Hubble's Menagerie of Galaxies

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Soon after the discovery that we live in a separate galaxy and that there are many other galaxies in the universe, Hubble designed a classification scheme of galaxies based on their appearances. It was such a robust scheme that it continues to be one of the basic tools of modern astronomy, and motivates astronomers to look for connections between different types of galaxies.

Galaxies are the building blocks of our universe. They come together to form different structures, such as clusters and superclusters of galaxies, which fill our universe. But they are not building blocks in the sense of atoms being the fundamental building blocks of matter. Each galaxy looks different and one would be lost in the zoo of galaxies if there were not some broad classes into which galaxies could be separated. It was Edwin Hubble who first classified galaxies according to their appearance.

This classification scheme has now become the bedrock of modern astronomy, and astronomers have even wondered if there is something in this classification scheme that goes beyond mere appearances. For example, is there a physical basis to these categories? Going further, astronomers have even wondered if Hubble's galaxy types form an *evolutionary* sequence: does one type of galaxy evolve *into* another?

1. The Discovery of Galaxies

Astronomers began to ponder these issues only after they discovered what was meant by a galaxy. It was in the 1920s that astronomers realised that we live in a separate galaxy, and that other galaxies were 'islands'

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in the vastness of space. Earlier astronomers had noticed a few diffuse patches of light in the starry sky, and wondered about them. The first recorded observations of these 'diffuse patches of light' were made by a Persian astronomer named Abd al-Rahman al-Sufi (popularly known in the west as Azophi), who observed the Andromeda galaxy in 964 AD, as well as two other 'clouds', now called the Large and the Small Magellanic Clouds. Ferdinand Magellan observed these clouds when he sailed around the world in early sixteenth century, and wrote about them.

After the invention of telescopes, in mid-eighteenth century, Charles Messier made a catalogue of 'blurry' objects that did not move, so that he did not mistake them for comets, which were his main targets. A number of objects in his list (the Messier Catalogue) were later revealed as separate galaxies. Around that time, the German philosopher Immanuel Kant hypothesized that we live inside a 'cluster' of stars, which we call the Milky Way, and wondered if the blurred 'nebulae' were distant versions of our own Milky Way. After a century, the Earl of Rosse made sketches of some of these nebulae (*Figure* 1), which showed structures like spiral arms emanating from a central region.

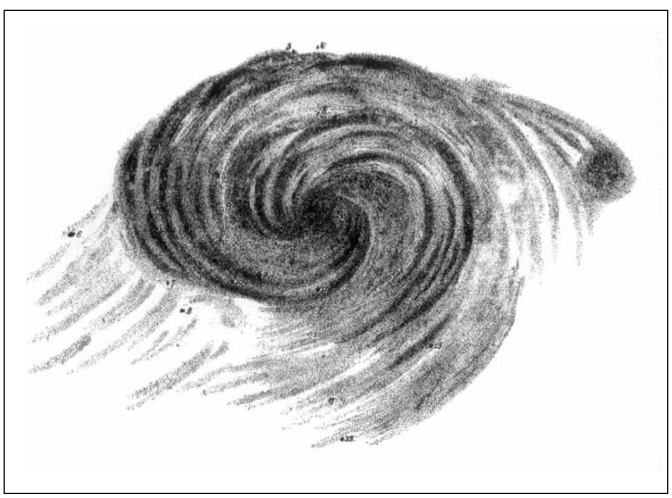

Figure 1. A sketch of the Whirlpool galaxy (Messier 51) by William Parsons (The Earl of Rosse) in the 19th century.

Astronomers made some progress in learning about these nebulae when they began to study their spectra in the early twentieth century. Vesto Slipher at the Flagstaff observatory (Arizona) found that lines in the spectra of some of them were shifted to the red side. If we study the spectrum of the Sun, we find a number of dark lines superposed on a background of the rainbow colours from blue to red. These dark lines are caused by absorption by atoms in the outer parts of the Sun. The spectra of nebulae also showed these dark lines, but often slightly shifted toward the red.

