Extension 22: The Use of Spectroscopy in Astronomy

1. Prerequisites

The ideas that form the background to this extension unit are listed in the table below.

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Quantitative analysis	334B
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Absorption and emission spectra	389
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**B indicates that the topic is treated in a boxed feature on that page.*

2. Introduction

In Unit 22 we looked at the principles and applications of spectroscopy. Spectroscopy is used in both and qualitative and quantitative analysis. In other words, it is used to find out 'what is in' a sample, and to find out 'how much of something' is in the sample.

If we wanted to analyse some soil for lead using a spectroscopic technique, we would start by collecting the sample and taking the soil back to the laboratory. But if the sample is part of the sun, a planet, a distant star or an intergalactic dust cloud, we cannot collect samples in the ordinary way. In these cases we analyse information about the sample sent through space to the earth. For the planets within the solar system, an unmanned exploration satellite (such as one of the famous Voyager satellites), may carry out the spectroscopic analysis and the results relayed back to earth. In order to gain information about the sun and objects outside our solar system, we are entirely dependent upon the light transmitted through or by the samples themselves. The light reaching us is often the emission or absorption spectrum of the distant source, and in these cases we have a way of analysing the sample (i.e. the light source) both qualitatively and quantitatively. The wavelength of the light involved in such 'signals' covers the whole range of the electromagnetic spectrum, and includes ultraviolet, visible, infrared, microwave and radio wavelengths.

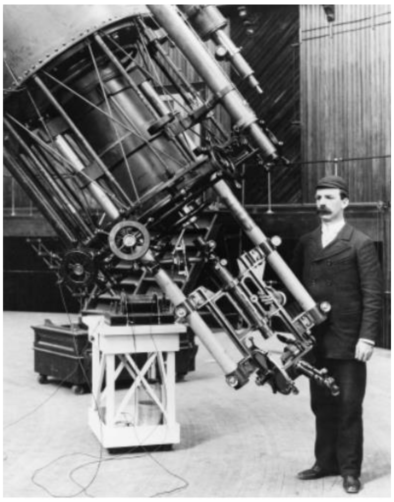


Fig. 22.1 Lick Observatory Telescope 1893. The use of spectroscopy in astronomy was in its infancy in the 1890s. Prisms were placed at the base of the telescope to disperse light into spectra. Astronomers are no longer dressed like this! Photograph courtesy of The Mary Lea Shane Archives of the Lick Observatory, University of California, Santa Cruz.

Being able to determine the composition of a distant galaxy by analysing its spectrum is remarkable because of the distances involved (Fig. 22.1). Some galaxies are thousands of light years away! But the idea of analysing light is very familiar to us from everyday life. To take a more familiar example, we can see whether or not a bonfire is lit because of its light emission (its flames) – we don't have to touch the bonfire – and this 'signal' is easily transmitted over many miles.

Table 1 summarizes how spectra in the different parts of the electromagnetic spectrum are used by astronomers. High energy spectra (at gamma, X-ray and ultraviolet wavelengths) cannot be observed on earth because such radiations are absorbed by the atmosphere. In this extension unit, we concentrate on the use of spectra in identifying elements (H, Na, Mg etc.) and compounds (CO, C_6H_6) in stars, planets and in deep space.

Table 1 Regions of the electromagnetic spectrum used by astronomers

Wavelength region	*How the spectra are detected*	*What the spectra tell us*
X-rays and gamma rays	From space satellites, e.g. the Chandra observatory, launched in 1999.	Emissions at these wavelengths originate from some of the most energetic and exotic bodies in the universe. For example, the emission of X-rays is used to identify the location of black holes.
Ultraviolet	From space satellites.	Detects emission from H (Lyman series) in stars and of H_2 in nearby galaxies. Also reveals the structure of the sun and of other stars.
Visible region	From ground-based spectrometers attached to telescopes	(1) What elements are present in stars (2) Star temperature
Infrared	From high-altitude observatories (e.g. on Mount Hawaii) or on space satellites or probes	Infrared pictures of the sky reveal many new stars that are otherwise invisible because they give out too little visible light to be observed. 'Near-infrared' (longer wavelength infrared) is used to detect water in nebulae and planets.
Microwave and radio	From ground-based radio telescopes at high altitudes	Detects H throughout interstellar space (through the 21 cm line), and the signals presence of molecules in dust clouds.

