Astronomy: images of the Universe

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Introduction

The purpose of astronomical images is straightforward: by recording images of particular regions of the sky, we can identify what objects are out there in the Universe and where they are located. Imaging the Universe enables us to understand its structure and contents. Images provide a wider context within which astronomers can use tools like **spectroscopy** to investigate the detailed physics and chemistry of individual objects.

In this course, you will explore how astronomers use images to measure the properties of **stars** and galaxies. You will also examine different types of images used by astronomers, from detailed images of the structure of a nearby **star cluster** to maps of the entire northern sky, and from visible light to images in other parts of the electromagnetic spectrum.

This OpenLearn course is an adapted extract from the Open University course S284 Astronomy.

1 Images and measurements

Astronomical images record distributions of brightness, and how that depends on an object's position on the sky. For optical astronomy this is now usually done using CCD (charge-coupled device) detectors. These are similar to cameras in modern mobile phones, although typically larger and/or more sophisticated.

Making images in parts of the electromagnetic spectrum beyond visible light can require less intuitive methods, such as interfering electric signals together from multiple antennae to produce radio **wavelength** images. But however an image is made, the basic end result – as shown in Figure 1 – is a two-dimensional (*x*, *y*) array of pixels: a grid that records the brightness at related locations on the sky.

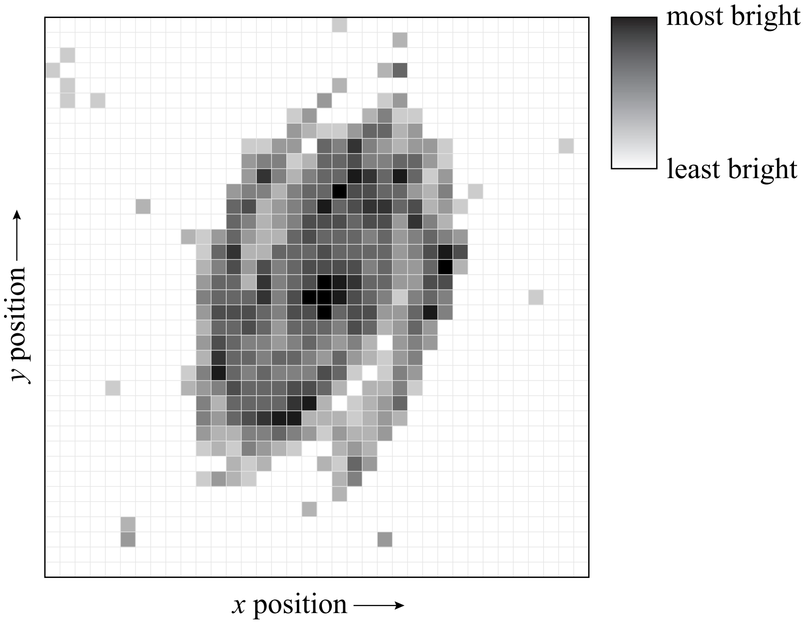

Figure 1 How information is stored in a simple (greyscale) astronomical image. The data are stored as an *x*, *y* grid, where each pixel has an associated brightness.

Additional information, such as the astronomical coordinate system and details of when the observation was made, is typically stored within the image file as metadata.

We need to employ careful methods to make measurements from images such as Figure 1 if we are to make reliable inferences about stars and galaxies. In this section, you will examine how these measurements are made, and what they can tell us.

1.1 Understanding brightness

The ultimate aim of an astronomical observation is usually to answer a question about the intrinsic properties of an astronomical object. For example, we might want to understand how much energy a star is producing, or perhaps how many stars are likely to be present in a distant **galaxy**.

Astronomers refer to the brightness of astronomical objects in several ways. When referring to how bright a star or galaxy *appears* to be, astronomers use the concept of **apparent magnitude**. The brightest objects in the night sky have apparent magnitudes of around 1, whereas the faintest that can be seen with the naked eye have apparent magnitudes of around 6. Because of the way in which human eyes work, objects with magnitude 6 are in fact about 100 times *fainter* than those with magnitude 1: each decrease of one magnitude corresponds to roughly a 2.5 times reduction in brightness. Using a large telescope, objects as faint as magnitude 25 may be detected. A 25th magnitude star is around a hundred million times fainter than those near the limit of perception for unaided human eyes.

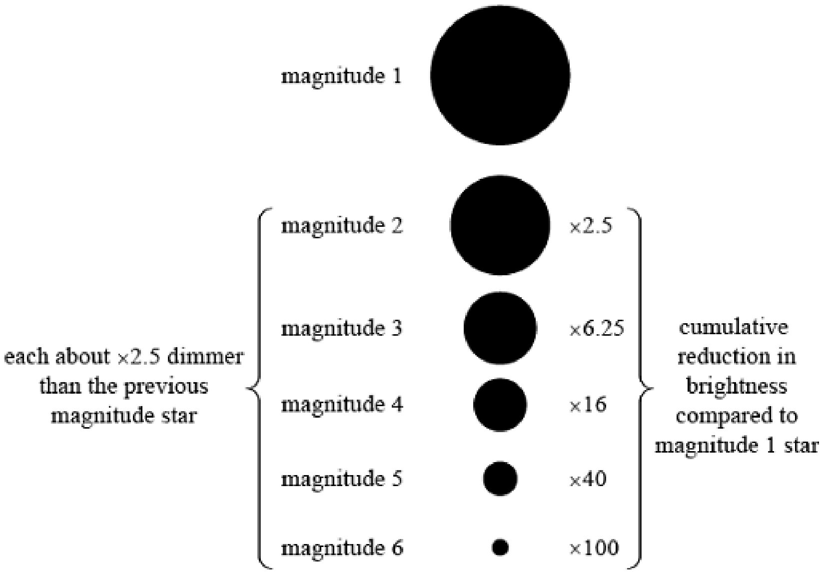

Figure 2 An illustration of apparent magnitudes. Note that although stars of different magnitude are conventionally indicated as having different sizes, as they are here, in reality almost all stars appear to us as pinpoints of light.

There are two reasons why different stars may have different apparent magnitudes: they may emit different amounts of light or they may be at different distances away from us. Two identical stars situated at different distances from us will have different apparent magnitudes, purely because the light emitted by the more distant star is spread out over a larger area by the time it reaches us. In order to allow comparison between the brightness of stars at different distances, the concept of **absolute magnitude** is required. The absolute magnitude of a star is (arbitrarily) the value of its apparent magnitude if it were placed at a standard distance away of 10 **parsecs** (about 3×10^{17} m). The absolute magnitude of a star therefore gives a measure of its intrinsic brightness, or the amount of energy it emits per unit of time.

While apparent and absolute magnitudes are a useful convenience for astronomers, it is often helpful to use more conventional measurements of brightness when measuring stars and galaxies. We may therefore distinguish between the **flux** of light from a star or galaxy and its **luminosity**. Luminosity is a measure of how much energy in the form of light (or other **electromagnetic radiation**) is emitted by a star or galaxy in a given time interval. It is an intrinsic property of the star or galaxy itself and may be measured in the SI unit of power, which is watts (W) or equivalently joules per second ($J\ s^{-1}$). Luminosity can be related to absolute magnitude. On the other hand, flux is a measure of how much energy in the form of light (or other electromagnetic radiation) we observe from a star or galaxy in a given time interval. It therefore depends both on the luminosity of the star or galaxy in question and on its distance away from us. It is measured in the SI unit of power per unit area, which is watts per square metre ($W\ m^{-2}$). Flux can be related to apparent magnitude.

1.2 Measuring brightness

In this section so far you've encountered several astronomical quantities associated with the brightness of objects: specifically, apparent and absolute magnitude, flux, and luminosity. Importantly, the brightness we measure from an image does not, on its own, tell us anything about the physics of the star or galaxy. Until we know how far away it is, we are only measuring how bright it looks to us on the sky. Sometimes we can make beautiful images of the sky from which it is quite difficult to draw conclusions about the science of what we're looking at, because it is not possible to measure accurate distances.

In principle it is easy to measure the apparent magnitude – or flux received – from an astronomical object in an image:

- first, identify which pixels in the image correspond to the object of interest
- then, sum up the brightness measured in each pixel.

Figure 3 shows two images with **photometric apertures** drawn on them. These are regions (defined by the astronomer analysing the image) within which the brightness of each individual pixel is added together. The sum of the brightness of each pixel within the circular aperture is the total brightness for each star or galaxy.

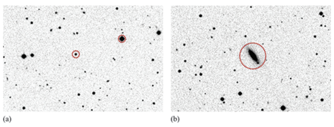

Figure 3 Photometric apertures (dashed circles) placed on images to measure the flux of (a) two stars of different magnitudes and (b) an **extended** galaxy.

It is not necessarily straightforward to decide how big to make the aperture. The blurring effects of the atmosphere and telescope optics, and the underlying shape of the light distribution from large objects such as galaxies, mean that defining the aperture size can be tricky. A large aperture will include a greater proportion of the source flux, but may also suffer from higher contamination from the surrounding background flux (the grey 'noise' between the darker stars and galaxies in Figure 3).

Figure 4a shows how the **surface brightness** of a star (its flux or magnitude per unit area) is measured to decrease with distance from its centre. Such plots can be referred to as radial **surface brightness profiles**. The light is spread out over a number of pixels, despite the true **angular size** of the star being smaller than one image pixel. The way that light from a star is distributed across multiple pixels by a particular telescope is known as the telescope's **point-spread function (PSF)**.

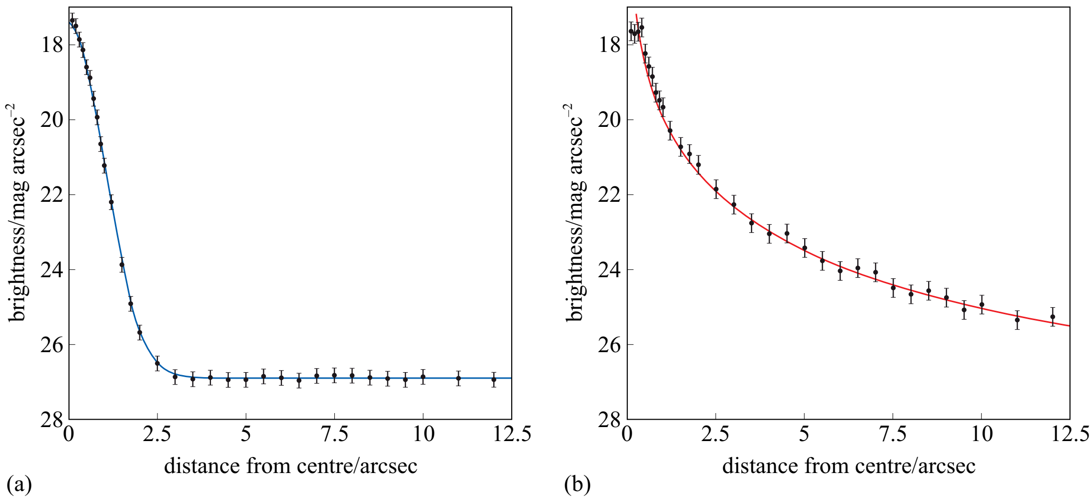

Figure 4 The radial surface brightness profiles of (a) a star (i.e. a point source) and (b) a galaxy (an extended source).

Figure 4b shows the radial surface brightness profile for a galaxy. To make these graphs, the surface brightness is measured in circular 'annuli' (rings) centred on the source. Such profiles for bright stars in the field can be used to determine the shape of the PSF for your observation – in other words, they enable careful measurement of the degree to which the light emitted by the star is being blurred across a wider area in the image we see. This allows aperture sizes to be chosen that optimise the quality of the measurements.