One interpretation of these 'redshifts' was that these nebulae were moving away from us. When we listen to the sound coming from a receding source, its pitch appears to decrease, implying that the wavelength of the sound has increased. The same phenomenon happens in the case of light as well, because light is an electromagnetic wave. So, the light from a receding nebula appears red because the wavelength shifts towards the red part of the spectrum, and the amount of reddening is proportional to its speed relative to us.

Slipher had discovered redshift in the case of some nebulae, and speculated that they did not belong to our Milky Way. Hubble happened to attend a seminar by Slipher during his student days, and was possibly inspired to investigate this further. Much later, he was able to resolve six peculiar stars in the image of Andromeda galaxy, taken with a 100-inch aperture telescope at Mount Wilson, in 1924. These stars were peculiar in the sense that their brightness varied in a regular fashion, and they had been earlier studied by Henrietta Leavitt[1] in 1912. She had discovered that the time period for the brightness variation in these 'Cepheid stars' was inversely proportional to their actual brightness. The longer a Cepheid star took to go through a cycle of brightness variation, the brighter it was. And once one knows the actual brightness of an object, the com-

[1] See article by Biman Nath in *Resonance*, Vol.6, No.6, pp.2–3, June 2001.

parison with its *apparent* brightness gives its distance from us.

Hubble used the data of Cepheid stars in Andromeda galaxy to deduce its distance, and found that it lay at a distance much larger than the size of our Milky Way (which was estimated earlier, again from using Cepheid stars in our Galaxy). The picture of our universe was at once transformed by this measurement: Kant was correct after all, and the nebulae-like Andromeda were separate galaxies like our Milky Way.

In the decade after this, Hubble studied thousands of galaxies, and sought to bring some order into the zoo of myriad galaxies. His classification scheme was based on the appearance of the galaxies. It makes sense to classify objects according to their morphology when their physical constituents are not well known. Naturalists in previous centuries had divided the plant and animal kingdom into different classes mostly based on the outwardly appearances and behaviour of different species[2]. One however hopes that the classification scheme would reveal some underlying pattern that has some *physical* meaning as well. In this respect, Hubble was fortunate; his scheme has proved to be so robust that it has not only survived until now, but also has become an essential tool in studying galaxies.

[2] The classification of plants and animals was done by Carl Linnaeus in the eighteenth century. We now know that it is related, to a large extent, to common descent based on the theory of evolution by natural selection proposed by Darwin and Wallace.

2. Hubble's Galaxy Classes

Hubble divided galaxies broadly into three types: elliptical, spiral, and irregular, with subdivisions within each class.

Elliptical galaxies are called so because they *look* like ellipses. They are denoted by the letter 'E' and a number that describes the galaxy's apparent shape: 0 for a completely round shape, 5 for one for which the length is twice its width, and 7 for apparently flat (but actually elliptical) galaxy. Of course, from the image of a galaxy, one cannot infer its *true* shape. A galaxy may look flattened by a different degree if viewed from a different direction.

Spiral galaxies are marked by spiral 'arms' around a bright, nuclear region, often called the 'bulge'. They are divided into two branches, called ordinary (and denoted by 'S') and barred ('SB'). Barred spiral galaxies appear to have an elongated rod-like feature in their centre, and the spiral arms begin at the ends of this 'bar'.

These two branches are further subdivided into a sequence Sa, Sb, and Sc (with parallel subdivisions in the barred branch, SBa, SBb, and SBc). This sequence tracks two aspects of spiral galaxies: (1) the brightness of the central bulge, and (2) the tightness of the winding of arms. Spiral galaxies with a bright bulge and tightly wound arms fall into 'Sa' category, and those with a relatively less bright bulge and loosely wound arms are called 'Sc'. Those with intermediate bulge brightness and tightness of arms are put in the 'Sb' category. The barred branch of spiral galaxies has a similar subdivision, depending on the brightness of the bulge and tightness of their arms.