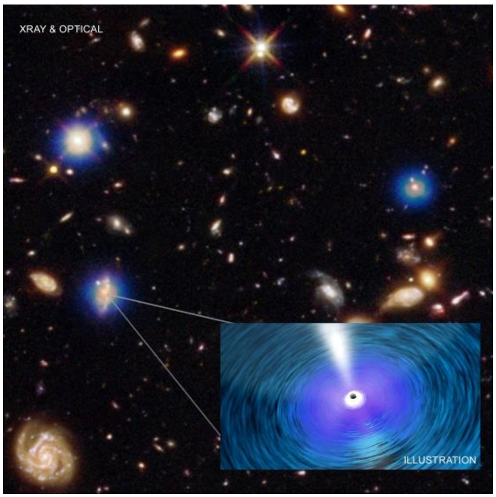


Fig. 22.2 Composite photograph of distant galaxies obtained from visible, infrared and X-ray (Chandra) telescope photographs. X-ray emissions are coloured blue. The illustration represents a black hole in one of galaxies. Photograph courtesy of NASA.

3. Solar spectrum and the Fraunhofer lines

The sun, like many hot bodies, gives out a continuous range of wavelengths from the X-ray, ultraviolet, through the visible, infrared, microwave and radio frequencies. The visible part of the sun's emission is easily separated (dispersed) using a prism or diffraction grating into the colours of the rainbow, a sequence of colours known as the **solar spectrum**.

If we use a high-quality prism or grating, the solar spectrum is seen to contain dark narrow lines (Fig. 22.3). These lines are known as the **Fraunhofer lines**, in honour of their discoverer. Some Fraunhofer lines are shown in the bottom of Fig. 22.3.

The fact that the lines are dark means that light is absent at these wavelengths. As the sun, like a very hot fire, gives out a continuous range of frequencies, this must mean that some substance is absorbing light at the wavelengths of the Fraunhofer lines. One explanation is that substances in the earth's atmosphere are absorbing certain wavelengths of sunlight, but it turns out that most of the lines involve absorption within the sun itself. The spectrum in Fig. 22.3(a) shows the absorption spectrum of iron vapour. The fact that there are lines in the solar spectrum at exactly the same wavelength at lines in the iron spectrum proves that iron is present in the sun. Fig. 22.4 shows how the lines are produced.

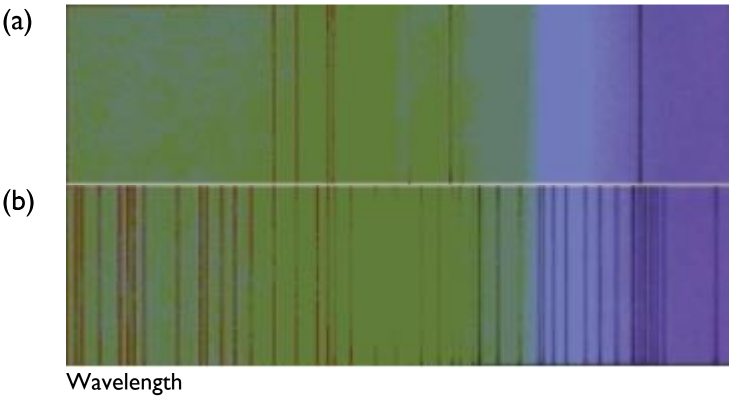


Fig. 22.3 (a) The absorption spectrum of iron obtained by passing white light through iron vapour; **(b)** The solar spectrum, obtained by dispersing sunlight with a prism.

Other Fraunhofer lines are formed in a similar way to that due to Fe. Elements giving lines in the spectrum include calcium, magnesium, hydrogen (including H in the Balmer series) and aluminium. The pair of sodium lines at 589.6 and 589.0 nm are also present, confirming the presence of sodium in the sun. The spectrum of a star depends on the temperature of its outer layer. The spectra of stars at visible wavelengths is used by astronomers to classify stars as O, B, A, F, G, K, or M. This is usually remembered by the mnemonic 'Oh Be A Fine Girl Kiss Me'. O stars are the hottest and appear white. M stars are the coolest and appear red. Our own local star, the sun, is classified as a 'G' star.

