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ASTM-052: Extragalactic Astrophysics

by

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Note 1. Introduction

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NOTE 1: INTRODUCTION

1. Extragalactic Astrophysics

We are now so familiar with the realm of the galaxies that it is comes as a surprise to remember that astronomy was confined to the study of objects within our own Milky Way galaxy until the beginning of the twentieth century. Bigger telescopes, better equipment and more sophisticated techniques now allow us to take a broader view of the universe and to see that the Milky Way is but one of hundreds of billions of galaxies in the visible universe. This course explores the physics of this universe. It will deal with the overall structure and dynamics of galaxies and look at various processes occurring within them, particularly those responsible for the violent events occurring in so-called active galaxies. In the rest of this opening chapter, I review very briefly the evidence that leads to our present view of the overall structure of the universe.

2. The Discovery of Galaxies

2.1 The Form of the Galaxy

Nowadays galaxies are a major subject of astrophysical research: more than half of the funds and more than half of the telescope time awarded by the Particle Physics and Astronomy Research Council are for extragalactic research. Galaxies are comparative newcomers in the long history of astronomy, however. Until the 1920s it was generally believed that the universe consisted of the distribution of stars making up what we now call our Galaxy[1], although other ideas had been advanced, as I shall mention below.

Even the distribution of stars in our own Galaxy was not well known in the early years of this century. It was clear that we lived in a flattened system of stars. You have only to go out on a clear night (away from the lights of London!) to observe this flattening; the bright band of light forming the Milky Way stands out because the column density of stars is greater in these directions than in others. Far from city lights, or on a high mountain, the Milky Way is spectacular. The Greeks likened it to a stream of milk (γαλα), from which the word galaxy is derived.

The details of the galaxy distribution were deduced by counting the number of stars in each direction as a function of magnitude. It was found that the numbers fell off more rapidly with magnitude in all directions than would be expected from an infinite and uniform distribution of stars. These studies, culminating in the work of work of Jacobus Kapteyn[2], resulted in the finite model of the Galaxy shown schematically in Figure 1-1.

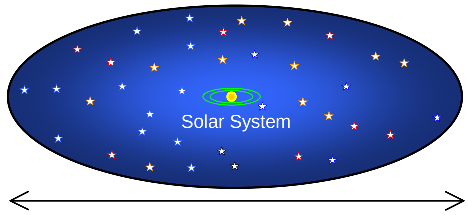

Figure 1-1. Kapteyn model of Galaxy (not to scale!).

It was unsettling that the solar system appeared to be roughly at the centre of this model: since the time of Copernicus and Galileo, we have an aversion to anything that suggests an anthropocentric vision of the cosmos. We know now, though, that Kapteyn's model is wrong in many respects but principally because it is too small and fat and because it *does* put the solar system at the centre. The reason is that Kapteyn was unaware of the existence of interstellar dust, concentrated in the plane of the Milky Way[3]. This dust obscures most of the stars in the directions of the Milky Way whilst having less effect in perpendicular directions, thus giving us a distorted view.

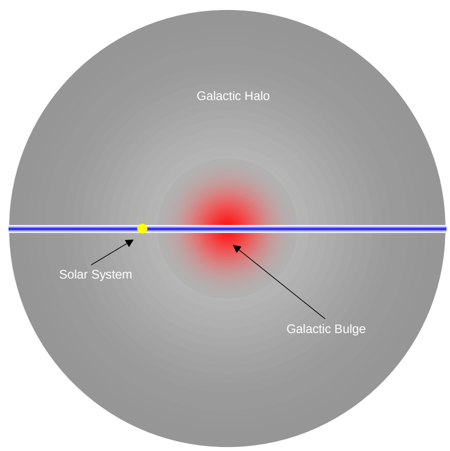

Figure 1-2. Schematic modern view of the Galaxy.

