UNIVERSITY COLLEGE LONDON

University Of London Observatory PHAS1510 – Certificate in Astronomy, 1213.01

PHAS1510-05: The Classification of Galaxies and the Hubble Deep Field

Name:____________________________________

An experienced student should aim to complete this practical in 2–3 sessions.

1 Objectives

The aims of this practical are to demonstrate the principal features of the basic Hubble classification scheme, and to give you experience applying it to a mixed sample of galaxy types. The classification skills practised in the first part of the exercise are then applied to a more challenging set of data – the galaxies of the Hubble Deep Field (HDF) – to give you a taste of how classification is used in the study of galaxies today.

For background reading, see ref. 1 or 2, or a copy of ref. 5 for background on the HDF.

2 Items required

You will need

- A folder of images of 'standard' galaxies; and *either*
- ⋆ One of the large laminated colour prints of the Hubble Deep Field (HDF) and
- ⋆ One of the A4-size, black-and-white HDF 'finder charts'; *or*
- ◦ a PC running the ImageJ software (available on the Certificate's ULO website).(Before running the program you should ensure that the MS-Windows default printer on the desktop of the ULO computer you are using is set to the 'ULO-NWcolourprinter'. Ask a demonstrator to make the change for you if you are unsure how to do this.) Incidentally all images except the standard galaxies are on the PCs and can be view using ImageJ.

3 Introduction

One step towards understanding any realm of natural phenomena is to construct and apply a classification scheme of some kind. Classification of morphological distinctions between objects, to be useful, should reflect underlying physical distinctions between classes. The classification of galaxies was first attempted in the early part of this century. The basic features of the classification scheme developed by Edwin Hubble have indeed been found to be related to important physical characteristics of galaxies, such as their dynamical state and the evolutionary stage of their stellar content. Although there is no consensus on a theory that explains galactic origins and evolution, all of the most promising proposals are based in part on observational studies that include classification.

4 Historical Background

The realisation that there is a class of nebula which lies outside the Milky Way only became universally accepted among astronomers in the mid-1920s, although evidence favouring this conclusion had been accumulating throughout the previous 70 years, from spectroscopy and from observations of novae. Spectroscopy indicated that some nebulae were not gaseous, as their diffuse appearance suggested, but were more likely to be collections of stars at great distances. Moreover, direct imaging of these 'nebulae' allowed some novae to be identified. These were the only stars bright enough to be resolved routinely but, due to the unclear distinction between novae and supernovae at that time, accurate distances were not determined.

In 1918 the 100-inch Mount Wilson reflector was commissioned. For the first time, it was possible to resolve the brighter 'normal' stars in some of the nebulae. In 1924 Edwin Hubble was able to obtain distances to the nearer nebulae, using observations of variable stars called Cepheids. The distances Hubble determined put these nebulae outside the Milky Way, and hence they were termed *extragalactic nebulae*: star systems outside and (for the most part) independent of our own Galaxy.

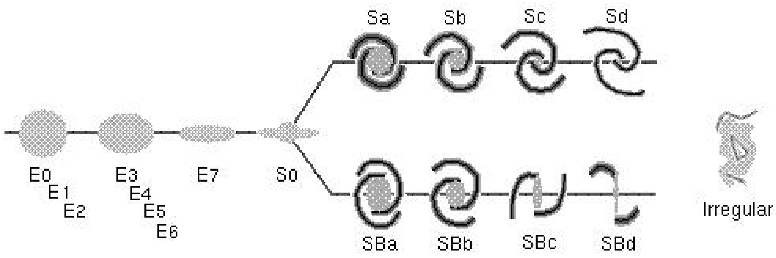
Once it was established that the extragalactic nebulae, or galaxies, were very distant from our own Galaxy, it also became clear that these galaxies appeared in a large variety of forms – hence the need to attempt some kind of morphological classification.