For sources whose true angular size is larger than a single image pixel, such as the galaxy in Figure 4b, the radial brightness profile is broader than the PSF, and follows a characteristic shape based on the distribution of stars. Model galaxy profiles can be used to help determine the best aperture size, and/or correct for missing flux beyond the chosen aperture radius.

1.3 Measuring sizes

With a few exceptions (the Sun, and a few nearby **red giant** stars), we cannot measure the sizes of individual stars. The observed size of a star in an image is determined by the PSF and is typically much larger than the true size. But much of our knowledge of *systems* of stars – **binary stars** and stellar clusters, **star-forming regions** and galaxies – is built on measurements of their sizes, as calculated from astronomical images.

The size measured directly from an image does not on its own tell us about its true physical size. We initially measure angular size, the angle the object spans on the sky, but we need to know its distance to determine how big it is in kilometres or parsecs.

Figure 5 shows two images taken by the same telescope as part of the Digitized Sky Survey project. On the left is a **globular cluster** and on the right is a nearby galaxy. The two objects span a similar number of pixels on the Survey's CCD detector.

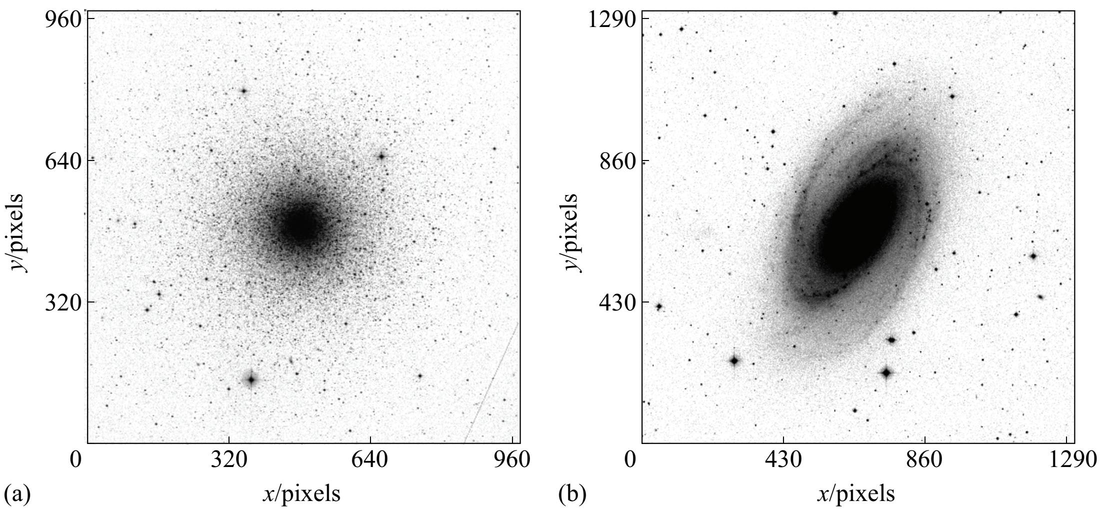

Figure 5 Images of (a) a globular cluster and (b) a galaxy.

- Using an astronomy software tool, the star cluster and galaxy are measured to span 540 pixels and 900 pixels, respectively. What additional information would you need in order to compare the true sizes of the two astronomical objects?
- You would need a way to convert between pixels and angle on the sky. You also need to know the distances to each of the two objects.

The conversion factor between pixels and angular size or separation in arcseconds or arcminutes will be different for different telescopes. It is known as the telescope's **pixel scale**.

Example 1

Imagine that you read the documentation for the Digitized Sky Survey 2, the source of these images, and find that the pixel scale is 0.0170 arcmin pix^{-1}. Calculate the angular size of the globular cluster.

Solution

The angular size is given by multiplying the size measured in pixels by the pixel scale of the telescope detector. The angular size is therefore:

$$540 \text{ pixels} \times 0.0170 \text{ arcmin pix}^{-1} = 9.18 \text{ arcmin}$$

The globular cluster has an angular size of 9.18 arcminutes.

- Repeat the calculation in relation to Example 1 to determine the angular size of the galaxy in Figure 5b.
- $$900 \text{ pixels} \times 0.0170 \text{ arcmin pix}^{-1} = 15.3 \text{ arcmin}$$

  The galaxy has an angular size of 15.3 arcminutes.

You research the star cluster and the galaxy (e.g. by looking up their names on the SIMBAD astronomical database), and discover that the cluster is at a distance of 10.4 kpc (it is within the Milky Way), while the galaxy is at a distance of 2.6 Mpc.

Converting an angular size of an object into a physical size is a straightforward trigonometrical calculation, as long as we know the distance to the objects. The equation relating these quantities is

$$\sin\theta = \frac{D}{d}$$

Where θ is the angular size, *D* is the physical size and *d* is the distance to the object. It is also useful to recognise that, for small angles measured in **radians**, $\sin\theta = \theta$.

- Now calculate the physical sizes of the two objects, and compare them. (*Hint*: if you are stuck, you may wish to review the information above this question.)
- The cluster's angular size in radians is

$$\frac{2\pi}{360^\circ} \times \frac{9.18 \text{ arcmin}}{60 \text{ arcmin degree}^{-1}} = 0.00267 \text{ rad}$$

The small-angle approximation discussed previously ($\sin\theta = \theta$, where $\theta \leq 0.2$ rad) applies both to **angular separations** and angular sizes. Hence the cluster's physical size (D) is related to its angular separation (θ) and its distance (d) by

$$\begin{aligned} D &= \sin\theta \times d \\ &= 0.00267 \text{ rad} \times 10.4 \text{ kpc} \\ &= 0.0278 \text{ kpc} \end{aligned}$$

A similar calculation for the galaxy gives a physical size of 11.6 kpc. Therefore the galaxy is around 400 times larger than the star cluster.

1.4 Measuring shapes

As well as measuring the brightnesses and sizes of astronomical objects, images allow us to measure and interpret their shapes and structures.

Stars are simple objects that are usually close to spherical. In most cases we cannot obtain information about their shapes and structure from images (deviations from a spherical shape can sometimes be identified by other means, e.g. variability). But the shapes and structure of a diverse range of other astronomical systems – for example, star-forming regions, galaxies and their sub-components, **jets** of material produced by stars and **black holes** – can be examined using images across the electromagnetic spectrum.

Remember that our images show the distribution of light *as it is recorded by our telescope detector*, which is located at a particular position in space. The detector records a two-dimensional image, but the light originates from a three-dimensional object.

We are used to 2D images of 3D scenes from ordinary cameras. However, to interpret a photo of a landscape, or a group of people at a party, we have a wealth of extra information – from lighting, shadows, and our own intuition about the contents of the picture – to help our brains interpret the photo as a three-dimensional scene. Astronomical images often have fewer clues available to help us work out the underlying three-dimensional shapes, as shown in Figure 6.

Figure 6a shows an astronomical object shaped like a dinner plate (perhaps a galaxy) as viewed from three different directions. This scene depicts the effect of **projection**, where the object is tilting away from the plane of the sky. Note that this situation is mathematically similar to an inclined elliptical orbit.

Figure 6b shows the effect of orientation on the inferred length of a linear extended structure (perhaps an extended gas cloud or a jet-like feature).

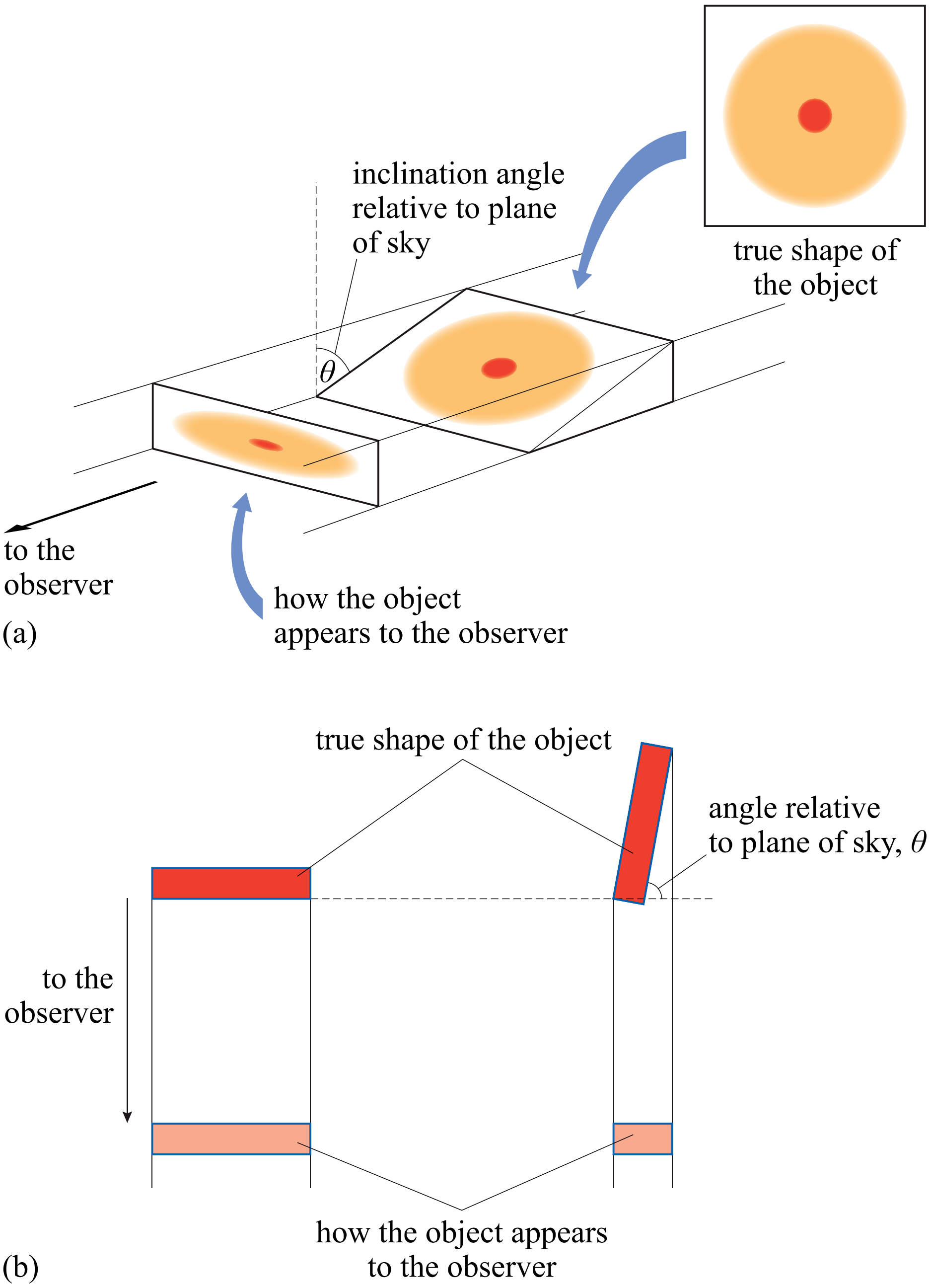

Figure 6 The effects of orientation on measured sizes and shapes of astronomical objects: (a) a disc-shaped object, and (b) a rod-shaped object.

- At what angle relative to the plane of the sky will the linear object appear shortest in an image?
- The greater the angle away from the plane of the sky, the shorter the structure appears when observed in an image. The object will therefore appear shortest at an angle of 90 degrees to the plane of the sky.