Hubble put ellipticals and these two branches of spiral galaxies in the form of a 'tuning fork' diagram, in which the sequence of barred spirals mirror that of the ordinary spirals, with the difference that they have an additional bar. (*Figure* 2a and 2b)

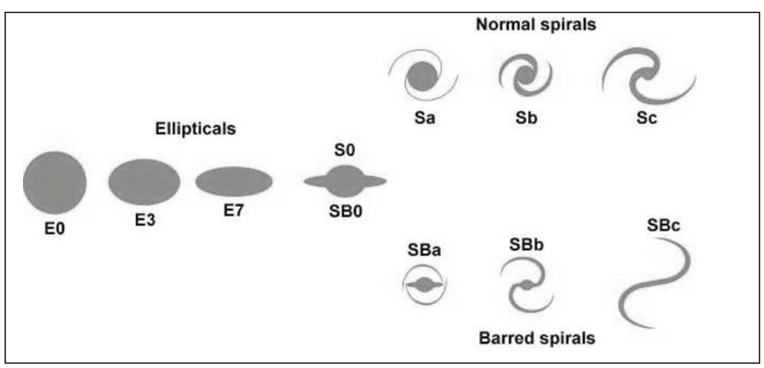

Figure 2 a. Hubble's galaxy classification scheme can be shown in the form of a 'tuning fork' diagram: elliptical galaxies are on the left, with spherical to more flattened galaxies arranged from left to right; and spiral galaxies are put in two parallel branches, for ordinary and barred spirals, in a sequence of gradually loosening of spiral arms and diminishing brightness of the central bulge.

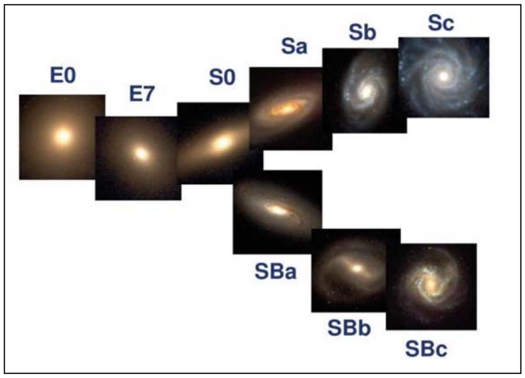

Figure 2b. Hubble's 'tuning fork' diagram with actual images of galaxies.

Then there are galaxies with no particular shape, and Hubble called them 'irregular' galaxies ('Irr'). After Hubble, astronomers also included an intermediate type of galaxies, between ellipticals and spirals, called SO. Hubble had hypothesized such an intermediate class, but it was recognized much later.

3. Physical Basis of the Hubble Sequence

Fortunately, the Hubble sequence of galaxies correlates with many physical aspects of galaxies, and not just their appearance.

***Stellar Population*:** Elliptical galaxies are dominated by an older population of stars, whereas light from young stars mostly determine the brightness of spiral galaxies. We know that stars shine because of thermo-nuclear reactions in their cores. Nuclei can be fused at high temperature and density that is available in stellar interiors, and the energy released in the fusion reaction is radiated by stars in the form of light. But stars have a peculiar property that more massive stars use up their nuclear fuel faster than a low-mass star. For example, a star like our Sun will take about ten billion years to use up its 'fuel' in the core, whereas a star ten times as massive will take as little as ten million years to do the same. This implies that short-lived stars are usually massive stars, and if one can observe a region of on-going star formation, one is likely to spot several of these short-lived and massive stars.

The colour of an object depends on its temperature: as one increases the temperature, the colour changes from red to orange to yellow and so on. The same thing happens to stars, and so the colour of the hot, massive stars is bluer than that of the rest.

Next, consider the relation between the colour of a star and its mass. Massive stars are usually hot, owing to the fact that gravitational pressure at the core of these stars is extremely large, which compresses the gas to a high temperature. We also know that the colour of an object depends on its temperature: as one increases the temperature, the colour changes from red to orange to yellow and so on. The same thing happens to stars, and so the colour of the hot, massive stars is bluer than that of the rest. Low-mass stars are, therefore, usually red. Our Sun is an average star as far as mass is concerned, and its yellow colour falls midway between the extremes of blue and red stars.

Elliptical galaxies, with a preponderance of old stars, therefore look red. The arms in spiral galaxies are usually sites of current star formation, and therefore look mostly blue. The central bulge of spiral galaxies, however, looks red because the stars there are mostly old and red. As a matter of fact, the colour changes from red to blue as one goes along the spiral sequence, from Sa to Sc. Tightly wound spiral galaxies, closer to the pivot in Hubble's tuning fork diagram, are redder than spirals at the end of the spiral sequence.