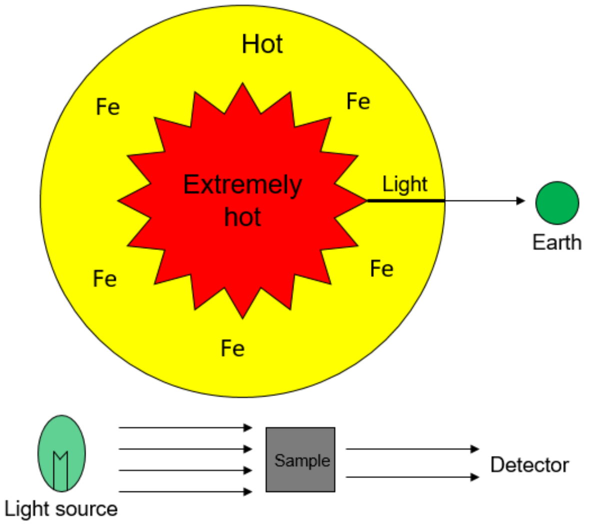


Fig. 22.4 The origin of the many dark lines (the Fraunhofer lines) in the solar spectrum, illustrated for iron. The outer region of the sun (marked 'hot' and 'Fe'), is at about 5500 °C and contains Fe atoms in the vapour state. The Fe atoms absorb certain frequencies of the white light emitted by the centre of the sun so that the light reaching the earth is deficient at those wavelengths. This is similar to a working laboratory spectrometer (bottom diagram), in which the sample absorbs some of the wavelengths emitted by the spectrometer source.

BOX 1: The Doppler Effect in Astronomy

Think of a vehicle with a siren that is speeding towards you. As it approaches, the pitch (frequency) of its siren gets higher. As the vehicle moves into the distance, the pitch of its siren falls. This is the Doppler effect and the effect operates with light as well as sound. This is illustrated for a single spectral line in the figure below. The line might, for example, be the H line in the Balmer series due to the transition $n = 2$ to $n = 3$. The line is observed in the solar spectrum at a wavelength of 656.3 nm. If the same transition occurs in a galaxy (like Andromeda) which is rapidly moving toward the earth, the line is detected on earth as occurring at higher frequency, i.e. at a wavelength of less than 656.3 nm. The reverse occurs if the source of the line is moving away from the earth, when the line is said to be 'reshifted'. The greater the Doppler shifts of the lines, the faster is the light source moving away (or toward) us.

4. Discovery of helium

The Fraunhofer lines were only explained when the wavelengths at which atoms of elements absorbed was measured in the laboratory and it was found that the laboratory values coincided with those observed in the solar spectrum. But there is one example of a line in the solar spectrum which led to the identification of an element which had not previously been isolated on earth. The element is helium.

The story starts in 1868, when the English astronomer Joseph Lockyer noticed a yellow line in the solar spectrum at 587.6 nm. Lockyer and E. Frankland attributed this to the absorption of sunlight by an as yet unidentified element which was later named helium (from *helios*, the Greek word for sun). The discovery of helium on earth involved many famous scientists of the day and the story is summarized in Box 12.6, page 205 in the book.

In 1869, a weak line was identified in the green part of the solar spectrum at 503 nm. This was attributed to another new element, named Coronium. Unfortunately for the discoverer, the line was not due to a new element, but to an ionized form of an existing element. It is now believed that the line is caused by light emitted by a highly ionized (Fe^{13+}) iron atom. But if the discoverer had been right . . . !

5. Spectrum of the hydrogen atom

Most of the universe consists of hydrogen, which exists as H atoms, as H_2 (molecular hydrogen) and as protons (ionized H atoms). We will concentrate upon the spectrum of the H atom.

The spectrum of the hydrogen atom is discussed in Unit 22. Both the Lyman series (in the UV) and the Balmer series (in the visible) of emission and absorption spectra are used by astronomers to show how fast galaxies are moving towards us (or away from us). This is achieved using the **Doppler effect** (see Box 1).

The Lyman and Balmer series of spectra are observed from intensely energetic bodies, like stars and star groups (galaxies), but are not detectable in the very low density regions between stars (the **interstellar medium**) where very little energy is available to produce the excited states needed to give lines in the Lyman or Balmer series because ultraviolet or visible light is absorbed by dust.

Hydrogen exists even in the near-perfect vacuum of the interstellar medium; the problem is how to detect it. To detect hydrogen atoms in deep space seemed impossible until scientists realized that the ground state of the hydrogen atom (corresponding to n = 1) is very slightly split according to whether the electron of the hydrogen atom is spinning in the same direction (or in the opposite direction) as the proton in the nucleus (see Fig. 22.5). If the electron is spinning in the same direction as the proton, the energy of the H atom is 0.000 57 kJ mol^{-1} higher than that of an H atom in which the electron and proton are spinning in opposite directions. The wavelength that corresponds to an energy gap of 0.000 57 kJ mol^{-1} is 21 cm (Fig. 22.6).