For a circular disc-like object, the observed major axis (i.e. twice the **semimajor axis**) corresponds to the true diameter of the **disc**, and the inclination angle (tilt, θ) relative to the plane of the sky is given by

$$\theta = \cos^{-1}\left(\frac{b}{a}\right) \quad \text{(Equation 1)}$$

where a is the measured semimajor axis and b the measured semiminor axis.

If a linear object is projected at an angle of θ to the plane of the sky, then its true length, L, is related to its measured length, l, by

$$L = \frac{l}{\cos\theta} \quad \text{(Equation 2)}$$

Example 2

You want to measure the shape of a galaxy that an image shows to have an ellipse shape, but you believe is in fact a disc (round dinner-plate shape) that is inclined relative to the observer, as in Figure 6a. The angle by which the galaxy is tilted, θ, is not known.

The semimajor and semiminor axes are measured from the image to be 20 arcmin and 13 arcmin, respectively. Calculate the angle of inclination, θ.

Solution

The longer axis tells us the true radius of the disc. The angle can then be calculated using Equation 1

$$\theta = \cos^{-1}\left(\frac{13}{20}\right) = 49^\circ$$

- A jet of gas is observed emerging from a young star. The length of the jet is measured to be 2.5 pc and the width is 0.3 pc. If the jet is cylindrical, and oriented at an angle of 30 degrees relative to the plane of the sky, what is its true length and ratio of its length to width (i.e. the ‘aspect ratio’)?
- Using Equation 2, the observed length l is related to the true length L via $l = L\cos(\theta)$.

  Hence the true length is

$$L = \frac{l}{\cos\theta} = \frac{2.5}{\cos\left(30^{\circ}\right)} = 2.9\ \mathrm{pc}$$

and the aspect ratio is

MathJax failure: MathML - MathML must be formed by a single element

In other words, the object is in reality more elongated than it appears in our images.

The conclusion to draw from these calculations is that frequently in astronomy we cannot be certain of the true shape or dimensions of objects. If you had not assumed the galaxy in the example was a circular disc, you could not have obtained the inclination angle.

Sometimes the problem can be solved by using additional information, such as that obtained from the spectrum of an object. The shift of spectral lines, or their broadened widths, may be caused by the **Doppler effect** which can provide clues about the motion or rotation of the object concerned. If we are studying very large samples, we sometimes expect that overall the orientations are random, which enables the use of statistical methods or **computer simulations** to determine the overall size and shape distributions of a set of objects. However, unknown orientation angles remain a major uncertainty in many astronomical studies.

2 Structure in images

You've now examined the basic quantitative information that astronomers can obtain from images: measurements of the brightness, sizes and shapes of astronomical objects.

Combining this information together tells us about the *structure* of the Universe: how individual stars, stellar systems, galaxies and their components relate to each other. Mapping out the structure of astronomical systems, both small and large, is an essential step in building our understanding of how stars and galaxies are born, live their lives (whether stable and unexciting or short-lived and dramatic), and eventually die.

In this section, you will explore the diverse types of spatial structure that emerge in astronomical images, setting the scene for more precise classifications of astronomical objects.

2.1 From point-like stars to diverse nebulae

Stars are fascinating and complicated objects, but for the most part this complexity does not reveal itself in individual images of single stars. Most stars are **unresolved** to our telescopes (i.e. their light is contained within a region smaller than the size of details we can distinguish).

To understand the structure of stars, astronomers have had to construct models based on information from spectroscopy, studies of binary star systems, and tools such as **asteroseismology**. However, there are a few exceptions.

We have exquisite structural information about the surface of the Sun (Figure 7a), from space missions such as the Solar and Heliospheric Observatory (SOHO) and Solar Orbiter. This information has enabled astronomers to understand the interplay of energy transport and **magnetic fields** in our nearest star. We also have a small number of **resolved** images of nearby giant stars. An example is π^1 Gruis (Figure 7b), which shows similar convective structure on its surface to that of the Sun.

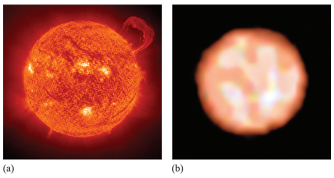

Figure 7 Stars as extended astronomical objects: (a) the Sun, taken by the SOHO mission, and (b) the nearby giant star π^1 Gruis.

For unresolved objects such as stars, the main properties that can be measured from images alone are location, brightness, and colour. But astronomers have known for several centuries that there are objects in the sky that are not **point-like** – they show extended and varied structure in images. (Extended astronomical objects are defined as those that have an angular size larger than the PSF of an image.) Identification of such fuzzy, 'cloud-like' astronomical objects dates back as far as early tenth-century Islamic astronomy.

Early astronomers classified these extended objects as **nebulae**: *nebula* being the Latin word for a cloud or fog. The term became used to describe any object that had a fuzzy appearance, rather than the sharper form of a star.

In modern astronomy, the term nebula is now used in a more precise way. However, until the early twentieth century the physical nature of many of the 'fuzzy' extended objects in the sky was not well understood, and so the class of nebulae provided a useful distinction between unresolved (point-like) and resolved (extended) structures.

Figure 8 shows some hand-drawn sketches of nebulae dating to the early nineteenth century. It is apparent that they do not all show the same structure: there are various different types of fuzzy, extended – and in some cases a little peculiar – objects visible in the night sky.

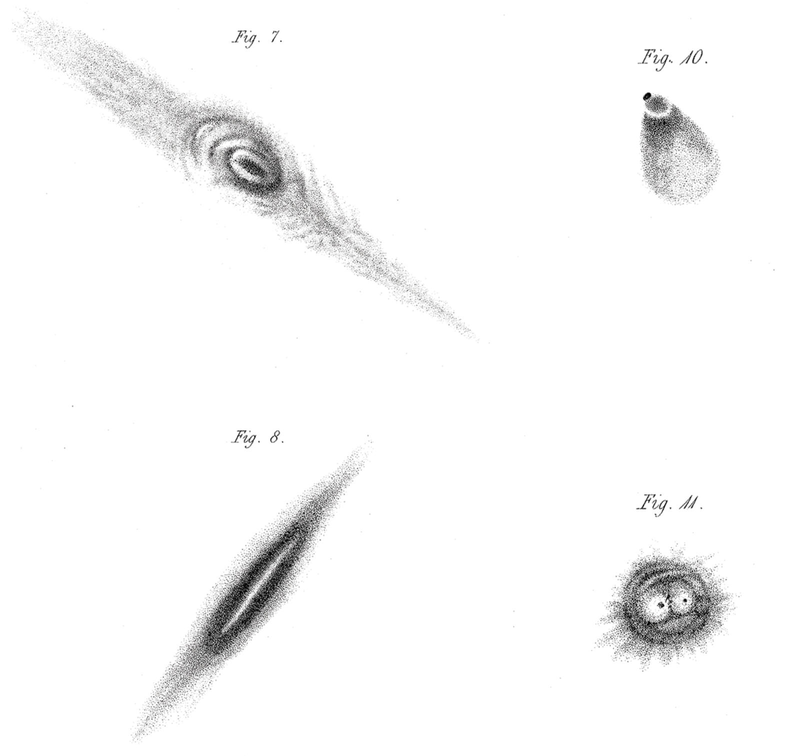

Figure 8 Images of nebulae, as viewed by the most powerful telescope of the nineteenth century, the Leviathan of Parsonstown, and hand-sketched by William Parsons, 3rd Earl of Rosse.

(Source: The Earl of Rosse (1805) 'Observations on the nebulae', *Philosophical Transactions of the Royal Society of London*, 140(499), pp. 499–514, www.jstor.org/stable/108449)

2.2 Exploring the Messier catalogue

The catalogue of Charles Messier provides an ideal starting point for exploring the variety of extended objects visible in the sky. More than 250 years after publication of the first part of his catalogue, it remains a treasure trove for amateur astronomers and astrophotographers looking to observe and make images of some of the most beautiful, complex and interesting deep-sky objects that can be observed without access to professional observatories.

In the following activity you will explore the range of objects that Messier found.

Activity 1 Exploring the Messier catalogue

Allow around 15 minutes

Task 1

Visit the Wikipedia page for 'Messier object' to find a full list of deep-sky, extended astronomical objects. (Make sure to open the link in a new tab/window so you can easily return here.)

Choose an object that sounds interesting, then look around online for a few different images of it, and some background information about what type of object it is. In most cases you should be able to find pictures from both professional observatories and amateur astronomers/astrophotographers. Indeed, if you are familiar with Messier objects (or even have your own collection of photographs), you may already have a favourite to select.

Task 2

Write a short paragraph (50–150 words) describing the appearance of your chosen Messier object, what type of astronomical object it is, and any facts you found interesting.

Provide your answer...

2.3 Types of extended objects

In your research for Activity 1, you will have probably come across several different types of extended objects. Optical astronomers now recognise five main classes of deep-sky object, shown in Figure 9. Here you will consider each of these in turn, focusing on the image structure they show.

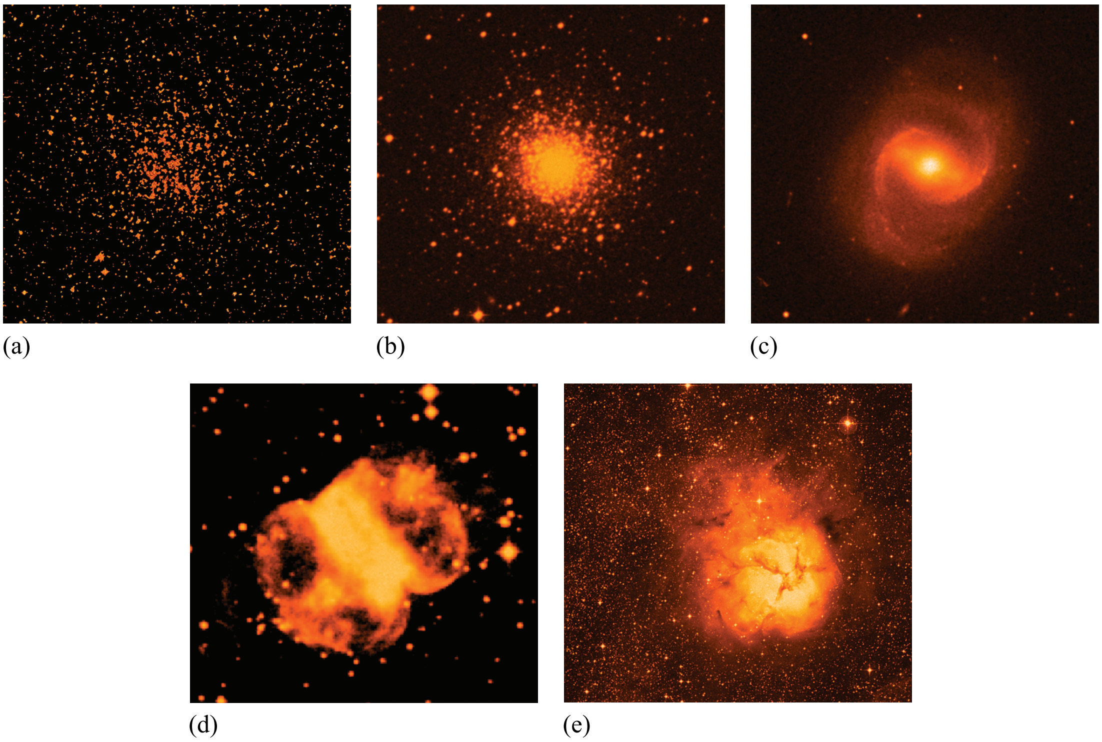

Figure 9 R-band images of the five main types of extended objects seen in optical images: (a) **open cluster**, (b) globular cluster, (c) galaxy, (d) planetary nebula and (e) diffuse nebula.