5 The Classification of Galaxies

The first attempt to classify galaxies was by Wolf, who in 1908 published a classification of nebulae which included both galactic and extragalactic objects (the distinction between the two not being established at that time). In 1926 Hubble published a classification scheme which forms the basis of most schemes in use today. The classification is based upon the appearance of the galaxies on photographic plates. For example, the classification of spiral galaxies uses criteria relating to the appearance of the nuclear bulge and the spiral arms, and the degree of condensation of the galaxy into stars and H II (*i.e.*, ionized hydrogen) regions. His famous 'tuning fork diagram' is illustrated in Fig. 1.

Various classification schemes based on the Hubble scheme are still in use today, incorporating modifications that take account of the improved quantity and quality of data which have become available. The principal extensions to Hubble's scheme include those by Holmberg (1958), de Vaucouleurs (1956, 1959), and van den Bergh (1960).

In this experiment the de Vaucouleurs extension of the Hubble classification scheme will be used. In the description which follows, refer to the sample types given on the photographs supplied and in the atlases given in the reference list.



The Hubble ''tuning fork'' Sequence of galaxy classification. Galaxies are classified by shape. The **elliptical** galaxies go from circular (E0) to significantly flattened (E7). The spirals are sub-divided into **regular spirals** and **barred spirals.** Each of them is further sub-divided into groups depending on the size of the central bulge and how tightly the arms are wound around the center. The **irregular** galaxies have no definite structure. This is **not** an evolutionary sequence!

Figure 1: The Hubble tuning-fork diagram

5.1 The Hubble classification scheme (de Vaucouleurs' extension)

For illustration of the classification scheme refer to the type examples provided, and to examples from the Atlases given in the reference list.

Images of nearby galaxies can show two major components: a central 'bulge' (in colour images this is seen to be composed of old, red stars), and a surrounding 'disc' (including relatively young, blue stars). This immediately leads to two broad categories of galaxies, more or less easily identified from first inspection of photographs: *elliptical* galaxies, with no discernible disc at all, and *spiral* galaxies, in which the disk is usually structured into spiral arms.

5.1.1 Elliptical galaxies

Elliptical galaxies generally show no internal structure at all; only an elliptical shape with a steep drop in brightness from the centre to the edge of the galaxy. The first page of type examples shows some elliptical galaxies; these are denoted by an 'E' classification, then further classified by their ellipticity, e, where $e = (a - b)/a$, and a and b are the major and minor axes respectively. This part of the classification is given by an integer n following the 'E', where $n = 10 \times e$. The value of n can range from 0 (circular) to 7 (cigar-shaped). Structureless 'elliptical' galaxies having n greater than 7, such as NGC 3115 in the examples, are classed as *lenticular* galaxies (see section 5.1.3 below).

Elliptical galaxies show little or no obvious gas or dust. They are composed almost entirely of relatively old stars, of which the brightest are red giants. Elliptical galaxies are therefore characteristically red in colour.

5.1.2 Spiral galaxies

Most spiral galaxies are immediately recognizable by their structure. The appearance of spiral arms is due to 'travelling waves' of star formation propagating azimuthally through the galaxy's disc. Most of the light in young, star-forming regions comes from massive, hot stars. Spiral arms are therefore typically blue in colour.

Spiral galaxies can be separated into two major groups: barred (SB) and non-barred (denoted 'SA' by de Vaucouleurs; just 'S' by many other workers, including Hubble).

They are further subdivided according to three, related, characteristics:
— the size of the nuclear bulge relative to the disc;
— the tightness of the winding of the spiral arms; and
— the degree of condensation or clumping ('floculence') of the arms and disc into stars and star-forming/H II regions.

The major subtypes are denoted by 'a', 'b', 'c', and 'd' (with a further subtype 'm' in the de Vaucouleurs' scheme, and a special class '0' for lenticular galaxies, discussed later). A spiral galaxy of type 'a' will have a prominent, fat nuclear bulge, tightly wound spiral arms, and little or no condensation into stars and H II regions. Going from type 'a' to type 'd' one finds:

(i) the nuclear bulge shrinks in size relative to the spiral arms;

(ii) the arms becoming more open and loosely structured; and

(iii) clumping of the arms and disc into stars and H II regions increases.