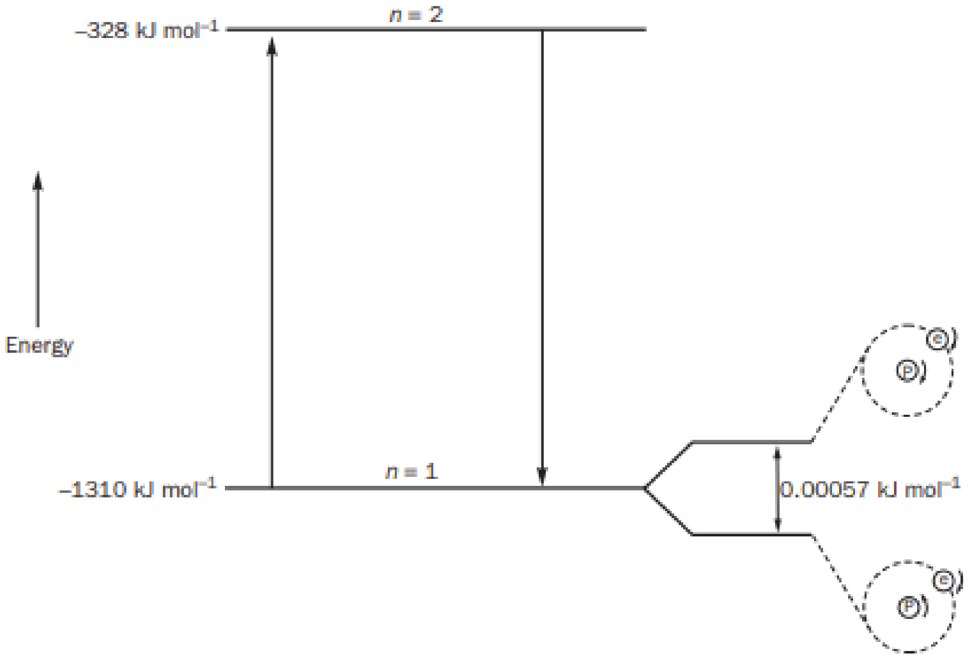


Fig. 22.5 Energy levels in the hydrogen atom. The spin of the proton and electron in the H atom can be parallel or anti-parallel, producing two states with very slightly different energies. This splitting of states is only 0.00057 kJ mol^{-1}, equivalent to a wavelength of 21 cm.

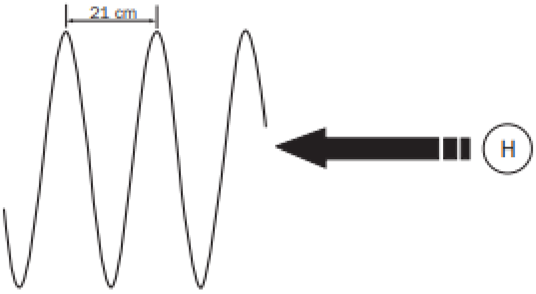


Fig. 22.6 The hydrogen-atom emits a radio signal at a wavelength of 21 cm.

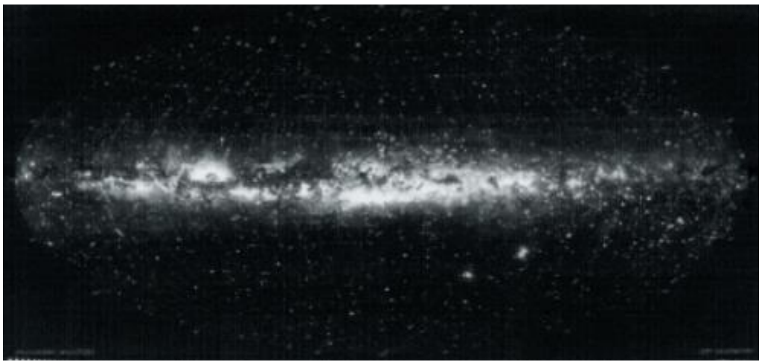
BOX 2: The 21 cm Emission Line of Hydrogen

We can confirm that this arises from an energy difference of 0.00057 kJ mol^{-1}, using the relationships given on p.388 of the book.

