Stars and **Galaxies**

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Prologue

Before the beginning

This course on galaxies runs over 14 lectures. The aim is to give you an overview of the types of galaxies we know, and to try to understand why galaxies look like they do, based on the physics we think that applies. In contrast to the beauty of stellar physics, you'll see that galactic physics is often much more murky and complex – a bit like weather predictions: we (think we) know the physics, but even so it still is difficult to make accurate calculations. And often, we don't know the physics very well – or even at all. On the bright side, galaxies are beautiful. And we can in principle probe physics on scales which are impossible to reach within the laboratory and so learn about really fundamental physics – just recall the recent excitement about the possible non-zero value for the cosmological constant. Anyway, I hope you'll enjoy the lectures.

As to the organisation of the course, I will basically follow the structure of Simon Morris, i.e. there will be hand-outs after each lecture, but more up-to-date versions will appear on the web in DUO. Look there as well for (most of) the pictures that I show during the lectures.

My name is Tom Theuns (tom.theuns@durham.ac.uk, tel 8275), and my office is room 307 in the Ogden Centre. This is the first time I teach this course, and in case I go too fast (or too slow), I count on you to tell me! Suggestions, and lists of errors, will be most appreciated.

And for those that are only interested in passing their exams: there will be two questions on galaxies. The first consist of 5 very short questions where you're asked to describe *very briefly* some concepts that we have discussed. For example, what is the interstellar medium, and how do we observe it. The second type of question usually starts from a derivation that we've done. The end of the question is something you have not seen, but is very similar to what we have done.

My source of knowledge

Although this field is continually evolving, much of the basics is of course text-book stuff. The web provides a very valuable source of information, not just for pictures. Often, satellite mission web-pages have extremely well designed pages. Some links you might want to look at (and where I got many of the pictures) are:

- http://www.seds.org/
- http://www.aao.gov.au/images.html/
- http://hubblesite.org/newscenter/archive/
- http://teacherlink.ed.usu.edu/tlnasa/pictures/picture.html
- http://astro.estec.esa.nl
- http://space.gsfc.nasa.gov/astro/cobe/cobe_home.html
- http://astro.estec.esa.nl/Hipparcos/
- http://astro.estec.esa.nl/GAIA/

and the books I've used are

1 Carroll & Ostlie, *Modern Astrophysics*, Addison-Wesley, 1996

2 Zeilik & Gregory, *Astronomy & Astrophysics*, Saunders College Publishing, 1998

3 Binney & Merrifield, *Galactic Astronomy*, Princeton, 1998

4 Binney & Tremaine, *Galactic Dynamics*, Princeton, 1987

(I'll refer to these as CO, ZG, BM, and BT.) The first two are clearly more general, [3] provides a nice overview on galaxies in much more detail than I'll do, and [4] of course concentrates on the dynamics of galaxies. [1] contains everything you *need* to know, in [2] you can often find the basics formulated in a very clear way, and [3] and [4] are where you could start looking if you want to know more.

A truly excellent web site where much of what I'll discuss is explained really well with many pictures, and by someone who knows what he's talking about, is by **Chris Mihos**, who is at the department of astronomy, Case Western University. You'll find it at: http://burro.astr.cwru.edu/Academics/Astr222/index.html, and you'll recognise some of the picture in my course as originating from here.

Chapter 1

Introduction

1.1 Historical perspective

Galaxies were discovered in the 20th century. This is a bit surprising, since you can see many of them on a clear night with the naked eye. They differ from stars in that, even with the naked eye, you can see that they are extended. For example, the nearby Andromeda galaxy has an extent of several degrees (compare to the diameter of full moon, which is 0.5 degrees). And the Large and Small Magellanic clouds, are even bigger (but you can only seem them in the Southern hemisphere). And the nearest galaxy (which was only discovered in the last years, extends over a significant fraction of the whole sky! The reason that they don't stand-out very clearly is not because they are *faint*, it is because they are so *large*. Since they are large, their light is distributed over a wide area, and our eyes do not pick-out the increase in surface brightness over the night sky.

To distinguish them from stars, they were called *nebulae*. However, there are other extra-solar objects which are also extended, like Planetary Nebulae, star clusters, and super nova (SN for short, and SNe for the plural) remnants, for example. Since before the 1920s we didn't know the distance to those objects, it wasn't clear what was the difference between all these types. And so many of the catalogues of nebulae, like Messier's catalogue (objects denoted by an 'M' , like M31, which is Andromeda), or NGC (New General Catalogue, Dreyer 1888), contain a baffling variety of different types of objects.