The American astronomer Harlow Shapley (1885-1972) produced the first recognisable modern model of the Galaxy in 1917. He used RR Lyrae variable stars to estimate the distance to globular clusters, which are mostly found away from the plane defined by the Milky Way. The most significant result was that the globular clusters appeared to form a spherical distribution about a point in the Milky Way some 10 kpc form the sun. Shapley took this point to be the centre of the Galaxy. The Milky Way thus appeared as a rather thin disc with a roughly spherical distribution of globular clusters and stars extending beyond this disc, as shown schematically in Figure 1-2.

[1] I shall use the accepted convention of referring to our own galaxy, the one in which the solar system resides, as the Galaxy with a capital *G*; other galaxies will have lower-case *g*.

[2] The 1m diameter British/Dutch/Spanish Jacobus Kapteyn Telescope (JKT), which partners the 2m Isaac Newton (INT) and 4m William Herschel (WHT) telescopes on the island of La Palma in the Canaries, is named in honour of this Dutch astronomer.

[3] See the course PHY-410 *The Interstellar Medium.*

2.2 The Problem of the Nebulae

As early as the eighteenth century astronomers were aware of fuzzy objects which were obviously not stars (all of which, except the sun, appeared as points of light in even using the most powerful telescopes). Some of these objects were rather featureless, like the planetary nebula shown in Figure 1-3, which is a star towards the end of its life.

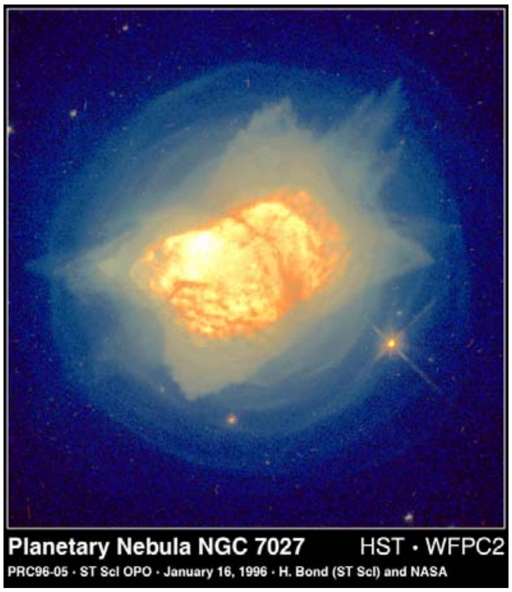

Figure 1-3. Hubble Space Telescope image of planetary nebula NGC 7072.

Others had pronounced spiral form, such as the spiral galaxy shown in Figure 1-4. All such objects were called *nebulae*, from the Latin word for mist. Emmanuel Kant was one of the first to put forward the hypothesis that these spiral nebulae might be systems of stars similar to and outside the Galaxy, forming little "island-universes".

Figure 1-4. Anglo-Australian image of the Whirlpool galaxy.

Having shown that the Galaxy was so much larger than had previously been thought, Shapley felt it unlikely that the spiral nebulae could really be outside it. More probably, he felt, they were similar to those nebulae that had already been recognised as being glowing clouds of gas within the Galaxy.

The debate between Shapley and the proponents of the island-universe idea, led by Heber Curtis (TBD), lasted several years and it is not appropriate to discuss the arguments here; the full debate is given in [1]. The question was resolved in 1923 by Edwin Hubble who used Cepheid variable stars to establish the distance to M31 (the Andromeda) galaxy. In modern terms – our whole scale of distance having changed since Hubble's time – Hubble put M31 at a distance of 500 kpc, clearly well outside the Galaxy, which is some tens of kiloparsecs in radius.

Table 102.1 Radial velocities of twenty-five spiral nebulæ

Nebula	Vel. km. [sec^{-1}]	Nebula	Vel. km. [sec^{-1}]
N.G.C. 221	− 300	N.G.C. 4526	+ 580
224	− 300	4565	+1,100
598	− 260	4594	+1,100
1023	+ 300	4649	+1,090
1068	+1,100	4736	+ 290
2683	+ 400	4826	+ 150
3031	− 30	5005	+ 900
3115	+ 600	5055	+ 450
3379	+ 780	5194	+ 270
3521	+ 730	5236	+ 500
3623	+ 800	5866	+ 650
3627	+ 650	7331	+ 500
4258	+ 500		

Slipher, V M, Proc.Am.Phil.Soc. 56 43-49 (1917)

Figure 1-5. Slipher's observations of the recession velocities of nearby galaxies.