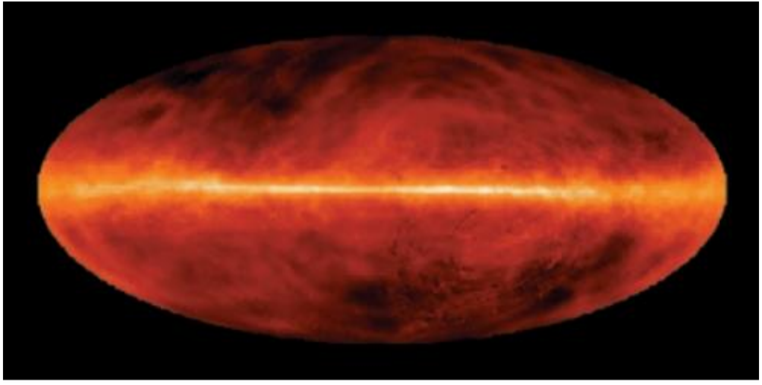
Since λ = 21 cm = 0.21 m

$c = \nu\lambda$ so that $\nu = c/\lambda = 3 \times 10^8/0.21 = 1.429 \times 10^9$ Hz

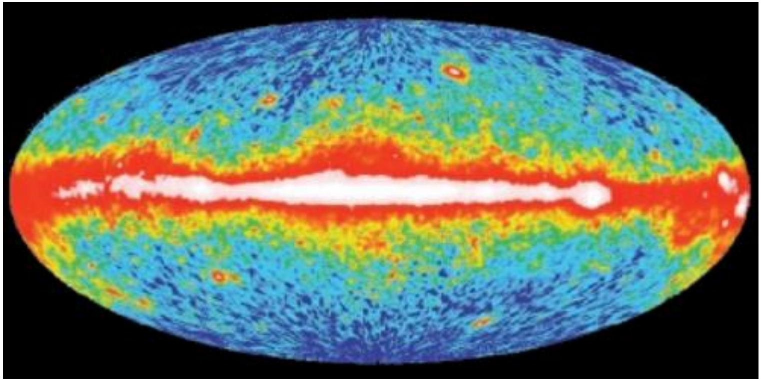
$\Delta E = h\nu = 3.99 \times 10^{-13} \times 1.429 \times 10^9 = 0.000\ 57$ kJ mol^{-1}.



(a) Reproduced courtesy of The Lund Observatory, Sweden



(b) Reproduced courtesy of J. Dickey (UMn) and F.J. Lockman (NRAO)



(c) Reproduced courtesy of NASA and Compton Gamma Ray Observation

Fig. 22.7 (a), (b) and (c) All-sky images at different wavelengths: **(a)** visible light; **(b)** 21 cm; and **(c)** Gamma radiation at 100 MeV. The images show emission in our own galaxy. The pictures show that the strongest emission lies in the central plane of our galaxy.

The 21 centimetre line of hydrogen is one of the most famous in all astronomy because it allows the concentration of H atoms to be plotted in all parts of the observed universe. As hydrogen is the most abundant element in the universe, a measurement of H atom concentration is a good indication of the total density of matter in that region. The 21 cm line may be detected on earth using radiotelescopes. Because its wavelength is relatively long, the 21 cm radiation is not absorbed by interstellar dust.

The intensity of light emitted by different parts of the universe is obtained by pointing earth- and satellite-based detectors at different directions in space. Measurements using detectors at 500 nm (a visible wavelength), 21 cm (H emission) and 100 MeV (a very high frequency) have been used to assemble the all-sky pictures shown in Fig. 22.7. Fig. 22.8 develops this theme and shows 21 cm emission in the famous crab nebula.

Fig. 22.8 An artificially coloured image of the famous Crab Nebula. The blue part of the image shows the H atom emission at 21 cm. Reproduced courtesy of Robert Grendler.

6. Identification of molecules in space by microwave and infrared spectroscopy

Molecules have been identified in the atmospheres of planets and in deep space by microwave and infrared spectroscopy.

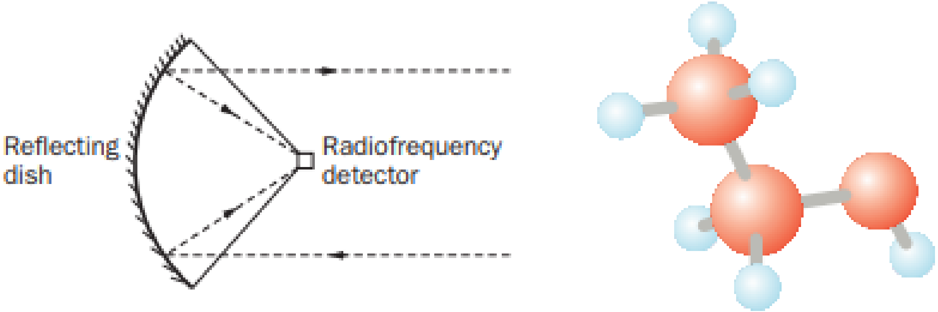


Fig. 22.9 Light of radiowave and microwave wavelengths from distant objects is collected using a radiotelescope dish. Using this technique, astronomers have proved that organic molecules, including ethanol (modelled on the right), are present in intergalactic clouds in minute quantities.