All three factors should be considered when classifying spiral galaxies – some criteria may be easier than others to use, depending on the tilt of the galaxy's disc to the line of sight.

In type 'm' (which stands for Magellanic-cloud type, after the dwarf companions to our own Galaxy), no nucleus is discernible, and the galaxy is a loose, sometimes chaotic, collection of stars and H II regions, with any spiral structure barely recognizable.*

The spiral sequence of indices therefore runs: SAa, SAb, SAc, SAd, SAm (or, for barred spirals, SBa, SBb, SBc...). Intermediate types are possible too, such as SAcd. In addition, at the end of the spiral sequence is the 'irregular Magellanic' type, denoted Im (or IBm), but the distinction between types SAm and Im is pretty subtle. Part II of the *Atlas of Galaxies* (ref. 4) shows several examples of types 'c', 'd' and 'm', and should be examined.

Seen edge-on, a spiral galaxy consists of a central nuclear bulge plus a distinct disc about the nucleus, often with dark dust lanes running through it. Such galaxies cannot be classified other than as 'spiral', although they can usually be distinguished from ellipticals; the brightness of the nucleus falls off steeply, as in elliptical galaxies, but the disc only slowly decreases in brightness with increasing distance from the nucleus.

5.1.3 Lenticular galaxies

There is one class of galaxy which is not obviously either spiral nor elliptical. Like the elliptical galaxies, this class generally shows no spiral structure but their shapes are more elongated than the elliptical galaxies; discs like those of the normal spiral galaxies are just discernible. These are the lenticular galaxies, denoted by 'SA0' or 'SB0' for non-barred and barred lenticulars respectively. These galaxies seem to be intermediate between the elliptical galaxies and the spiral galaxies. NGC 3115, shown on the first page of sample types, is an example; others can be found in reference 3. They can be rather difficult to classify with certainty, but can most simply be thought of as spiral galaxies in which the disc has not formed spiral arms.

*See plate 38 of the *Hubble Atlas of Galaxies* (ref. 3) for an image of the Large Magellanic Cloud.

5.1.4 Peculiar galaxies

Single galaxies which defy classification are known as peculiar, denoted 'P'. *This class does not include galaxies which may be interacting with one another.* However, galaxies which have peculiarities of some sort but which are otherwise normal may be classified as usual, and then a lowercase 'p' is appended to the classification, *e.g.*, SAcp.

5.2 Summary

- Elliptical galaxies are designated En, where $n = 10(a - b)/a$, and $0 \leq n \leq 7$. They show little or no internal structure, and are typically red in colour.
- Spiral galaxies fall into two groups, barred (SB) and 'normal' (S or, in the de Vaucouleurs' scheme, SA). Within these sequences, subtypes a–d are distinguished, with subtype 'm' reserved for galaxies whose spiral nature is barely evident.
- Lenticular galaxies have discs (like spiral galaxies), but no obvious spiral structure.

The de Vaucouleurs' scheme includes notation for various peculiarities, such as ring structures (the '(r)' qualifier for some galaxies in the folder of galaxy images), or luminosity (akin to the classification of stellar luminosity, where the most luminous objects are class I and the faintest are class V). The exploration of such details is beyond the scope of this practical.

The de Vaucouleurs version of the Hubble classification scheme may therefore be summarized as follows (excepting 'p'eculiar galaxies):

								SA0	SAa	SAb	SAc	SAd	SAm	Im
E0	E1	E2	E3	E4	E5	E6	E7							
								SB0	SBa	SBb	SBc	SBd	SBm	IBm

'Early-type'. . . . . 'Late-type'

where the SA0, SB0 galaxies are 'lenticular'.

Hubble originally thought this sequence showed evolutionary trends; hence the reference to 'early-' and 'late-type' galaxies. This simplistic interpretation is no longer considerd appropriate (although the full significance of the sequence is not yet understood); nonetheless, the terminology lingers. Moreover, observations have revealed some important physical trends along the sequence.

