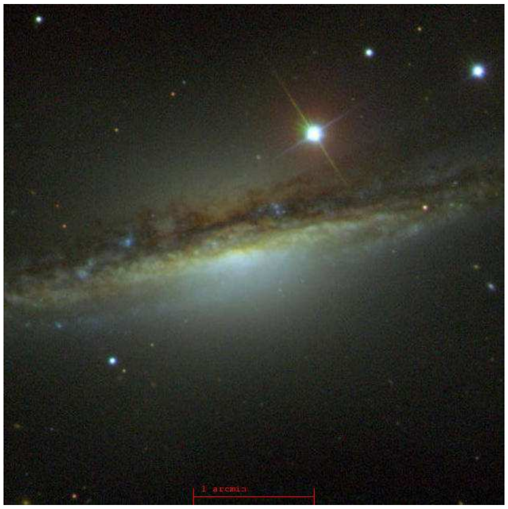


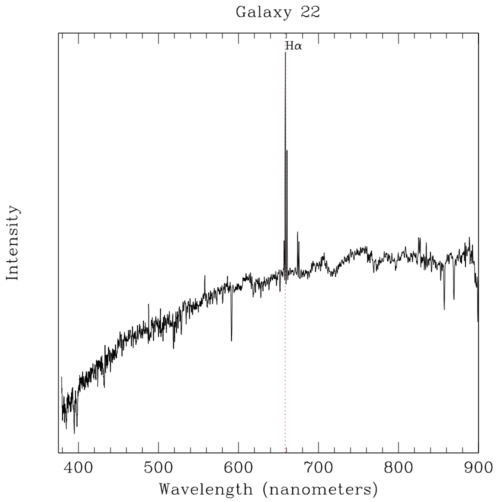




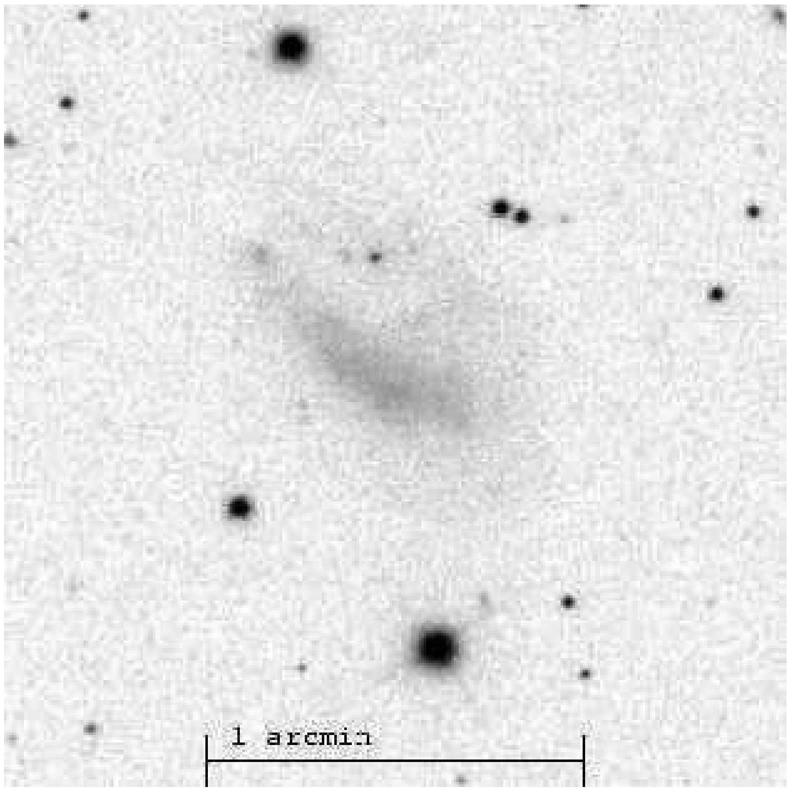
GALAXY #22 CLASSIFICATION:______________