A piece of evidence that played a part in the Shapley-Curtis debate was first noticed Vesto Slipher (1875-1969) [2]. He observed that almost all galaxies seemed to be moving *away* from the Galaxy and at speeds which, at hundreds of kilometres per second, were high compared with the peculiar motions of stars relative to the sun[4]; his results are shown in Figure 1-5. There seemed no reason for recession at these high velocities.

This recession of the galaxies appeared even more dramatic when Hubble showed that the velocity of recession of varied systematically with the distance from the Galaxy, as shown in *Figure* 1-6 [3. In fact, Hubble showed that the velocity v was proportional to distance d. This is now written as

$$v = H_o d \ , \tag{2.1}$$

[4] I shall show later that stars have *systematic* motions around the centre of the Galaxy of hundreds of kilometres a second but this is easy to explain in a simple dynamical model.]

where H_o is *Hubble's constant*. Equation (2.1) is known as Hubble's law.

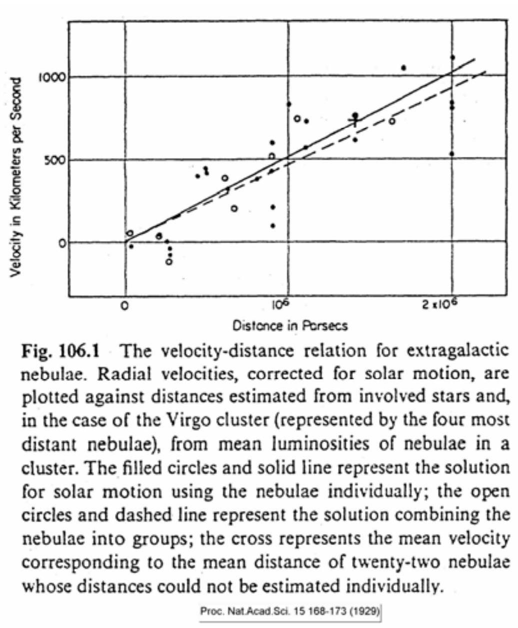

Figure 1-6. Hubble's plot of velocity against distance.

where H_o is a constant. Equation (2.1) is known as Hubble's law and H_o is called the *Hubble constant*.

As we shall see, the Hubble constant plays a fundamental rôle in extragalactic astrophysics and particularly in cosmology. Hubble's value for H_o was TBD but this in now know to be wrong by a factor of ten or more[5]. Even recently, its value was not known to within much better than a factor of two but, astronomers are converging on a value of around 65 km s^{-1} Mpc^{-1}, as shown in Figure 1-7. The latest value from the Hubble Space Telescope's *Key Project Team* is given as 72±8 km s^{-1} Mpc^{-1} [4].

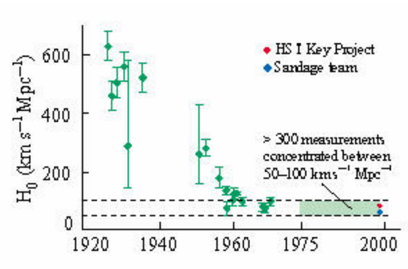

Figure 1-7. Measured value of the Hubble constant as a function of time.

Because of the uncertainty in the value of H_o, it is customary to write

$$H_o = h \times 100 \text{ km s}^{-1} \text{ Mpc}^{-1}, \tag{2.2}$$

where h is a dimensionless number in the range

$$0.5h \lesssim h \lesssim 1.0 . \tag{2.3}$$

Note that equation (2.1) determines the dimensions of H_o to be inverse time. Since $h \sim 1$, we find that

$$H_o^{-1} \sim 10^{10} \text{ y} . \tag{2.4}$$

2.3 Interpretation of Hubble's Law

The apparent recession of all galaxies from the Galaxy (and, as I shall show later, from each other) immediately suggests some sort of "explosion" occurring in the past. We can make a simple estimate of how long ago this occurred by assuming that all galaxies have retained the initial velocity given to them in the explosion. We shall have to abandon this assumption later when we consider more sophisticated models of the universe but the error introduced is no greater than the uncertainty in H_o.