Spectra in the microwave region of the electromagnetic spectrum are produced when molecules lose energy or gain energy, causing them to rotate more slowly (energy loss) or rapidly (energy gain). The energy jumps involved in these transitions are sufficiently small that the wavelengths of light emitted or absorbed are in the microwave region. This fact permits ground-based radiotelescopes (Fig. 22.9) to be used to detect the presence of molecules such as CO (carbon monoxide) and even ethanol (C_2H_5OH).

Table 2 Examples of species (molecules or radicals) detected by spectroscopy in (i) the interstellar medium (the part of our galaxy that lies in-between the stars and planets) and; (ii) outside our galaxy. A tick (✓) shows that the species has been detected by rotational spectroscopy. ✓* shows that the species has been detected by infrared (rotational-vibrational) spectroscopy only. For example, H_2 has been detected by rotational spectroscopy in our galaxy but by only by infrared spectroscopy outside our galaxy. O_2, HCl and $(CH_3)_2O$ have not yet been detected outside our galaxy.

Species	*Interstellar medium*	*Outside our galaxy*
H_2	✓	✓*
O_2	✓	-
OH	✓	✓
HF	✓	✓
CH	✓	✓
CN	✓	✓
CO	✓	✓
HCl	✓	-
H_2O	✓	✓
SO_2	✓	✓
CH_3OH	✓	✓
CH_3CHO	✓	✓
$(CH_3)_2O$	✓	-
C_6H_6	✓*	✓*
C_{60}	✓*	✓*

Data taken from the University of Koln website at https://www.astro.uni-koeln.de/cdms/molecules

BOX 3: Pressure and Concentration in the Interstellar Medium (ISM)

The gas pressure in the interstellar medium of outer space (in the space between stars and planets) is incredibly low and typically corresponds to about 1 molecule per cm^3 of space. This equal to the best vacuum ever obtained in the laboratory and even then the lab vacuum was only achieved using very powerful pumps to evacuate a small chamber.

A good laboratory vacuum corresponds to a pressure of about 10^{-3} Nm^{-2} (about 10^{-8} bar). Use of the ideal gas equation ($PV = nRT$) shows that at 300 K this equates to a concentration (= n/V) of about 4.0×10^{-7} mol m^{-3} or 2.4×10^8 molecules cm^{-3}. This concentration ratio between the 'good lab vacuum' and the ISM is:

$$\frac{2.4 \times 10^8}{1}$$

i.e. the good lab pressure has a molecular concentration which is about 240 million times higher than that of the ISM. The ISM is also much colder than even the draughtiest laboratories, with a temperature of about 2.7 K!

BOX 3: Pressure and Concentration in the Interstellar Medium (ISM) *continued*

If the total gas pressure of the ISM is so low, the concentration of absorbing species (see Table 2) must be even lower. How then can they be detected? The answer lies in the Beer Lambert equation introduced in Unit 22 of the book (p406). According to this equation, the absorbance of a species of concentration *c* at wavelength λ is given by:

$$A_\lambda = \varepsilon_\lambda \times c \times b$$

where ε_λ is a constant for that species at that wavelength. *b* is the thickness of the sample containing the absorbing substance. If *b* doubles, the experimentally determined absorbance doubles. In taking absorbance measurements from the ISM, the effective pathlength will be the equivalent of trillions of kilometres. (1 light year is equivalent to a distance of 9.461×10^{12} km!). Even so, the absorbances measured require highly sophisticated equipment and data analysis to be distinguished from background noise.

The 'pathlength effect' may also be observed in the laboratory using water. A beaker of water appears colourless, If however, a 3 m plastic or metal tube with glass windows at its ends is filled with water and the human eye placed in front of a window, the water appears blue. This is because water has a very weak absorption in the orange part of the visible spectrum and the 3 m pathlength amplifies the absorbance so that its 'true colour' emerges. For this reason, thick blocks of ice appear blue. If the experiment is repeated with deuterated water (heavy water, D_2O), no blue colour is observed and the D_2O appears colourless even with a 3 m pathlength. This is because deuterated water has a slightly different absorption spectrum, one that does not even weakly absorb in the visible part of the spectrum.