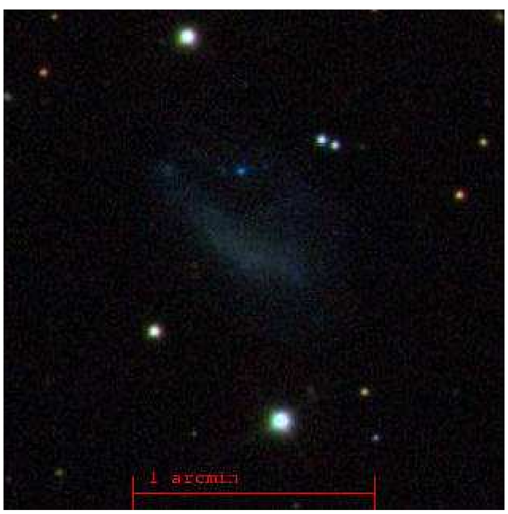


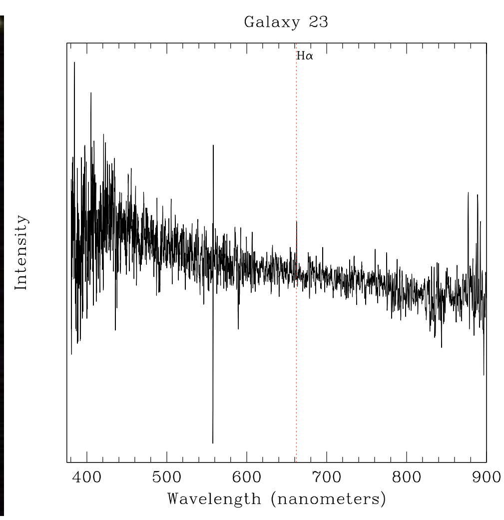




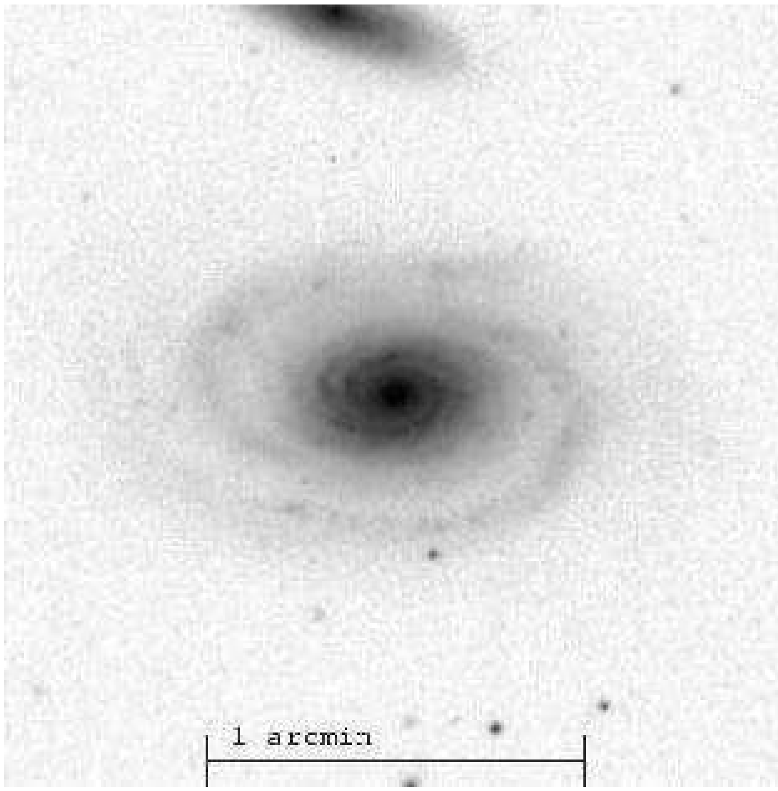
GALAXY #23 CLASSIFICATION:____________