Immanual Kant, the German philosopher, already figured out that we see the faint band of stars across the night sky – usually called the Milky Way (MW for short) – because on a larger scale most stars around us are distributed in a disk, and the sun is located in that disk. And so, when you look out at night in the plane of the disk, you see a faint band of light, which Galileo already had resolved into stars! And most of these other nebulae you see, were just other galaxies. Though this was a correct hypothesis, it took until the 1920s before the matter was settled. The historical introduction in BM is well worth reading.

As a final point: why do we study galaxies? Are they in some sense the most important building blocks in the Universe? I like BMs reasoning: stars are apparently huddled together in galaxies. And since (not surprisingly if you think about it) we (humans) can *see* stars, we are naturally inclined to study them. But, for example, although a cluster of galaxies contains thousands of galaxies, they are by no means the main constituent. Most of the *mass* is in dark matter – which we cannot see at all. But most of the baryons is in hot gas, which we can *observe* with X-ray satellites, but we cannot *see*. And so the choice to study galaxies is a bit human centred: our eyes can see them.

1.2 Bringing order to the zoo of galaxies

Before we start doing any calculations, it might be a good idea to look around us and make an inventory of what types of galaxies are out there. There are many good web pages to start, for example I like http://www.taas.org/gnto/astropic.html, because it shows pictures made with a small telescope – so those are galaxies as you might have seen them yourself, if your an amateur astronomer. http://www.aao.gov.au/images.html/ is very nice as well, it shows professional images. If you look at the more professional pages (such as the HST archive for example), beware of an amusing bias: professional astronomers tend to observe (and make picture of) unusual galaxies.

1.2.1 Vocabulary

Colours. These images are usually made through a broad-band filter, typically[1] V, Bor R, and so should be just black and white. The blackness

[1]The names give an indication of the corresponding wavelength region, B for blue, V for visual, R for red, U for UV (in the direction of the UV-that is), I for IR.

being a measure of how much, or how little of the light in that wavelength band fell on that part of the photograph/CCD. One often combines images in different filters to produce a colour image, which tries to mimic the colour your eye would see. Most of the galaxy images you'll see are of this type. However, often one of the filters is a narrow-band filter, e.g. in Hα or O[III]. Combing such an narrow-band image with images made with others filters gives a false colour image, i.e. the colour of the object is *not* how your eye would see it, but the colour coding has been chosen to bring out a particular feature. Those really pretty colour pictures of Planetary Nebulae are false colour images.

Surface brightness. The brightness of the images depends, apart from the size and quality of the optics of the camera, the integration time, and the transparency of the atmosphere (all of which we should be able to calibrate), on the apparent brightness of the galaxy. So this is what we want to characterise. Since galaxies are extended, the brightness varies over the image, and so what we want to measure is the surface brightness (SB). The SB measures how much light we receive from the galaxy, per unit solid angle (usually per arcsec^2) so it should have units of flux (e.g. in W), per unit wavelength range, per unit solid angle on the sky. So for example in units $L_{\mathrm{V}_\odot}\mathrm{arcsec}^{-2}$, in units of the solar V luminosity. Usually, SB is expressed in magnitudes, by taking $-2.5\log_{10}$ of the previous number – we say (incorrectly, or at least confusingly) that we measure SB in magnitudes per square arc seconds. (It's confusing, because this suggests we divide the magnitude by arcsec^2, but no: we first divide by the solid angle, and then take the logarithm). As is usual with magnitudes, we add a constant to it.

The number that characterises the intrinsic brightness distribution of the galaxy (as opposed to apparent) is how much light the galaxy emits per unit surface area, so in for example units of $L_{\odot\mathrm{V}}\mathrm{kpc}^{-2}$. Astronomers do not use separate names for these two types of SB, so check the units!