Open cluster

Figure 9a shows M11, an example of an open cluster of stars. With modern telescopes, you can make out individual stars in the cluster, but at low image **resolution** the light from the stars blurs together to form a fuzzy, nebula-like appearance.

Globular cluster

Figure 9b shows M75, a globular cluster. Like M11 this is a collection of many stars, but its spatial structure is different. This cluster has a round shape and more regular appearance, and it is brighter in the centre and fainter at the edges. The stars are packed closely together in the cluster centre but are more spread out at larger distances.

Galaxy

Figure 9c shows M91, which is a galaxy. Like M11 and M75, M91 is a collection of stars, but its structure is very different. We cannot identify individual stars, but you can see a spiral structure. The smooth, diffuse nature of the light tells us that it comes from a much larger number of stars than is the case for star clusters.

Planetary nebula

This class of nebulae show extremely diverse structures – the example in Figure 9d is M76 (the Little Dumbbell nebula). **Planetary nebulae** have nothing to do with planets; they are the debris of a Sun-like star that has reached the end of its life. The name comes from their coloured, disc-like appearance in early images.

Some planetary nebulae have round circularly symmetric structures, while others are 'bipolar', showing butterfly-like linear symmetry.

Diffuse nebula

Figure 9e shows M20, an example of a diffuse nebula. This final category encompasses objects where images show a smooth light distribution not made up of individual stars, which is less regular in structure than the planetary nebulae. The light from diffuse nebulae comes from warm, glowing gas and **dust** associated with star-forming regions.

In the next activity, you will further compare these examples of the five types of extended objects.

Activity 2 Comparing the scales of Messier objects

Allow around 15 minutes

The Scales Tool plots the sizes and distances of all the Messier catalogue objects, including the five Messier objects shown in Figure 9 (M11, M75, M91, M76 and M20).

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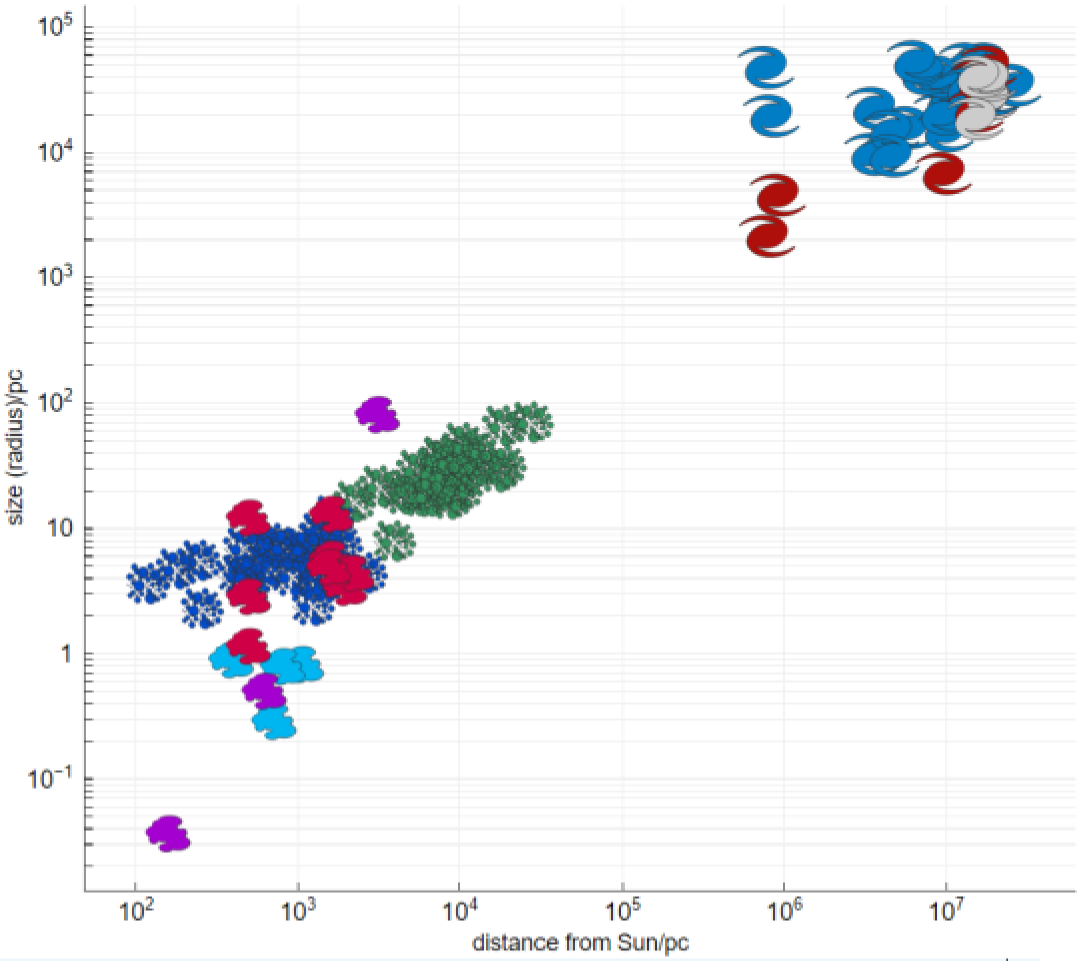
The Scales Tool



Use the tool to investigate the properties of the five objects from Figure 9 and to determine the following information. Note that it is likely to be helpful to use the 'Messier object types' key at the top to show only the relevant categories of object when searching for a particular Messier object on the distance–size graph.

a. List the five objects in order from smallest to largest, and then again from nearest to most distant.
b. Note how much larger the largest of these Messier objects is than the smallest.
c. Note how much further away the most distant of the objects is than the nearest.
d. Find the Messier object you studied in Activity 1, and note how it compares to the five in Figure 9.

Provide your answer...

Discussion

a. Smallest to largest: M76, M11, M20, M75, M91 (planetary nebulae are larger than stars, but typically smaller than diffuse nebulae and star clusters, which in turn are much smaller than galaxies). Nearest to most distant: M76, M20, M11, M75, M91.

b. The Messier objects span a very wide range of sizes. The largest object, the galaxy M91, is around 35 000 times larger than the smallest, M76.
c. M91 is also the most distant of the objects in Figure 9, and M76 is the nearest. M91 is around 19 000 times more distant than M76.
d. Your findings will depend on your choice of Messier object, but this activity should have given you a sense of the varied sizes and appearances of extended objects in the night sky.

3 Colour in astronomy images

So far you have focused on brightness, size, shape and structure in astronomy images, but have neglected one of the most important methods for obtaining physical insights from images: the use of **colour** information. The colour of starlight encodes information about the temperature of a star. Indeed, colour provides clues to a range of physical processes of interest to astronomers.

This section will explore how telescopes record colour in the visible part of the spectrum, and how we can use that information. It will also examine the full range of light information astronomers can access, from radio waves to X-ray and **gamma ray** images.

3.1 Broadband images

To compare astronomical measurements of brightness for different objects reliably, and to make physical interpretations (e.g. estimate the temperature of stars, understand the effect of dust obscuring our measurements), we require precise information about the *range of wavelengths* of light that are recorded in an image. Telescope filters provide us with a way to do this.

By using a filter that only allows red light – from a specific range of wavelengths – to pass through, brightness and colour information can be recorded in a standardised way. Other astronomers will be able to reproduce exactly the same observation, and should measure the same amount of red light from the same object (unless it is variable).

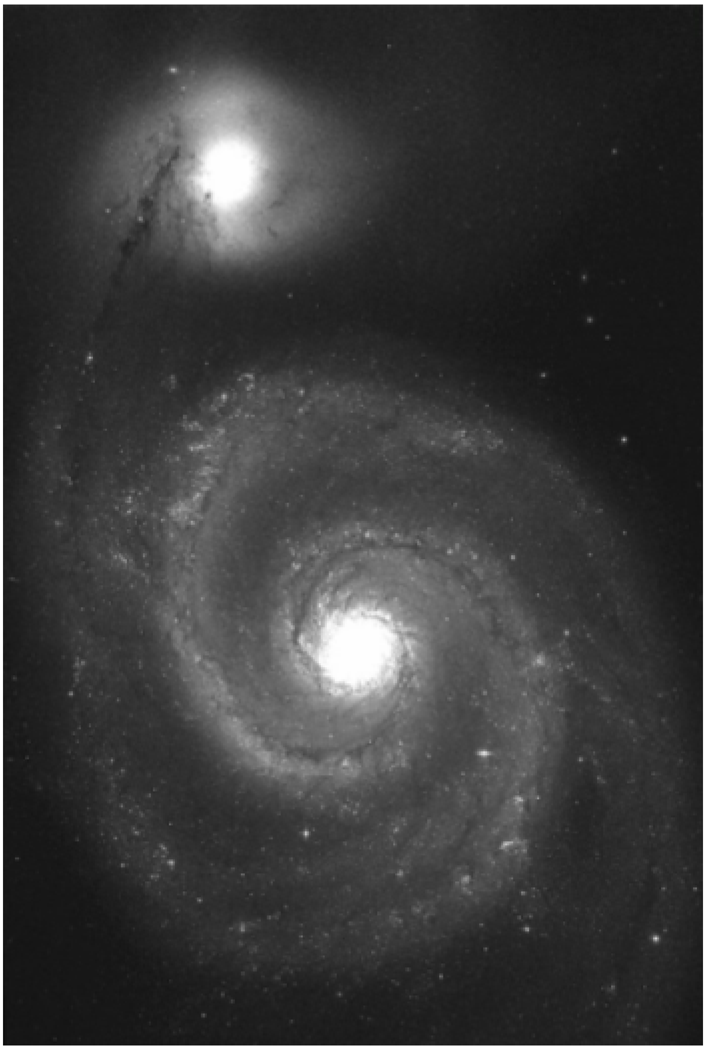
The standard optical U, B, V, R and I filters are referred to as 'broadband filters', although they typically encompass considerably narrower wavelengths than broadband spectra. Each of these filters spans a wavelength range of a few hundred nanometres. The U filter passes light in the near-ultraviolet (near-UV) range of the spectrum; the B filter passes blue light; the V filter passes green–yellow light; the R filter passes red light, and the I filter passes light in the **near-infrared** (near-IR) part of the spectrum.

Most of the astronomical images we see in news stories, press releases, and astrophotography exhibitions are in colour, but it is important to emphasise that these rarely represent exactly what our eyes would see (if they were as sensitive as a telescope). **Colour images** are usually made by combining together images taken in three, or sometimes more, different filters. Each image on its own is simply a record of the brightness in each pixel, so might best be represented by a greyscale image.

Video 1 initially shows such a greyscale image from one filter. The images recorded through three different filters are then assigned (typically) red, green and blue colour ranges, and then added together to form a multicolour image that shows which parts of the object have redder or bluer light.

Video content is not available in this format.

Video 1 The process of making a colour image from optical telescope data. (Note: this video has no sound.)



But telescope filters typically do not match the response of our eyes to light very closely, and various decisions need to be taken in combining different filters together. So there is no single 'right answer' to the question 'what does this astronomical object look like in colour?'

Colour images are useful visualisations to help understand the structure of objects, but if we want to draw scientific conclusions from them it's important to keep a careful record of the properties of the telescope filters and how the images were combined together.