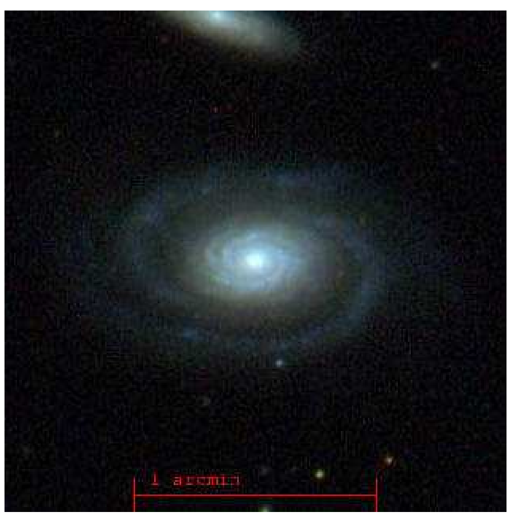


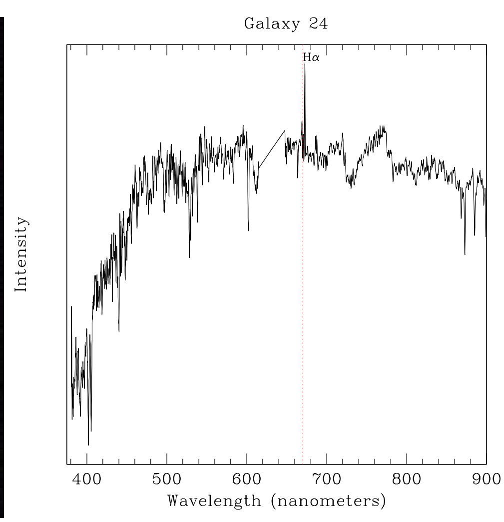




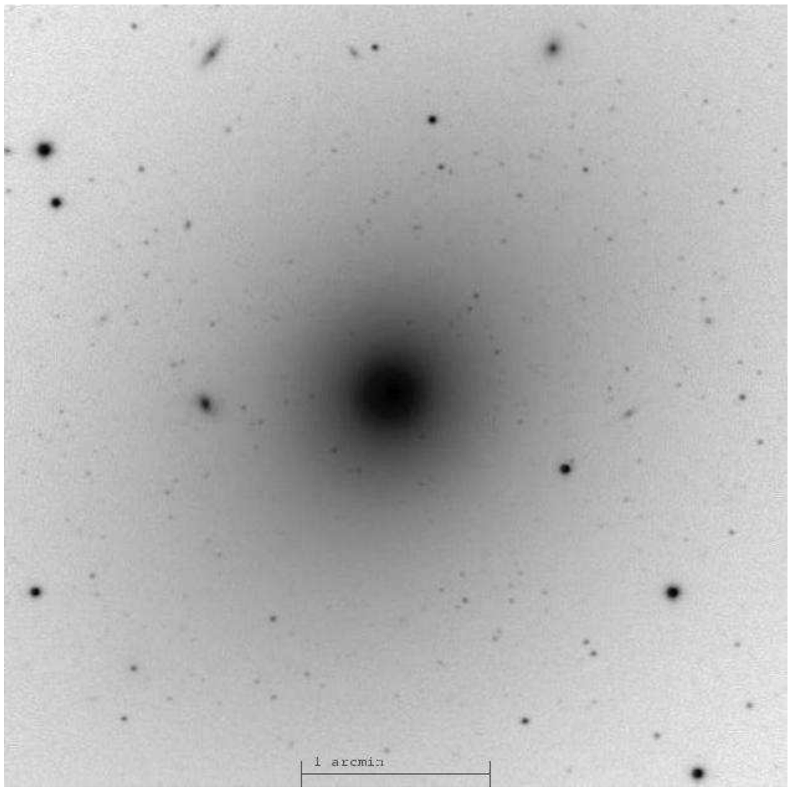
GALAXY #24 CLASSIFICATION: Sbc