Star counts To quantify this a bit more, assume you observe a distribution of stars, all of the same absolute luminosity L, and with uniform number density n (in stars per pc^3, say). The flux you receive from a single star, when at distance r, is $l = L/4\pi r^2$ (in $\mathrm{W\,m^{-2}}$). The number of stars at distance between r and $r + dr$, and within a solid angle $d\Omega$ on the sky, is $dN(r, d\Omega) = nr^2 dr d\Omega$. Combining[2] these two, the luminosity of all stars within r and $r + dr$, and within $d\Omega$, is

$$dl = l\, dN(r, d\Omega) = \frac{Ln}{4\pi} d\Omega dr\,. \tag{1.1}$$

The surface brightness is $\propto dl/d\Omega = Lndr/4\pi$. For an external galaxy, you could integrate $\int ndr$ along the line of sight through the galaxy, to get the surface density of stars, $\int ndr = \Sigma$ of stars. The SB is then $L\Sigma$. The important thing to notice is that it is *independent* of the distance r. Going back through the calculation, you can see what has happened: the luminosity from a single star at distance r *decreases* $\propto 1/r^2$, but the number of stars within $d\Omega$ *increases* $\propto r^2$. And since the SB is proportional to the product of these two, it is independent[3] of r. (You might object saying we've assumed all stars to have the same luminosity. So just redo the calculation with the *average* luminosity then!)

When looking-out into a stellar distribution – for example when counting stars in the Milky Way – we should be able to infer $n(r)$ by counting how many stars we see as function of their luminosity. Here is how to do it: the number of stars within a solid angle $d\Omega$, and with distance between r and $r + dr$, $dN(r, d\Omega) = nr^2 dr d\Omega$, as we had before. Now again assume them to have all the same intrinsic luminosity L. The trick is to change variables from distance r to apparent magnitude m, using

$$m = -2.5 \log(L/r^2) = M + 5 \log(r)\,, \tag{1.2}$$

up to a constant. Recall where this came from: since the observed luminosity $\propto L/r^2$, the apparent magnitude $m = -2.5 \log(L/r^2) = -2.5 \log(L) - 5 \log(r) = M - 5 \log(r)$, up to a constant.[4] $m - M$ is called the *distance modulus.*) Now we're almost done, since rearranging

$$r \propto 10^{0.2(m-M)}\,,$$

and by differentiating

$$dr/dm \propto 10^{0.2(m-M)} \propto r\,.$$

[2]For the whole sky, $d\Omega = 4\pi$, and so the number is $dN(r) = 4\pi nr^2 dr$, which is the product of the volume of the shell, $4\pi r^2 dr$, with the density n of stars.

[3]On cosmological scales this argument does not hold, and the SB of very distant galaxies decreases with distance, an effect called surface brightness dimming.

[4]Also recall that, by convention, $m = M$ for a distance of $r = 10$pc. And hence the proper equation is $m - M = 5 \log(r) - 5$, when r is expressed in pc.

Substituting this in the expression for dN gives

$$dN(m, d\Omega) \propto n(m) 10^{0.6(m-M)} dm\, d\Omega\,. \tag{1.3}$$

For example, if the number density is constant (and hence also $n(m)$ is constant), then, $dN(m+1, d\Omega)/dN(m, d\Omega) = 10^{0.6} \approx 4$. In other words: by going one magnitude fainter, we get around 4 times as many stars. If we get fewer, then either the more distant stars are intrinsically fainter, or light has been lost on the way, or the density of stars drops (or some combination).

As a last exercise: we found that the luminosity of all stars in a shell, within a given solid angle, was independent of the radius of the shell. So, integrating over all radii, we get an infinite luminosity. Which clearly conflicts with the fact that the night sky is dark. This is called Olber's paradox. What is wrong with this reasoning?

1.2.2 Galaxy properties

Looking at the different images of galaxies, it becomes immediately clear that there are two basic types, elliptical and spiral galaxies.

Ellipticals (also called early type galaxies)

- have smooth light distributions, where the isophotes (lines of constant SB) have (nearly) elliptical shapes. They are denoted as En, where $n = 1 - b/a$, and a and b are the semi-major and semi-minor axis of the ellipse. So, an E0 is round, and an E7 is flattened, $n = 7$ is about how flattened E's get. A 3D ellipsoidal shape, with semi-axes a, b and c (ordered as $a \geq b \geq c$), is called oblate when $a = b > c$ (a pancake), prolate when $a > b = c$ (a cigar), and tri-axial when $a > b > c$ (a squashed American football). We think that E's are probably tri-axial.
- have no current star formation
- have old stars
- have little gas and dust
- occur preferentially in groups and clusters of many Es
- have little evidence for rotation, so the stars must have large random motions to keep the system from collapsing (also called a hot stellar system)