Quantitative measurements of colour involve taking the difference in brightness as measured by two different filters (e.g. $(B - V)$). Colour index is measured by doing **photometry** (recall Section 1.2 of this course) separately on images from two filters and then subtracting the magnitudes.

- If working with colour indices, why is it essential to use standard telescope filters with known wavelength ranges?
- As with comparing brightness measurements of stars or galaxies, it is only possible to make reliable comparisons between colour measurements for different astronomical objects and/or measurements taken with different telescopes if exactly the same ranges of light are being compared.

3.2 Multiwavelength images

Modern astronomers can carry out observations using light with wavelengths spanning a range from a few metres to 10^{-20} m. This means we can now work with broadband images made across this full range of wavelengths.

Figure 10 shows images of a **supernova remnant** (the debris of an exploding star), the Crab nebula. These images were obtained by telescopes spanning the radio to the gamma ray regimes – a factor of more than 10^{18} in wavelength!

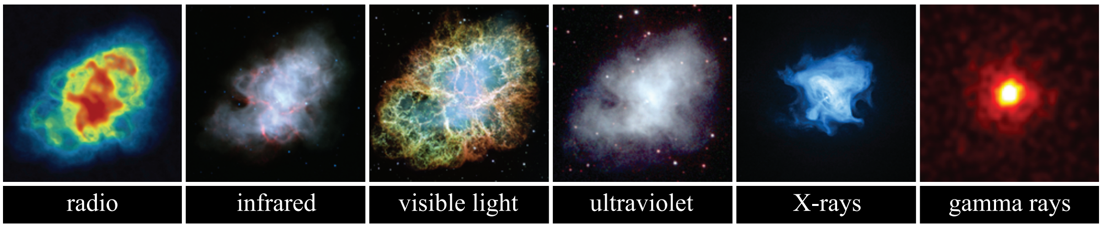


Figure 10 The Crab nebula viewed across the extremes of the electromagnetic spectrum.

An important point that these multiwavelength images should help you to grasp is that the distribution of light on the sky (whatever wavelength we're using to look) doesn't always directly map the distribution of underlying matter that is producing the light. For example, in Figure 11 the left image shows an optical view of the nearby Andromeda galaxy, while the right image shows an infrared view of the same part of the sky.

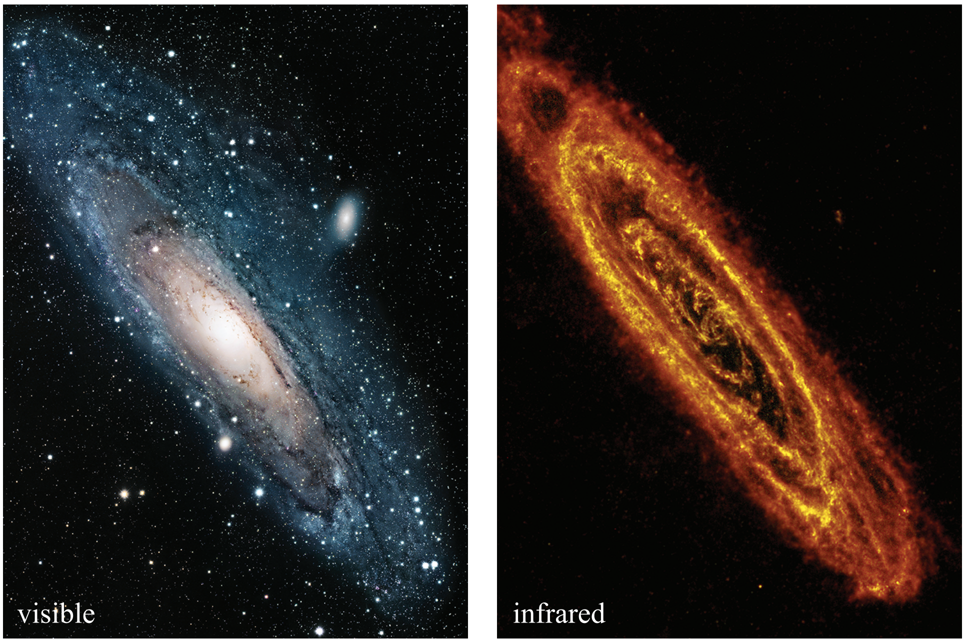


Figure 11 The Andromeda galaxy in optical (left) and infrared (right) emission.

- What do you notice that is different about the appearance of the Andromeda galaxy in the optical and infrared images?
- Regions that are dark in the optical image are lit up in the infrared image – the two wavelength regimes seem to be tracing different underlying matter.

Similarly, in Figure 12 the left image shows another galaxy, NGC 6964, in optical light, while the right image shows a radio map (with the same scale).

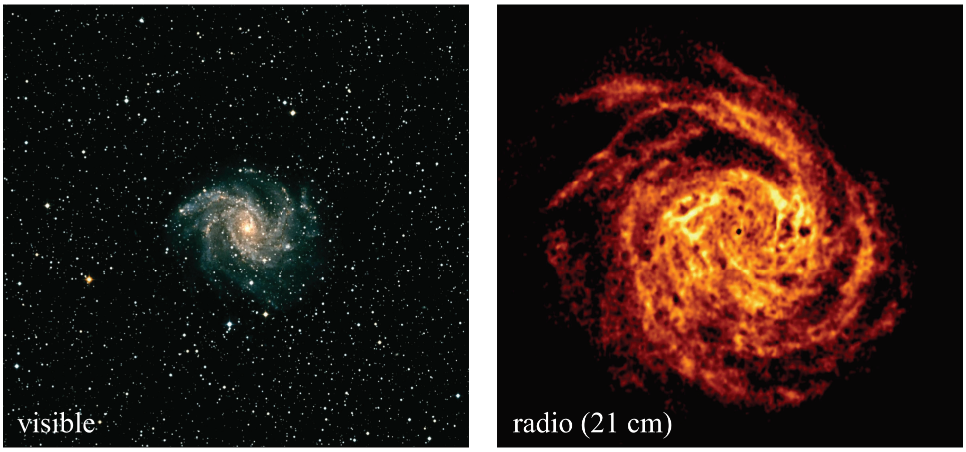


Figure 12 The galaxy NGC 6964 in optical (left) and radio (right) emission.

You might be wondering, for both Andromeda and NGC 6964: which of the two images in the set is better at telling us where the matter is located in the galaxy? How can we tell?

In the case of Andromeda, the optical light indicates where the stars are. However, some of the dark regions are dark not because there are no stars, but because dust obscures the stars and prevents their light from reaching us. In contrast, the infrared light is tracing the locations of warm dust, which glow because of its heat. The two images are thus tracing different forms of matter, and we will only be able to build a true picture of where all the matter is in Andromeda by combining together images at different wavelengths.

Similarly with NGC 6964, the optical and radio light look different: the galaxy appears much larger at radio wavelengths than in the optical. The reason for this is that the radio light does not come from the stars. It comes from atomic (**neutral**) hydrogen gas (HI) via the 21 cm **emission line**. In this particular galaxy the gas is spread over a much larger region than most of the stars. Without the extra information from the radio image we would not have a true picture of where all of the matter is located.

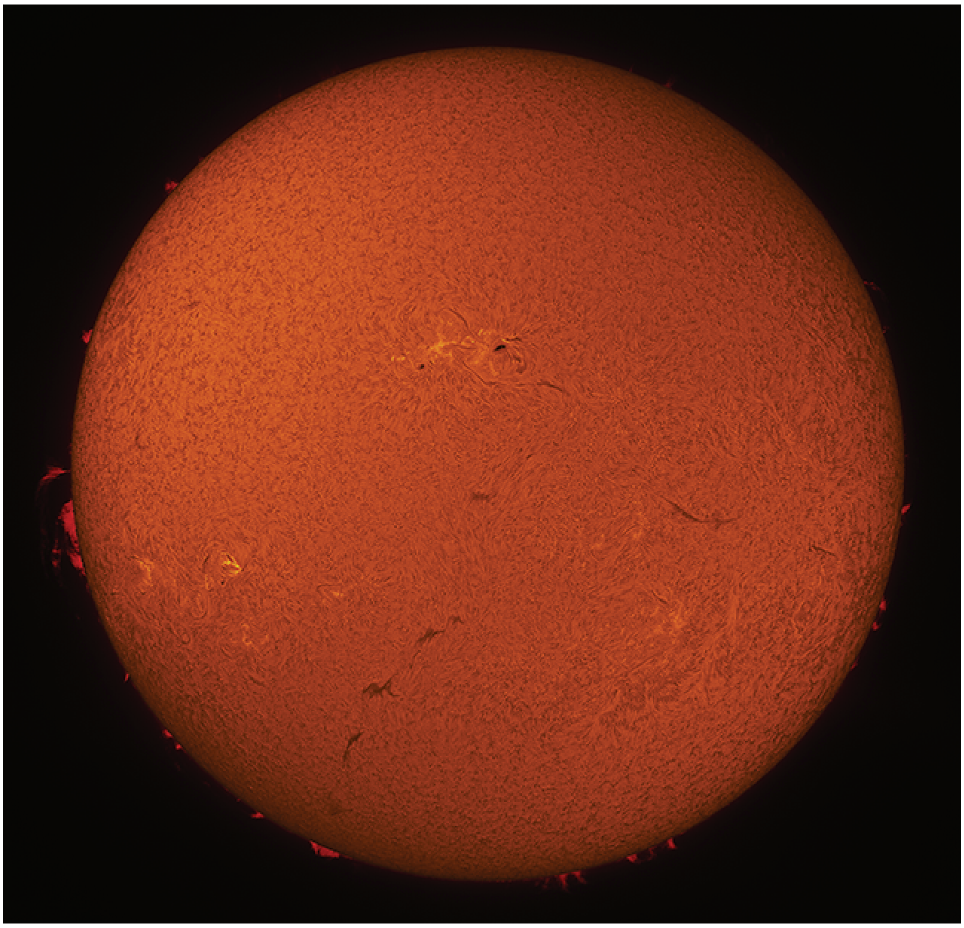
3.3 Narrow-band images

The radio image of NGC 6964 you've just examined is an example of a particular type of astronomical image that can be extremely scientifically useful. It is a **narrow-band image**, which means that the filter used to record the light spans only a very narrow range in wavelengths.

The atomic composition of astronomical objects leads to emission and **absorption** features that provide us with information about physical conditions (e.g. temperatures, densities, and chemistry). This is why spectroscopy is one of the most powerful tools available to astronomers. However, we can also use image methods to study these emission lines, by filtering out all of the light coming from the continuum and making an image of just the brightness of light produced by a single emission line.

The **radio astronomy** technique of HI mapping at 21 cm is an example of this, but it is used across the full electromagnetic spectrum. A common example in the optical part of the spectrum also relates to emission from hydrogen.

The H_α emission line (the first of the **Balmer series**) is produced in regions that have high temperatures. Figure 13 shows some examples of H_α images, and the sort of details that they can reveal. A typical H_α filter spans a wavelength range of 0.07 nm, which is over 1000 times narrower than typical broadband filters.



(a)

(b)

Figure 13 Examples of narrow-band H_α images: (a) the structure of the Sun's surface, including prominences – luminous streams of gas; (b) a red H_α image superimposed on an ordinary optical image, revealing glowing hydrogen gas that has been blown out of the starburst galaxy M82.

Other emission lines that are studied in the visible light range using narrow-band images include:

- the $[\mathrm{OIII}]$ 500.7 nm emission line, which is produced in planetary nebulae and active galaxies
- methane features, which are particularly interesting for studying planets because of methane's association with biological and/or geological activity.