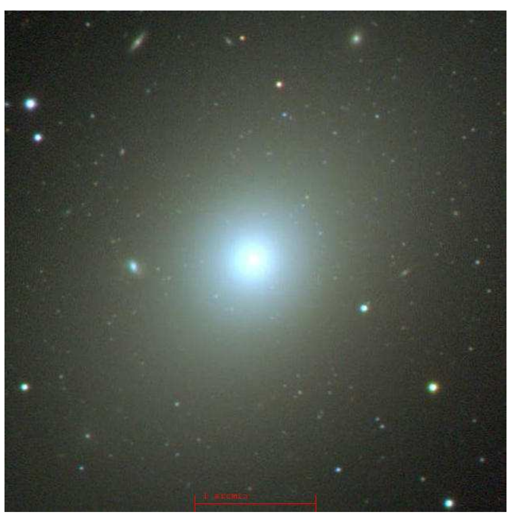


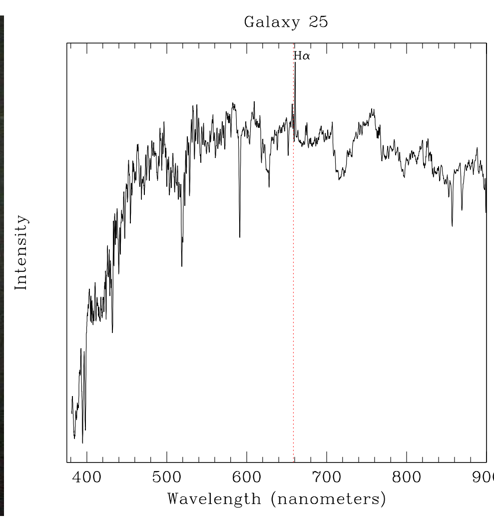




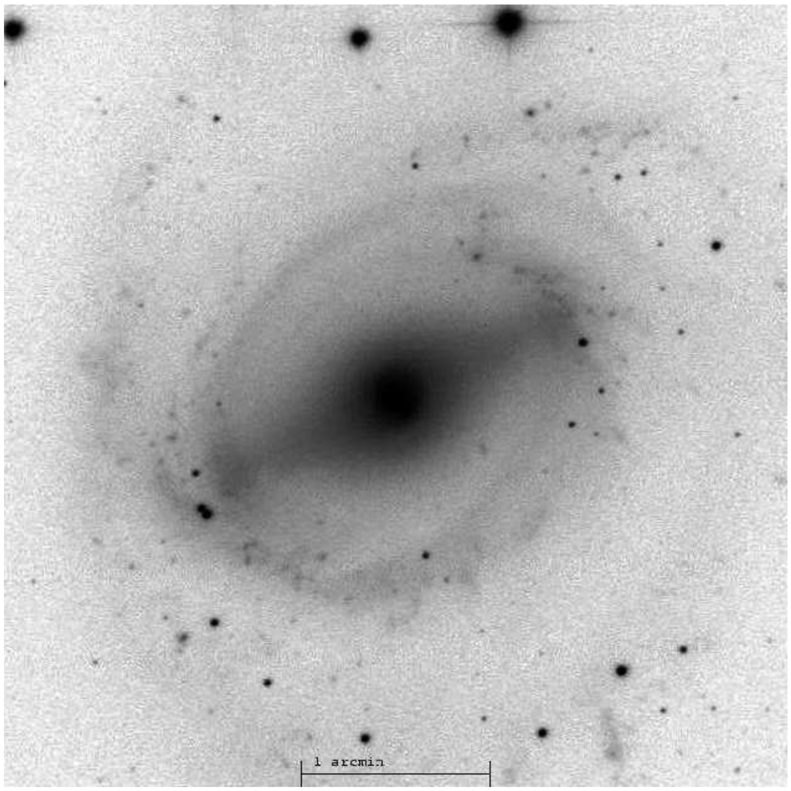
Galaxy #25 Classification: E