The Hubble sequence of galaxies is a sequence of their colours (from red to blue as one goes from the left to right of the tuning fork diagram), and an age sequence of stars from old to young.

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***Gas and Dust Content*:** The Hubble sequence of galaxies also turns out to be a sequence with increasing amount of diffuse gas, from almost dust and gas-free ellipticals to dust and gas-rich spiral galaxies. Also, Sc (SBc) galaxies contain more dust and gas than Sa (SBa) and Sb (SBb).

This sequence can be understood in terms of star-formation activities. Stars form in dense gaseous clouds, which are also very cool (with temperatures about 10–100 K). It is important to have a low temperature cloud to be able to form a star, because otherwise the collapse of a gaseous cloud cannot proceed to very high densities that are needed to form a star. A crucial ingredient to keep the gas cool is molecules, and it is extremely important to have dust grains in these clouds to be able to form molecules in the first place. So, galaxies which show young stars (and are therefore blue in colour), also have a lot of gas and dust.

Our Milky Way (a spiral galaxy) and our neighbouring galaxy, the Andromeda galaxy, are members of a loosely bound group of about two dozen galaxies.

***Galaxy Environment*:** When one studies the immediate environments of galaxies in the Hubble sequence, one is again struck by another correlation, that of between a galaxy's appearance and the density of galaxies *around* it. Elliptical galaxies are usually found in regions of space where galaxies crowd together to form 'clusters of galaxies'. These clusters usually have no spiral galaxies in their cores, but only in their periphery where the crowding is less. Spiral galaxies are most often found in less densely crowded 'galaxy groups'. For example, our Milky Way (a spiral galaxy) and our neighbouring galaxy, the Andromeda galaxy, are members of a loosely bound group of about two dozen galaxies.

We therefore find that Hubble's classification scheme that was originally designed solely on the basis of the appearances of galaxies, actually correlates with many physical properties of galaxies. This is why Hubble's tuning fork diagram remains an essential tool in the study of galaxies in modern astronomy.

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4. Evolution of Galaxies?

In the original scheme, Hubble used the terms 'early-type' and 'late-type' for ellipitcal and spiral galaxies. He insisted that he did not have any *evolutionary* sequence in mind though, only the position of a galaxy along the tuning fork diagram. But whether or not the Hubble sequence has any evolutionary significance has remained one of the hotly debated topics in astronomy for decades. Since spiral galaxies have young stars and ellipticals are mostly made of old stars, does it mean that spiral galaxies somehow *evolve* into elliptical galaxies?

Some astronomers have suggested that this kind of evolution may be triggered by collisions of galaxies. It may appear at first sight to be an unlikely occurrence that two galaxies separated by millions of light years would ever collide with one another. But observations have thrown up many examples of either galaxies going through a collision, or of galaxies with tell-tale signs of having collided in the past (*Figure* 3).

In such collisions between spiral galaxies, the spiral arms are likely to be destroyed, and astronomers think that the likely result of such a collision is an elliptical galaxy. Perhaps this is why one finds a preponderance of elliptical galaxies in dense and crowded regions of galaxy clusters, because they are the result of past collisions.

Recent observations with large telescopes have allowed astronomers to take a look at very distant galaxies. The light from these galaxies would have taken a long time to reach us, and so they formed very early. Thus a peek at these galaxies allows astronomers to find out how galaxies have evolved. And it does not appear to be a simple story.

Figure 3. Example of a pair of colliding galaxies in Canis Major constellation.
Image courtesy: NASA

There are instances of ellipticals in the early universe, implying that they were probably not the result of collisions between spirals. Observations show that they formed in a monolithic manner and formed very early in the history of the universe. At the same time, many early galaxies appear to be very irregular.

So, there must be a mix of different physical processes that govern the appearance of galaxies, and it may not be possible to find a simple sequence of evolution for the Hubble type of galaxies. Studies with bigger telescopes in the future will certainly tell us more about how the population of galaxies has evolved from the dawn of the universe till now.

Suggested Reading

[1] E P Hubble, *The realm of the nebulae*, Dover Publications, 1958.

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