The Hubble Space Telescope currently has more than 25 different narrow-band optical filters available to carry out different types of scientific investigations. While examining spectra is very powerful, for extended objects narrow-band images provide an invaluable method for exploring which regions are producing particularly strong emission lines, as in Figure 13b.

In the X-ray part of the spectrum, narrow-band images can be particularly powerful, because many heavier elements such as sulfur, silicon, magnesium and iron produce strong emission lines at X-ray wavelengths. These can be used to provide detailed information about the atomic composition of gas in regions as diverse as supernova remnants and clusters of galaxies. Most importantly, they trace the temperature of the gas really closely, so they can provide information about the thermodynamics of energetic behaviour in the Universe.

4 Mapping the sky

A driving force behind improving telescope technology over hundreds of years has been the desire to make sharper, more detailed images. In other words, to improve the **spatial resolution** with which we can measure the sky, allowing us to obtain these detailed views of individual objects. But in parallel with these precision views, astronomers have developed the ability to map structure in the sky on scales much larger than individual stars and distant galaxies.

In this section, you will explore astronomical images that span these large areas of sky, allowing us to consider some broader questions about our cosmic surroundings.

4.1 The Milky Way and the Galactic plane

What does our own Galaxy look like? Figure 14 shows one perspective. If you are lucky enough to find yourself on a clear night in a very dark location, you will be able to see a smooth band of light stretching across the sky, with dark clumpy regions caused by clouds of gas and dust that block starlight from reaching us.

Figure 14 The Milky Way, as viewed in a panoramic image from a particularly dark Southern Hemisphere site (the location of the European Southern Observatory telescopes in Chile).

The following activity allows you to view our Galaxy from some other perspectives.

Activity 3 Exploring the multiwavelength Milky Way

Allow around 20 minutes

Astronomers at Cardiff University have produced a web tool called Chromoscope, used for exploring maps of our Galaxy taken in many different parts of the spectrum. You will use this tool to complete this activity.

First, open the Chromoscope website in a separate browser tab or window, so that you can return to the instructions here. The default view is a visible light image of our Milky Way, which you can pan round and zoom in on. The full image spans an area of 186 × 20 degrees: a section of sky hundreds to thousands of times larger than the images of individual stars, galaxies and diffuse objects seen in this course. It was made by astrophotographer Nick Risinger, who carefully sewed together over 37 000 individual exposures.

A menu allows you to view this same field in images captured using light from different parts of the electromagnetic spectrum. Alternatively, there are keyboard shortcuts, which you can find more about by pressing ‘h’ for ‘Help’ (or from the ‘Help’ link in the bottom-left corner of the website).

Task 1

Explore the visible light image of the Milky Way and comment on any differences between this map compared to the image in Figure 14. Why do you think it has a different shape?

Provide your answer...

Discussion

The Milky Way appears as a straight line across the centre of the image, rather than as a curved line across the sky. The images here are projected into **Galactic coordinates**, which means that all positions along the Milky Way’s disc have a latitude of zero and so fall on a line. Whereas the curve in Figure 14 comes from a different mapping to a 2D image of the curved surface of the ‘celestial sphere’.

Task 2

Now switch between the visible and X-ray images. Note what happens to the dark regions near to the Galactic equator when you switch between the two views. Suggest an explanation for any similarities or differences between the two images.

Provide your answer...

Discussion

The dark regions remain dark in the X-ray image. This tells us that gas and dust clouds that absorb and block starlight in the visible image are blocking the X-ray light as well as the optical. Absorption of X-ray light can be a useful tool for studying gas and dust.

You may have noticed some large dark stripes in the X-ray images: these are areas of sky where there is no usable data to make the image.

Task 3

Now look at the near-infrared, **far-infrared** and H_α images. Note how the infrared images differ from the visible (and X-ray) images – why do you think this is? What features can you identify in the H_α image that are not present in the others?

Provide your answer...

Discussion

The Galactic equator glows very strongly in infrared light. The dark features seen in visible and X-ray light have disappeared. This is because the gas and dust clouds that produce them are warm and glow in infrared light, rather than absorbing it.

There are a number of bright swirly regions in the H_α image not visible at other wavelengths (they are slightly visible in the optical image – this is because the H_α

filter is contained within the R wavelength band and the R band is one of several visible light filters). These are star-forming regions, full of young stars that are ionising the surrounding gas.

4.2 Surveying beyond the Milky Way

The Milky Way spans a large region of the night sky, but the Milky Way images explored in the previous section are not the only type of ‘wide-area’ sky images we can examine. **Deep images** of areas of sky away from the path of the Milky Way (often referred to as the ‘extragalactic’ sky) reveal very large numbers of galaxies beyond our own. Figure 15 shows a single deep galaxy image, which is roughly 2.6 arcmin on each side, or around one-tenth of the angular size of the full Moon.

Figure 15 Deep survey by the Hubble Space Telescope of a very small area of sky, showing around 1000 distant galaxies.

Astronomers have also undertaken enormous efforts to map out the locations of galaxies across larger areas of the sky, as well as the three-dimensional neighbourhoods and environments of galaxies. Galaxy surveys compile together thousands of individual images to map large areas of sky. An example is shown in Figure 16, where around 60 000 images of the Northern and Southern Hemispheres have been combined to produce a map that charts the positions of millions of galaxies.

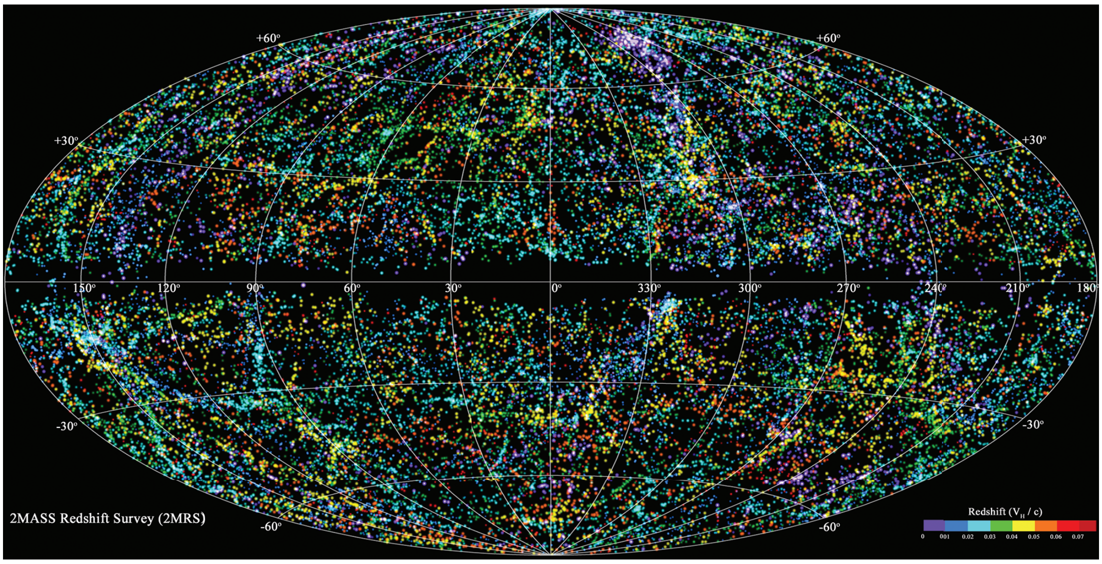


Figure 16 The positions of millions of galaxies from the Two Micron All Sky Survey (2MASS).

Figure 17 shows an even more zoomed-out region of a galaxy survey, projected using redshift information to form a three-dimensional map. The radial coordinate is redshift – so the centre of the diagram is nearby and the outer parts more distant – while the angular coordinate is **right ascension**. Each dot is an entire galaxy, containing hundreds of billions of stars!

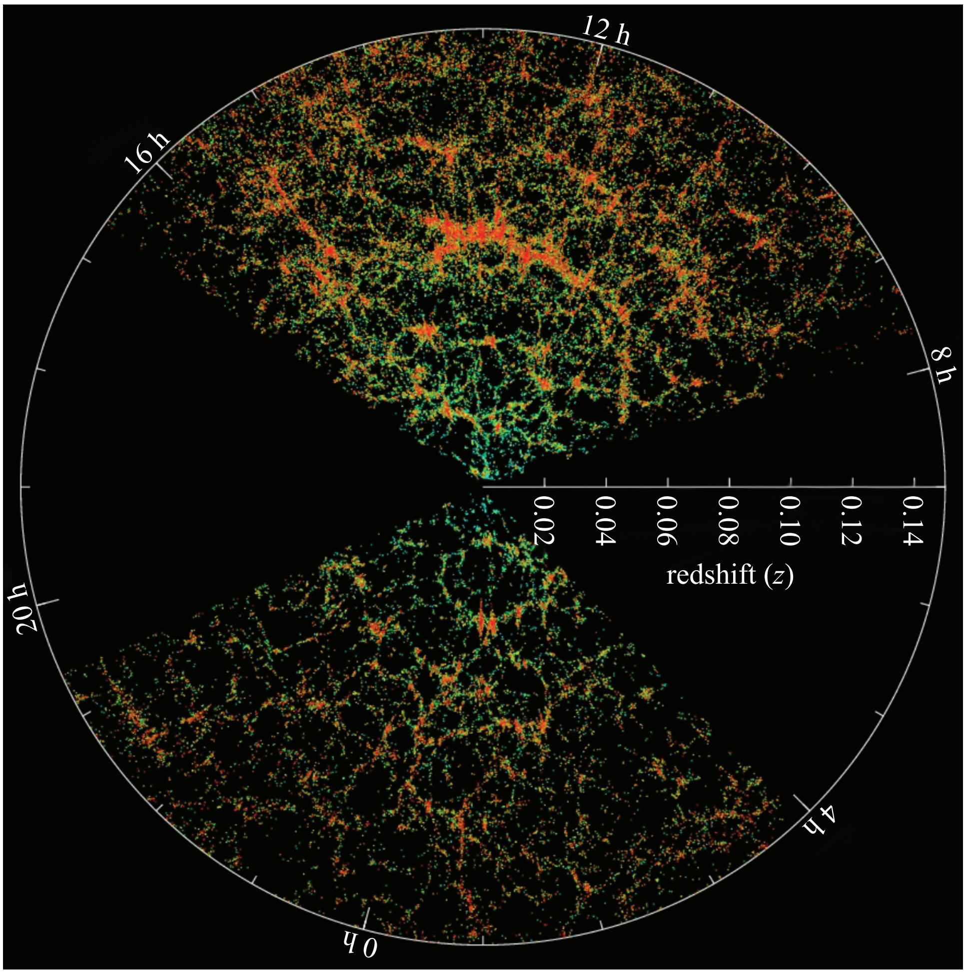


Figure 17 A 3D map of the sky made from a galaxy redshift survey.

- What do you notice about the way that galaxies are distributed on the sky? Is the structure random?
- The distribution of galaxies is not random. There are bright clumps where large numbers of galaxies cluster together – for example in a band running approximately from 11 h to 14 h of RA at a redshift of 0.06 – and emptier gaps in between them.

Together the locations of these galaxies form a map of what is known as the cosmic web. The brightest points in the web are **galaxy clusters**, where many galaxies cluster together. These brighter regions are connected together by **filaments**, and void regions where there are far fewer galaxies.

The 'large-scale structure' of the Universe, this cosmic web visible in Figures 16 and 17, is a consequence of the influence of gravity. Evidence suggests that galaxies and larger structures are built up over the history of the Universe, with smaller clumps being pulled together by gravity to form larger ones.

Astronomers have carried out many different surveys, which have investigated different parts of the Universe. In the following activity you will compare two important recent galaxy surveys.