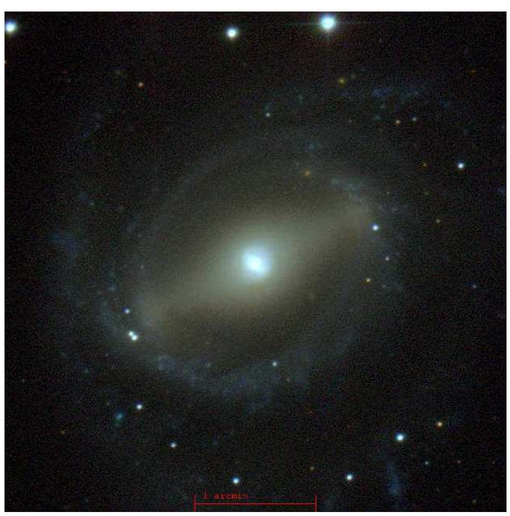


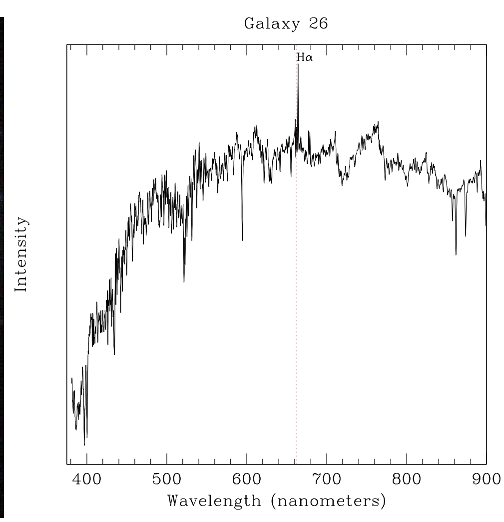




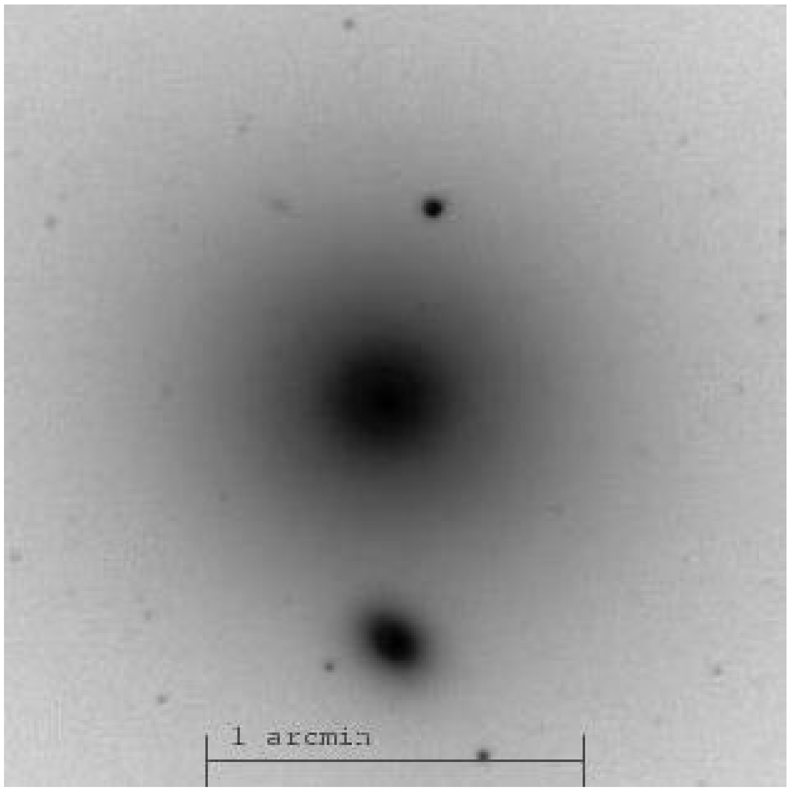
Galaxy #26 Classification:__________