Infrared spectroscopy is discussed in Unit 22. Infrared spectroscopy is used by probes to analyse the composition of planets. An example is shown in Fig. 22.10, where the use of satellite based infrared filters have shown that the atmosphere of Jupiter contains high concentrations of methane.

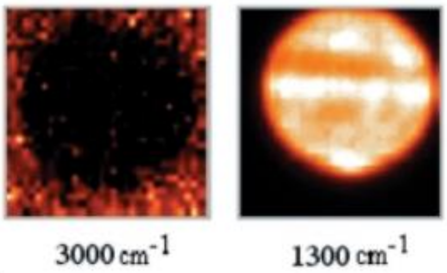


Fig. 22.10 (a) Jupiter observed using infrared filters operating (approximately) at the wavenumbers shown.

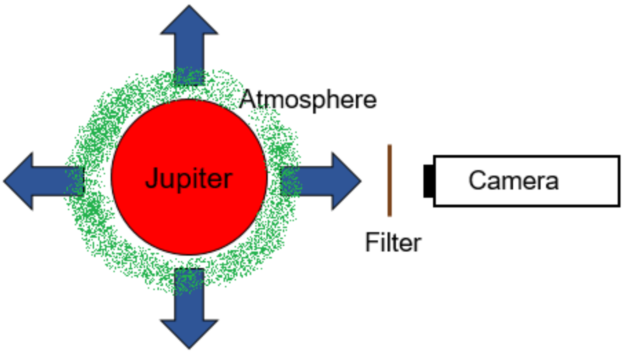


Fig. 22.10 (b) Diagram explaining the observation that the image obtained using the 3000 cm^{-1} filter is black. The heat energy (coloured blue) emitted by the planet at 3000 cm^{-1} is almost completely absorbed by the methane in its atmosphere. There is much less absorption of light at 1300 cm^{-1} because no species in the Jovian atmosphere absorbs strongly at this frequency.

7. The cosmic microwave background

It is believed that about 14 billion years ago, the visible universe was only a few mm across. Highly energetic photons existed within the universe but they could not escape from this tiny volume. The universe suddenly expanded – an event called the Big Bang.

The Big bang theory is supported by three observations. The first, is that the lightest atoms – those of the elements H, He and Li, are very abundant in the universe and this is consistent with them being formed very early in the history of the universe before the universe expanded. During the history of the universe after the Big Bang, nuclear reactions change lighter atoms to heavier atoms, but there hasn't been time yet for more of the lighter atoms to be used up.

The second observation is that the universe appears to be continually expanding. Although parts of the universe (even individual galaxies close to our own) may be moving toward us, the overall picture is that the universe is getting bigger. The expansion must not be thought of as the result of a simple explosion within the containing universe, as when a grenade is exploded inside a garden shed. The expansion of the universe ('cosmological expansion') involves a continuous increase in time, and a continuous increase in the three dimensions of space (the x, y and z axes). Returning to the grenade analogy, it is the shed itself (and the dimensions of its walls) that is increasing. Evidence for the expansion of the universe comes from the 'red shift' of spectral lines (see Box 1). The cause of the redshift is not a simple Doppler effect whereby an object is moving away from us, but the result of a cosmological expansion of the universe and for this reason it is sometimes called a **cosmological redshift**.

The third observation is that of the **cosmic microwave background** (CMB). After the Big Bang, the energetic photons (with wavelengths in the UV region of the electromagnetic spectrum) were free to travel and they travelled outwards as the universe expanded. Once again, the Doppler effect kicked in, and some 14 billion years later, the light waves associated with the photons have been stretched in wavelength from the UV to the (invisible) microwave. Since the photons causing this microwave emission started in the Big Bang, the cosmic microwave background should be all around us and detectable in all directions of space.

The microwave background is an emission that may be detected using a spectrometer, but the emission is not at one wavelength but at a spread of wavelengths. The intensity/wavelength profile that makes up the emission spectrum emitted by any object depends only on its temperature[1]. For this reason, the CMB data is converted to temperature, in K.