Activity 4 Comparing astronomy surveys

Allow around 20 minutes

Figure 18 shows the distribution of galaxies in terms of:

- their position on the sky
- their distance from Earth.

The plotted data are taken from two modern galaxy surveys – the Hubble Deep Field (HDF, shown in Figure 15), and the Sloan Digital Sky Survey (SDSS) – together with the galaxies included in Edwin Hubble's famous 1929 paper that demonstrated what we now know as the **Hubble–Lemaître law** (the relationship between distance and recession speed: redshift).

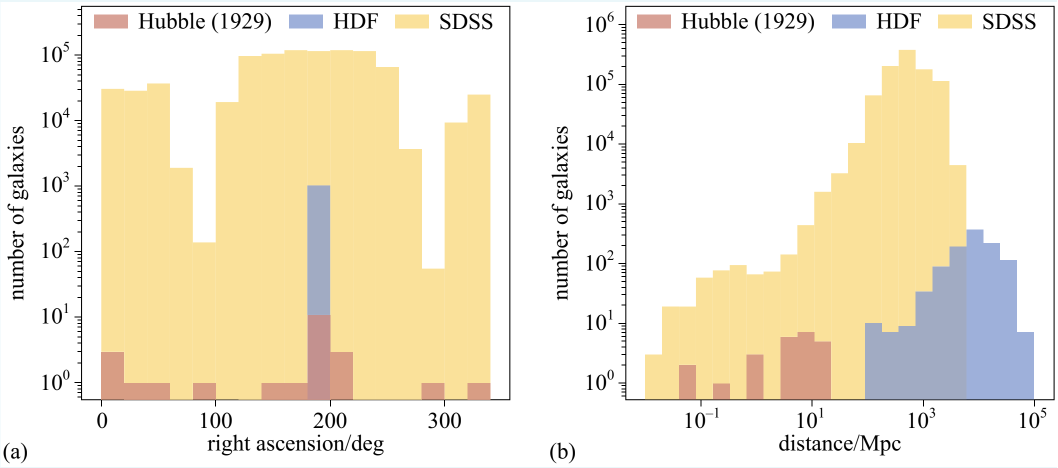


Figure 18 Galaxy data taken from several astronomical surveys: (a) the distribution of each sample of galaxies on the sky; (b) the distribution of their distances.

Examine the two graphs, and answer the following questions to compare what we can learn from different types of galaxy survey.

a. The SDSS is a wide-area sky survey. With reference to the two plots, can you suggest some advantages of wide-area surveys?

Provide your answer...

Discussion

By surveying a large area of sky (see the wide range in right ascension shown in panel (a)), the total number of galaxies included is very large. This means that the survey is likely to include examples of rare or unusual galaxies, and is also less affected by any biases due to the structure that might be present in one particular sky direction (see, for example, the uneven distribution of galaxies in Figure 16).

b. The HDF is a deep-sky survey, which is very sensitive to faint objects. With reference to the two plots, what do you think is the main advantage of a deep-sky survey?

Provide your answer...

Discussion

The sensitivity of such surveys to faint objects means that it is possible to include galaxies at much larger distances (compare the upper boundary of distances for the HDF data to that of the other two surveys in (b)). This is useful for studying how galaxies evolve.

c. Once more with reference to the two graphs, can you think of any limitations of wide-area sky surveys, such as SDSS, that it might be important to consider when analysing their results?

Provide your answer...

Discussion

Wide-area surveys cannot usually observe galaxies to distances as large as single deep images (again, see the differences in the data returned by the various surveys in (b)).

Going beyond the data in the figure, on a more practical level, such surveys are made up of many individual telescope observations, and therefore require a lot of telescope observing time. This means that they take a long time to complete. They also require a large amount of scientific processing and analysis work to produce large catalogues of galaxy information – they are 'big data' projects.

d. Finally, in light of these graphs, can you think of any limitations of deep-sky surveys, such as the HDF, that it might be important to consider in analysing their results?

Provide your answer...

Discussion

A deep image of a small patch of sky – for example, the narrow range of right ascension of the HDF data shown in Figure 18a – may not be representative of the overall properties of the Universe. As an example, the number of galaxies per square degree will depend on which part of the cosmic web is being looked at: a deep image of a void, a cluster or a filament would give quite different results.

In contrast, overall numbers inferred from a wide-area survey like SDSS will provide a better big-picture 'overview' of the contents and structure of the Universe, although out to smaller distances.

4.3 Surveying the variable Universe

Once astronomers have made a detailed map of the sky you might imagine it is ‘job done’, and the survey telescope could be dismantled. Happily this is not the case, because the objects in the night sky are not constant and unchanging – there is much work for astronomers in mapping astronomical objects whose appearance can change from one observation to another.

Figure 19 shows two images of a galaxy taken 41 days apart. Can you spot the difference? It shouldn’t be difficult to spot the presence of a very bright ‘star’ in the second image, which has been further highlighted by a position indicator (a vertical and a horizontal bar). This is a supernova: the light comes from the explosion of one of the galaxy’s stars.

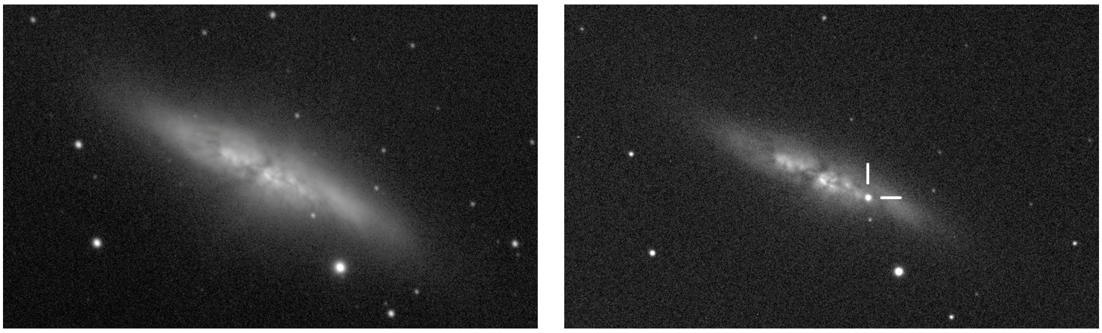


Figure 19 Spot the difference: two images of the same galaxy taken 41 days apart, with the location of a supernova highlighted by the white lines in the right-hand image.

In some cases a supernova can briefly outshine all of the other stars in its galaxy, before fading away and the galaxy returning to its usual appearance.

There are many ‘spot the difference’ astronomy surveys underway, comparing images of the same stars or galaxies taken at different times to identify any changes. Finding supernovae is one of the aims of projects such as the Legacy Survey of Space and Time (LSST). The LSST, carried out by the Vera C Rubin Observatory, will survey the sky all night, every night, through six broadband filters. It will cover the entire visible sky twice per week, and so build up **light curves** of billions of stars and galaxies, each spanning ten years. It will also detect huge numbers of transient and variable objects whose brightness varies with time. But there are many other types of variable objects in the sky, including binary star systems and active regions associated with black holes in the centre of galaxies.

Time-domain surveys (i.e. surveys that image the same area of sky many times to look for changes) can be used to study all of these things. Indeed, modern time-domain surveys are able to look across a large area of sky for both periodically varying objects and ‘transients’ – objects such as supernovae that appear and then disappear over a relatively short timescale.

The ESA Gaia survey is another example of a time-domain survey, which has exceptional ability to pinpoint changes in the positions of stars so as to determine their distances through **parallax**. It can also be used to study changes in brightness, rather than position, including discovering supernovae.

Conclusion

The focus of this course has been on how astronomers use images to make measurements and map the contents of the Universe. These were some of the key learning points:

- An image consists of a two-dimensional array of information, recording brightness as a function of position. In the visible part of the spectrum (and some other wavelength regimes), images are typically made using CCD detectors.
- The main measurements obtained directly from images are observed quantities that reflect the light signal measured at the Earth, rather than the intrinsic properties of the source. These include flux or apparent magnitude, angular size, and surface brightness.
- Brightness measurements are obtained via **photometric apertures**, and surface brightness profiles can be used to optimise the size of the aperture used. Profiles can trace the **point-spread function (PSF)**: the blurring due to telescope optics and atmospheric **seeing**.
- Angular sizes are measured in units of pixels from an image, and must then be converted to units of arcsec, arcmin or degrees using the **pixel scale** appropriate for the detector. Angular size can then be converted to physical size (in units of metres, or pc, kpc, Mpc) if the distance to the astronomical source is known. However, the effects of orientation must also be considered.
- For non-spherical objects, the shapes measured on an image may not reflect their true shape, due to the effects of orientation and 2D projection of a 3D object. If the inclination relative to the line of sight is known, then true proportions, and hence shapes, can be obtained. In some cases, particularly for more complex and irregular objects, there is insufficient information to determine the underlying three-dimensional shape.
- For a circular disc-like object, the observed major axis corresponds to the true diameter of the disc, and the inclination angle (tilt, θ) relative to the plane of the sky is given by

  $$\theta = \cos^{-1}\left(\frac{b}{a}\right) \qquad \text{(Equation 1)}$$

  where a is the measured semimajor axis and b the measured semiminor axis.
- If a linear object is projected at an angle of θ to the plane of the sky, then its true length, L, is related to its measured length, l, by

  $$L = \frac{l}{\cos\theta} \qquad \text{(Equation 2)}$$

- Astronomical objects can appear in images as point-like or extended, depending on whether they are resolved by the telescope. Extended objects have angular sizes larger than the image's point-spread function.
- There are five main types of extended astronomical object in visible light images: open clusters, globular clusters, galaxies, planetary nebulae, and diffuse nebulae.
- Astronomical images taken with different telescope filters, spanning different wavelength ranges, can be combined to produce colour images. Quantitative measurements, such as colour index, are usually made by carrying out photometry separately on images from individual filters and then combining the measurements.

- **Narrow-band images** can be made using filters that allow through only light associated with a particular emission line. One of the most commonly used examples is H_α, which highlights the locations of regions of hot gas.
- Images are also made across the electromagnetic spectrum. **Multiwavelength astronomy** involves using images spanning a wide range in wavelength, from radio waves to gamma rays, which highlight different regions and features.
- Images from small areas of sky can be combined together to make **sky maps**. The Milky Way spans a large area of sky and has been mapped in detail at many wavelengths. Surveys are also made of the extragalactic sky, producing wide-area images and maps of the locations of millions of galaxies beyond our own. **Time-domain surveys** compare images taken at different times to identify variable phenomena.

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Glossary

absolute magnitude

(Symbol, *M*.) A numerical measure of the intrinsic brightness of a star, equal to the apparent magnitude (*m*) the star would have if observed from a standard distance of 10 parsecs, in the absence of interstellar absorption. The absolute magnitude provides a measure of the star's luminosity.

absorption

The process by which a photon is absorbed by an ion, atom or molecule resulting in an increase in energy of the ion, atom or molecule.

angular separations

How far apart two astronomical objects appear to be, calculated as the difference between the coordinates of their positions on the sky.

angular size

How big an astronomical object appears to be, calculated as the difference between the coordinates of the extremities of the extended object.

apparent magnitude

(Symbol, *m*.) A numerical measure of the apparent brightness of a body. For a star, it is a measure of the flux received.

asteroseismology

The study of stellar interiors from observations of global oscillations of their photospheres.