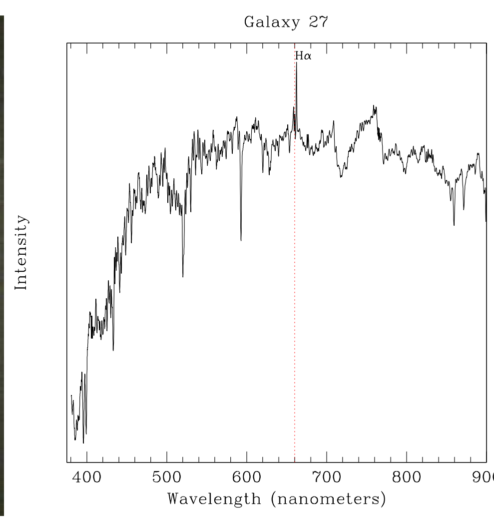




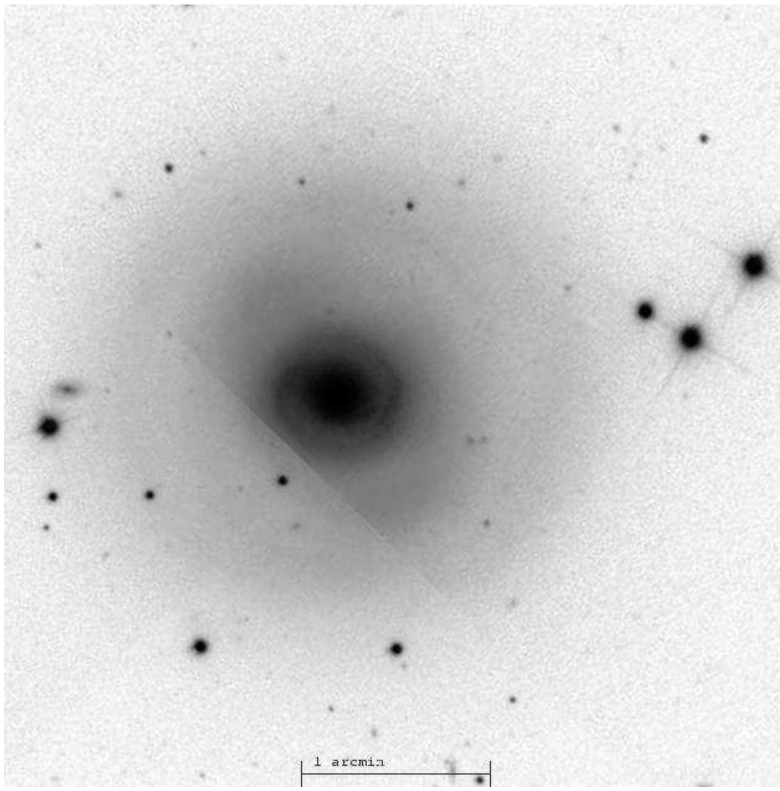


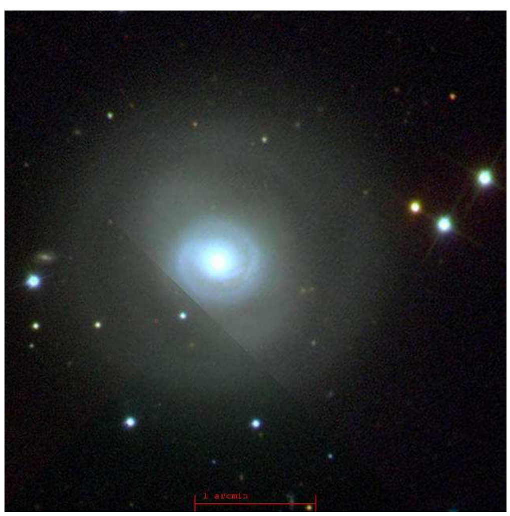
Galaxy #27 Classification:_______________