If galaxies move with constant velocity away from the point[6] of the explosion, those with the higher velocities will have travelled further after any given time. In fact, if a galaxy has velocity v, then at a time t after the explosion it will have travelled a distance d given by

$$d = vt . \tag{2.5}$$

Suppose the explosion occurred at time t_o ago. Then the *present* distance d_o of a galaxy with velocity v is given by

$$d_o = vt_o . \tag{2.6}$$

Comparing equation (2.6) with Hubble's law, equation (2.1), we see that

$$t_o = \frac{1}{H_o} . \tag{2.7}$$

In other words, the reciprocal of the Hubble constant tells us how long ago the explosion took place. Using the value of H_o given above, we find that the explosion occurred some 10^{10} years ago.

If we were to reverse all the motions of the galaxies, that is if we were to run the universe backwards in time, then after a time t_o all the galaxies would collide at one point. Obviously they would then be unrecognisable as galaxies and, indeed, the universe would be in a somewhat excited state. Presumably therefore it was in this state when the explosion took place and it is difficult to know how to go about investigating what conditions were like *before* the explosion. It is therefore convenient to consider the explosion as being the origin of the universe that we can reasonably explore. Our crude estimate of the age of the universe is, therefore, some ten thousand million years.

[5] Hubble mistakenly used WW Virginis stars.

[6] Later I shall be at pains to emphasise that there *was* no *point* in space at which the explosion took place! I use the expression here for simplicity and ask that you not take the concept literally.

Finally, let us consider the size of the universe as a whole, although we must be very precise about what we mean by this. I shall show later that there is some evidence that the universe is infinite. If we agree that the universe is of finite age, however, it is obvious that we can only see a finite amount of it – those regions from which light has had time to reach us. Again I will use a simple argument which I will refine later.

If the age of the universe is t_o, then the greatest distance R from which light – travelling at velocity c – can have reached us is given by

$$R = ct_o = \frac{c}{H_o}, \qquad (2.8)$$

where I have used equation (2.7). Putting in numerical values, we find that R is of the order of 3000 Mpc.

3. Clusters of Galaxies

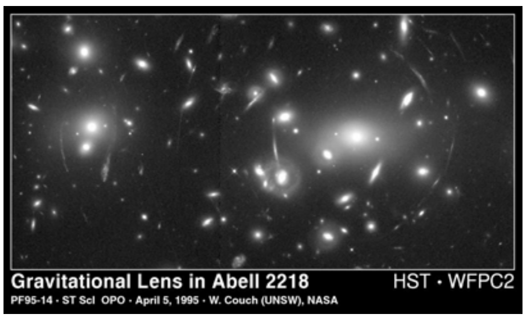

Figure 1-8. HST image of part of the Abell cluster of galaxies 2218.

So far, I have considered galaxies as isolated units, independent of each other. This is far from reality. Groups of galaxies, containing from a few to a few tens of galaxies, and clusters, containing hundreds or thousands of galaxies, have long been recognised. Figure 1-8 is a Hubble Space Telescope image of part of the cluster 2218 catalogued by George Abell. [It also illustrates *gravitational lensing*, to which we shall return.]

Modern research has revealed that the large-scale structure of matter is more complex than this simply subdivision and it tells us much about early evolution of the universe. I shall return to this in a later chapter.

Bibliography for Chapter 1

[1] Bull. Nat. Res. Council 2 171-217 (1921)
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[3] Hubble, E. *Proc. Nat. Acad. Sci.*, **15** 165-173 (1929)

[4] Freedman, W L, *et al.*, *Ap.J.* **553** 47-72 (2001)