Balmer series

The series of electronic transitions in the hydrogen atom that involve a change to or from the n = 2 state, associated with spectral lines mostly in the visible.

bar

An approximately linear extension to the central bulge seen in some spiral galaxies, from which the spiral arms emanate.

binary stars

A situation where two stars orbit each other.

black holes

A region of space in which matter is sufficiently dense that the action of gravity prevents both matter and electromagnetic radiation from escaping. Black holes may be classified as either 'stellar mass' (up to tens of solar masses) or as 'supermassive' (in excess of 10^6 solar masses) and characterised further by their Schwarzschild radius.

bulge

The region around the centre of a spiral galaxy, where the galaxy is thicker and brighter and the concentration of matter is greater than elsewhere. Its outer parts are dominated by the light of old stars, but towards the centre it may contain material associated with the inner parts of the disc, including sites of star formation.

colour

The difference, measured in magnitudes, of the brightness of an object in two specified wavebands (e.g. in the blue 'B' and red 'R' wavebands, in which case the difference is denoted $m_B - m_R$ or simply $B - R$). Sometimes referred to as colour index.

colour images

Images that incorporate information from multiple telescope filters, so that variation in colour represents the relative variation in the proportions of emitted light at different wavelengths.

computer simulations

Numerical models within a computer used to model star or galaxy formation.

convection

A process of energy transfer in which a fluid in a gravitational field is heated from below to the point where the hotter, less dense fluid rises upwards, displacing the cooler, denser fluid downwards.

cosmic web

The largest-scale strucure of galaxy clusters and filaments comprising the Universe.

deep images

Images that are sensitive to the very faintest emission that our telescopes can detect. The 'deepest' existing astronomical images are produced using very long exposures by space-based or very large ground-based professional observatories.

degrees

Units of angular measure. There are 360 in a complete circle.

disc

The flat, circular region in a spiral or lenticular galaxy in which most of the ongoing star formation is located, including spiral arms, if present. Disc-shaped structures are common in astronomy, also existing around protostars, and sometimes around stellar remnants.

Doppler effect

The effect whereby wavelengths are shifted to longer or shorter values as a result of relative movement between the source and the observer.

dust

Small solid particles, around 10^{-7} or 10^{-6} m across, found mixed with interstellar gas. Dust grains are predominantly composed of carbonaceous material and silicates, but may be surrounded by an icy mantle. Dust is very effective at absorbing and scattering ultraviolet and visible light.

electromagnetic radiation

A form of radiation in which the transfer of energy from place to place may be attributed to the passage of wave-like disturbances in the electric and magnetic fields between those places (i.e. electromagnetic waves), or to the passage of photons from one place to the other. The wavelength or frequency of the waves (or the energy of the photons) may be used to assign particular kinds of electromagnetic radiation to specific parts of the electromagnetic spectrum, resulting in their classification as light, radio waves, X-rays, etc.

emission line

A narrow wavelength or frequency range in a spectrum where the spectral flux density is greater than at adjacent wavelengths (or frequencies).

extended

An astronomical source of light whose angular size is larger than the point-spread function of a particular telescope.

far-infrared

The longest wavelength part of the infrared region of the electromagnetic spectrum. Far-infrared emission traces dusty regions, including planet-forming discs and distant protogalaxies.

filaments

In the context of star formation, a filament is a linear region of denser material. They result from the partial collapse of a molecular cloud. Material streams along them and stars typically form at their intersections. In the context of galaxy structures, filaments are thread-like structures comprising hundreds or thousands of gravitationally bound galaxies as part of the cosmic web.

flux

(Symbol, *F*.) A quantity describing the rate at which energy transferred by radiation is received from a source, per unit area facing the source. The SI unit of flux is the watt per square metre (W m^{-2}).

Galactic coordinates

A celestial coordinate system, whose two elements are Galactic longitude *l*, and Galactic latitude *b*, resembling longitude and latitude on the Earth. The orientation of the coordinate system is defined to make it useful for describing the locations of objects in the Galaxy from the viewpoint of the Sun. The Galactic equator is chosen to coincide with the Galactic plane, the direction (l, b) = (0°, 0°) is in the direction of the Galactic centre.

galaxy

A collection of luminous stars, non-luminous dark matter, and in the case of spiral and irregular galaxies some amount of gas and dust that are gravitationally bound to one another, and are separated from other similar structures usually by distances of tens of kiloparsecs or more. Various categories of galaxies may be defined based on their appearance, such as spiral galaxies (barred or normal), elliptical galaxies, lenticular galaxies and irregular galaxies.

galaxy clusters

A collection of hundreds or thousands of galaxies that are bound together by gravity.

gamma ray

The highest-energy form of electromagnetic radiation, produced in energetic processes like nuclear fusion.

globular cluster

Clusters of 10^5 to 10^7 very old stars, tightly bound by gravity into a spherical region of space less than about 50 pc in diameter. The 150 or so globular clusters associated with the Milky Way are found in a spherical distribution about the centre of our Galaxy. Similar distributions are seen in other galaxies.

Hubble–Lemaître law

A relationship between the apparent speed at which a galaxy is receding from us and its distance away.

inclinations

The angle between the plane of an orbital system and the plane of the sky.

jets

A long narrow linear feature emanating from an active galactic nucleus, seen in many radio galaxies and quasars, most often via its radio synchrotron emission but sometimes also at optical and X-ray wavelengths. Jets are also present in a small number of X-ray binaries and believed to be present in gamma ray bursts.

light curves

A diagram showing the variation of brightness (e.g. magnitude, flux or luminosity) with time, for a celestial object.

luminosity

(Symbol, *L*.) A quantity describing the rate at which energy is carried away from a luminous object by electromagnetic radiation. The SI unit of luminosity is the watt (W), where $1\ \text{W} = 1\ \text{J s}^{-1}$.

magnetic fields

The quantity, specified throughout some region of space, that determines the magnetic force that would act on a particle of given electric charge moving with given velocity through any point within that region. At each point in the region, the magnetic field possesses a strength and a direction. The magnetic field in a region may be produced by magnets or by moving charged particles (e.g. electric currents), but is deemed to exist irrespective of whether there are any other moving charged particles or magnets present to ‘feel’ its effect.

multiwavelength astronomy

Astronomy that makes use of images, spectra and light-curves made in multiple regions of the electromagnetic spectrum.

narrow-band image

An image made using a narrow-band telescope filter through which only light within a small range of wavelength can pass.

near-infrared

The shortest wavelength part of the infrared region of the electromagnetic spectrum.

nebulae

Extended astronomical objects having a fuzzy or cloud-like appearance in small telescopes.

neutral

With reference to an atom or molecule: not ionised; having no net electric charge.

open cluster

Clusters of up to a few thousand stars, loosely bound by gravity, that were formed from the same giant molecular cloud and so have roughly the same age. There are more than 1000 open clusters in the Milky Way, confined to the disc of the galaxy.

parallax

The phenomenon whereby the apparent position of an object changes when seen from different viewpoints.

parsecs

The distance to a celestial body that has an annual parallax of one arcsecond: 1 pc = 3.09×10^{13} km, or just over 3 light-years.

photometric apertures

A region (often circular) superimposed on an astronomical image within which the brightness values of individual pixels are added together in order to determine the total brightness of a particular astronomical object.

photometry

The science of the measurement of the brightness (magnitude, flux or luminosity) of astronomical objects.

photons

The particle of electromagnetic radiation in the photon model of light. The photon energy, E, is proportional to the frequency, f, of the associated radiation: $E = hf$, where h is Planck's constant.

pixel scale

The conversion factor between image pixels and angular separation for images from a particular telescope or instrument set-up.

planetary nebulae

The gaseous remains of the outer envelope of a low-mass star, which is illuminated by a luminous central white dwarf.

point-like

An astronomical source of light whose angular size is smaller than the point-spread function of a particular telescope.

point-spread function (PSF)

A mathematical description of the blurring effect caused by the telescope optics and atmospheric effects, so that light from a point-like source such as a star is spread over multiple pixels of an image.

projection

The shape that a 3-dimensional object produces when viewed in a 2-dimensional image, which may depend on its orientation.

protostar

A molecular cloud that has begun the process of collapsing into a star and has become opaque to radiation but which has not yet started nuclear fusion.

radians

Unit of angular measure. There are 2π radians in a complete circle.

radio astronomy

Astronomy carried out using images and spectra in the radio part of the electromagnetic spectrum, consisting of radiation with the lowest frequencies/longest wavelengths.

red giant

A large star with a photospheric temperature less than about 6000 K. Main sequence stars with masses of less than about 11 $M_{\odot}$ evolve to become red giants.

redshift

The increase in the observed wavelength of radiation relative to the wavelength at which the radiation was emitted (the frequency is correspondingly decreased). This can be due to either the Doppler effect arising from motion through space or the expansion of the Universe.

resolution

A measure of the smallest angular separation for which a particular telescope can distinguish two separate sources of light without them blurring together.

resolved

Indicating that a particular telescope can distinguish two separate sources of light without them blurring together.

right ascension

In the equatorial coordinate system, one of the coordinates used to define the positions of objects on the celestial sphere, analogous to terrestrial longitude. Often abbreviated to RA. It is measured in hours, minutes and seconds such that 1 hour of RA is equal to 15 degrees along the celestial equator.

seeing

The effect of atmospheric blurring which often characterises the resolution limit of ground-based astronomical telescopes.

semimajor axis

A distance equal to half the longest axis of an ellipse or elliptical orbit.

sky maps

Either an image or plot of catalogued positions that covers a large area of the celestial sphere.

spatial resolution

A measure of the ability of a telescope to distinguish between closely spaced features in an image.

spectroscopy

The range of electromagnetic radiation that is emitted, absorbed or reflected by an object, dispersed according to its constituent wavelengths, frequencies or energies is called a spectrum (plural spectra). The study of such spectra is referred to as spectroscopy.

spiral galaxy

A member of the Hubble class of galaxies that is characterised by having a disc and spiral arms. Membership of this class is indicated by the letter S, or SB in the case of a barred spiral galaxy.

stars

A ball of matter which, at some stage in its life, is self-luminous as a result of energy released by nuclear reactions in its core.

star cluster

A group of stars with more than a few members in a relatively small volume of space.

star-forming regions

A region of gas within the interstellar medium of a galaxy in which stars are in the process of forming.

supergiant

A star that lies along the top of the Hertzsprung–Russell diagram, i.e. the stars with the greatest luminosity. Main sequence stars with masses greater than about 11 $M_\odot$ evolve to become supergiants. Later, such stars become Type II supernovae.

supernova remnant

The gaseous remains of a stellar explosion, which may be caused by collapse of a massive star or thermonuclear explosion of a white dwarf. The explosion sends a shock wave into the interstellar medium, causing it to radiate in multiple parts of the electromagnetic spectrum. Often abbreviated to SNR.

surface brightness

A quantity that describes the brightness at a particular position on an extended object, such as a galaxy. The surface brightness at any chosen point is the amount of radiant flux that would reach 1 m^2 at Earth from a small, uniformly bright, square region, of angular area 1 $arcsec^2$, surrounding the chosen point. A common SI unit of surface brightness is W m^{-2} $arcsec^{-2}$.

surface brightness profiles

Plots of the surface brightness of extended astronomical objects as a function of radial distance from its centre.

time-domain surveys

An astronomical survey that records images or other measurements at the same locations at multiple points in time, so as to record information about how positions and brightness of objects change.

unresolved

In relation to an astronomical image, an object whose light is contained within a region smaller than the size of details that may be distinguished.

voids

Under-dense regions of the cosmic web between the filaments and galaxy clusters.

wavelength

The distance over which a periodic wave repeats itself, e.g. the distance from one peak of the wave to the next.