Fig. 22.11 shows the CMB of the visible satellite as measured by the COBE satellite, displayed as the distribution of temperature throughout the universe as visible from the satellite. Fig. 22.11(a) shows the CMB displayed at low resolution. At low resolution, the temperature of the entire visible universe is remarkably constant in all directions, with a mean (and very low) temperature of about 2.7 K. Fig. 22.11(b) shows the temperature at higher resolution, so that tiny differences of temperature may be shown. The colours differ by only 0.0034 K: so that the uniformity of the temperature of the cosmic background is all the more impressive and of course, the mean remains at

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[1] The temperature is known as the 'blackbody temperature'. Once the blackbody temperature is known, the emission intensity/wavelength profile (i.e. emission spectrum) for that object may be calculated using several equations, including Planck's equation. The remarkable thing though, is that emission spectrum depends only on the temperature of that object. For example, a copper block and a lump of iron will both have the same emission spectrum if they are at the same temperature.

2.7 K. Fig. 22.11(c) shows the distribution of temperature at an even higher resolution, where the colours represent differences of only 0.000018 K. These small differences are predicted by the detailed mathematics of the Big Bang Theory.

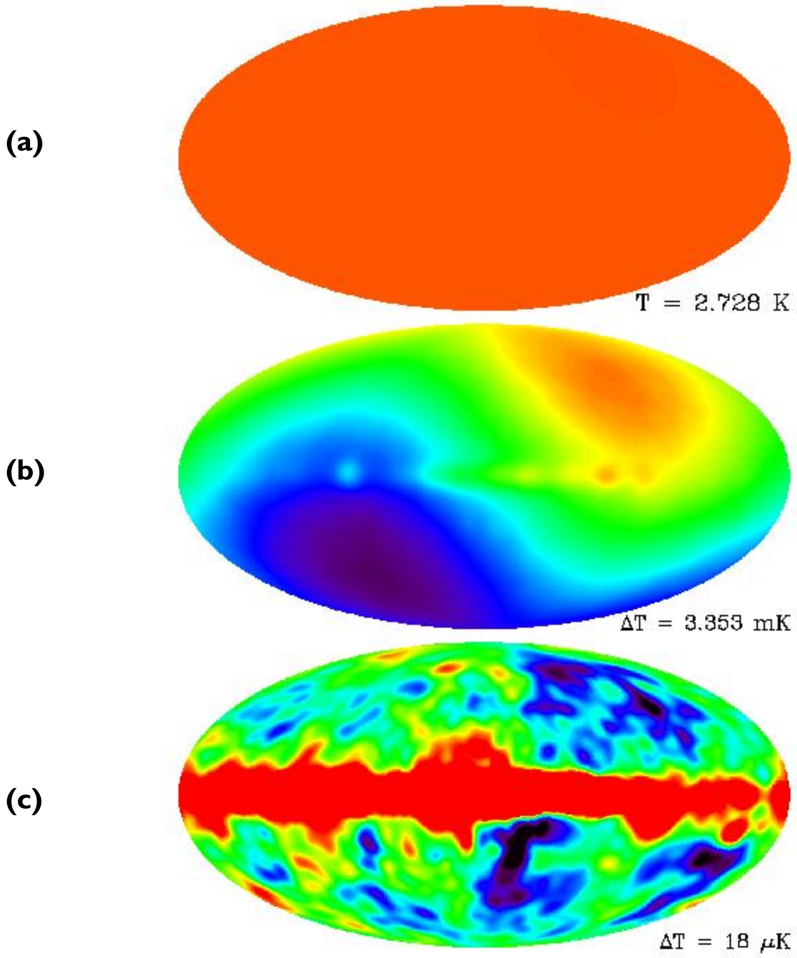

Fig. 22.11 Cosmic Microwave Background images of the visible universe from the Cosmic Background Explorer satellite (images courtesy of NASA). The images show the temperature of the background radiation at different resolutions (in K).

8. The applicability of the laws of nature throughout the universe

The analysis of spectrum from distant parts of the universe depends on an assumption: that the laws of physics and chemistry and the rules of mathematics that apply on earth are universally applicable. For example, that the Law of Conservation of Energy, applies equally well in Amsterdam or Andromeda. Such an assumption can never be proved. Nevertheless it is an act of faith. The philosopher and mathematician Bertrand Russell, famously summarised this by stating that *‘…..even* in the remotest *depth* of stellar space *there are still three feet to a yard’. A more modern version might that there are still 100 cm in a metre!*

References

The NASA site contains a wealth of information on astronomical spectroscopy and the spectrometers used in satellites.

https://www.nasa.gov/

Just type in ‘spectroscopy’ in the search box and away you go!

Further information on the Big Bang will be found on the NASA site at: https://science.nasa.gov/astrophysics/focus-areas/what-powered-the-big-bang