6 Experiment

The exercise is divided into two parts. First, you will examine and classify a dozen or so galaxies according to the scheme described above. The aim of this part is to acquaint you with the basic Hubble types, and to become familiar with some of the techniques and difficulties of galaxy classification.

In the second part, you will apply your experience to the classification of some very distant galaxies in the Hubble Deep Field (HDF). This will give you the chance to apply your classification skills to a sample of modern data of considerable significance; astronomers need to classify galaxies in the HDF in order to draw conclusions about the evolution of galaxies. You will discover the particular difficulties of classification of faint, distant galaxies, and the assumptions and limitations of the method.

6.1 Classification of Hubble types

The data consist of a set of type examples of the de Vaucouleurs classification scheme and a set of photographs of 'unknown' galaxies for classification, taken at the Mount Wilson and Palomar Observatories.

Study the type examples provided, and refer to the Atlases given in the reference list to familiarize yourself with the basic appearance of different galaxy types.† Then classify the 12 unknown galaxies on the sequence summarized in Section 5.2 above, using the criteria described in Section 5 – you should *not* simply try to match the unknowns with images published in the Atlases. For ellipticals, you will need to measure with a ruler their major and minor axes to determine the ellipticity classification, n. Peculiar or interacting galaxies should be noted as such.

Fill your results in the tables in the worksheet at the end of the script, with columns for: the photograph number; your classification; notes to justify your classification based on the criteria given above; and any descriptive comments you might wish to add, like unusual features or ambiguities, *etc.* Don't expect to be 100% confident in every classification you assign – this is, to some degree, a subject process, and there is not always a unique 'right answer'.

6.2 Galaxies past: the Hubble Deep Field

The classification of galaxies provides a framework for studies of the evolution of the Universe. One key observation, designed in part to tackle the question of how galaxies evolve, was made in a remarkable series of exposures carried out by the Hubble Space Telescope (HST) in December 1995. Over a period of 10 days, the HST 'stared' at a portion of sky in Ursa Major; nearly 300 exposures through four different colour filters were combined into the deepest colour image of the sky ever obtained: the Hubble Deep Field (HDF; in astronomical parlance, 'deep' means capable of detecting very faint objects). A similar observation was subsequently conducted in a southern-hemisphere field: the HDF–South.

If you have access to the World Wide Web, you may wish to obtain further information on the HDF project, and results, from the URLs (WWW addresses) given in the reference list.

Nearly all the objects in the HDF are galaxies (a few may be faint stars); and in general, fainter in the HDF means further away. The HDF is a window on the past – as we look further away, we look back in time. It is believed that the most distant galaxies in the HDF are seen as they were when less than a thousand million years old – *i.e.*, when the Universe was less than one tenth of its present age.

By classifying galaxies in the HDF, we can try and understand how galaxies have evolved since such early times in the history of the Universe. Of course, one problem is that galaxies in the early Universe could look very different from how they look today – our existing classification schemes, based on nearby galaxies, may no longer be valid!

6.3 Examining the HDF

In this part of the exercise, you will examine a part of the HDF and attempt to classify some galaxies using the classification scheme summarized above. According to your

†Ignore the luminosity types and classification of rings – denoted (rs), for example. These morphological details are rarely considered in depth.

personal preference and convenience, you can work with one of the laminated prints available in the classroom, or with a digital version, manipulated with the ImageJ software. In either case, use the accompanying identification chart to locate objects.

Classify the galaxies indicated by numbers 1–10 on the finder chart, according to the classification scheme introduced in the previous section. The classifications will be more difficult and ambiguous, but you should be able to classify objects at least into broad spiral, elliptical and peculiar types. (Look carefully at each galaxy and consider, for example, its *symmetry* and *central concentration.* Is there structure? Spiral galaxies often have blueish regions in their arms, where star formation occurs. Is there any evidence of this?)

Make sure you give the reasons for your classification, and use the galaxy colours to aid you in your classification. Note that the contrast in the image is such that the brightest parts of some galaxies appear white – but the fainter regions often show the actual colour more readily. Fill your results in the tables in the worksheet at the end of the script, noting any difficulties in classifying that you came across.