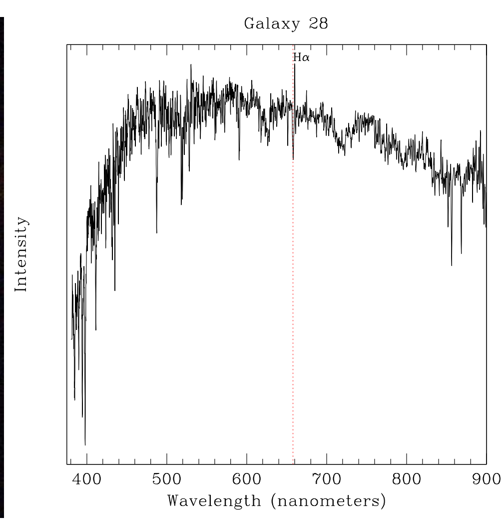




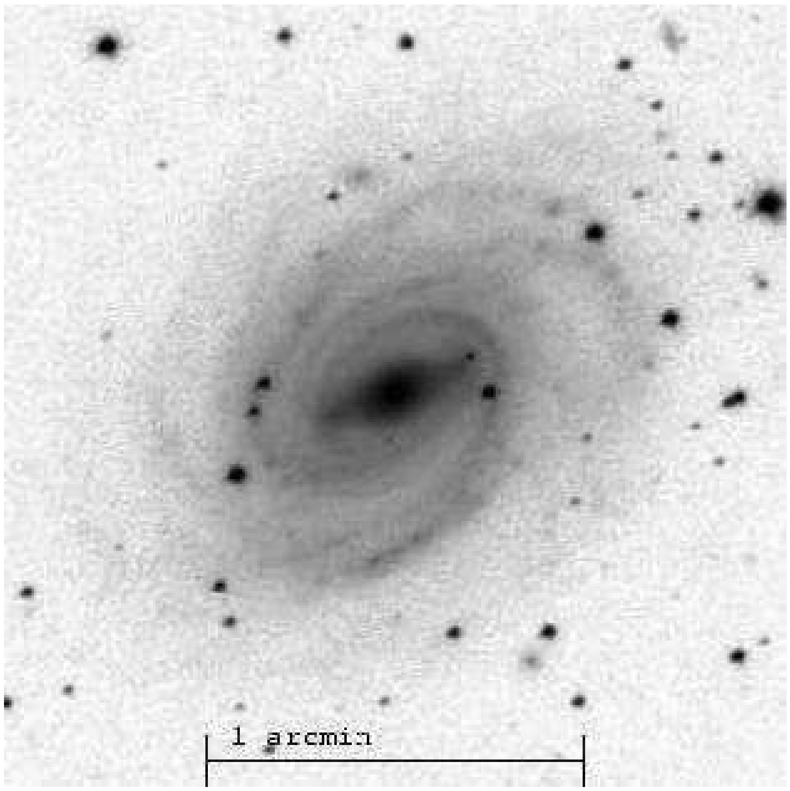
Galaxy #28 Classification:______________

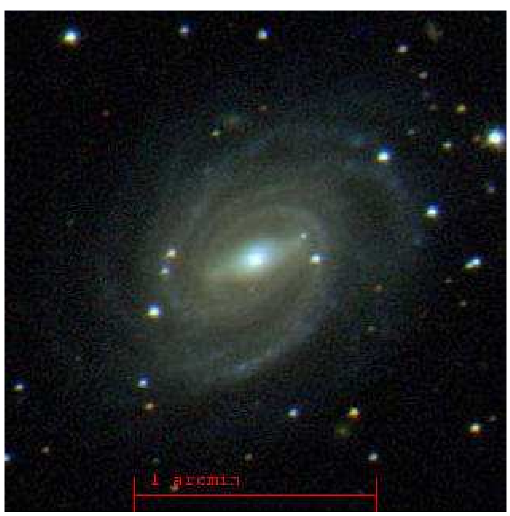


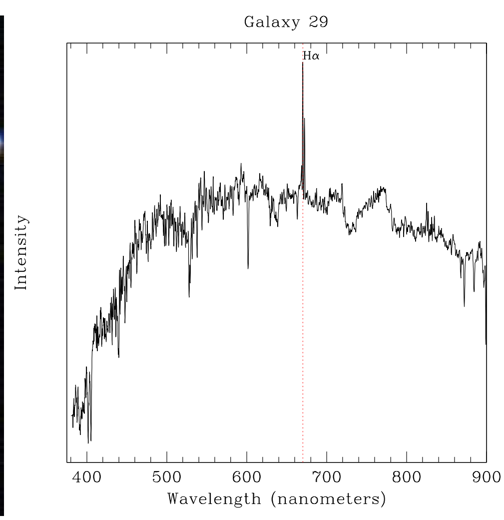




Galaxy #29 Classification: Sb







Galaxy #30 Classification: Sa