6.3.1 Using ImageJ

If you opt to use the digital image, start the ImageJ program and go to `File/Open Samples`. Open "Hubble Deep Field" from this menu. A window will open and you will see a high resolution image of the HDF. Move your mouse around the image. Notice that the coördinates of the mouse are displayed in the menu window. You can zoom in on a part of the image by selecting the 'magnifying glass' icon from the menu bar and then left-clicking on a part of the image. To zoom out, right-click. To scroll, you should use the 'hand tool'.

The galaxies that you will be looking at are labelled on the 'finding chart',also accessible from the `File/Open Samples` menu.

Zoom in on a galaxy. At high zoom factors you will see that the image is made up of discrete picture elements (pixels). To classify a given galaxy, it will be necessary to zoom in and make measurements, and zoom out to see the large scale structure.

7 References

1. Zeilik, M. & Gregory, S. *Introductory Astronomy and Astrophysics*, (4th edition). The 3rd edition, by Zeilik, Gregory & Smith, is very similar.

2. Freedman, R.A. & Kaufmann, W.J., *Universe,* 7th edition; Chapters 25 & 26, especially §§26–3 & 26–7.

3. Sandage, A., 1961, 'Hubble Atlas of Galaxies' (Carnegie Institution).

4. Sandage, A. & Bedke, J., 1988, 'Atlas of Galaxies' (NASA).

5. Ferguson, H.C., Williams, R.E. & Cowie, L.L., 1997, 'Probing the Faintest Galaxies', *Physics Today*, **50**, 24.

6. Williams, R.E., *et. al.*, 'The Hubble Deep Field: Observations, data reduction, and galaxy photometry', *Astron. J.*, **112**, 1335.

7. WWW addresses (these links are on the ULO home page at http://www.ulo.ucl.ac.uk/):
   Space Tel. Science Institute: http://oposite.stsci.edu/pubinfo/PR/96/01.html
   ST-European Coörd. Facility: http://ecf.hq.eso.org/hdf/hdf.html
   UK HST Support Facility: http://www.ast.cam.ac.uk/HST/hdf
   HDF – South: http://www.stsci.edu/ftp/science/hdfsouth/hdfs.html

Classification of Galaxies and the HDF: Worksheet

Classification of Hubble types

No.	Classification	Reasons for Classification	Any Descriptive Comments
1a			
1b			
1c			
1d			
2a			
2b			

Classification of Hubble types (continued)

No.	Classification	Reasons for Classification	Any Descriptive Comments
2c			
2d			
3a			
3b			
3c			
3d			

Classification of Hubble Deep Field galaxies

No.	Classification	Reasons for Classification	Any Descriptive Comments
1			
2			
3			
4			
5			
6			
7			

Classification of Hubble Deep Field galaxies (continued)

No.	Classification	Reasons for Classification	Any Descriptive Comments
8			
9			
10			

Questions

Q.1 The galaxy indicated 'M' on the finder chart is thought to be a pair of merging galaxies. Merging systems are often revealed by the appearance of two or more bright knots interacting closely. Find and describe another example of a merging galaxy. Sketch it (include a scale and orientation) and give its coördinates (in mm, measured from the bottom left corner of the white border to the colour print; or using the pixel coördinates given by ImageJ if you're using the digital version)).

How might you distinguish merging systems from two galaxies that lie in the same line-of-sight simply by coincidence, given only imaging information?

Questions (continued)

Q.2 If you examine the background of the HDF you will notice a large number of small, blue objects. Statistical counts of galaxies in the HDF have confirmed that, compared to the present-day (local) Universe, there are *too many* faint, blue irregular galaxies in the HDF. Suggest one reason why such galaxies might not be visible amongst the present-day population of galaxies.

Q.3 In addition to the many small blue objects, there is a scattering of very red, apparently point-like objects. What do you think these might be?

Q.4 You may have come across some other interesting objects in the course of studying the HDF print; if so, describe a couple (include sketches – include scale and orientation! – and coördinates).