CHAPTER ONE

WHY RECORD SPECTRA OF ASTRONOMICAL OBJECTS?

> ‘We will never know how to study by any means the chemical composition (of stars), or their mineralogical structure’
>
> – Auguste Comte (1835)

1.1 A Historical Introduction

In the first part of the 19th century, astronomers began to make parallax measurements which revealed for the first time how distant even the closest stars are from us. Since travel to the stars was, and still is, impossible with foreseeable technology, many scientists believed that the composition and character of the stars would forever remain a mystery. This view is pithily summarised by the quote from the positivist French philosopher Auguste Comte (1798–1857) given above.

Today, the composition of stars, and indeed of the diffuse material in the large spaces in between the stars, is well known. How did this situation come about? In fact the first steps to finding the solution to the problem had been taken even before Comte began writing.

In 1814, Joseph von Fraunhofer (1787–1826) used one of the high-quality prisms he had manufactured to diffract a beam of sunlight, taken from a slit in his shutters, onto a whitewashed wall. Besides the characteristic colours of the rainbow, which had been observed in this fashion since Newton, he saw many dark lines (see Fig. 1.1). He meticulously catalogued the exact wavelength of each dark line — which are still known today as

ASTRONOMICAL SPECTROSCOPY - An Introduction to the Atomic and Molecular Physics of Astronomical Spectra

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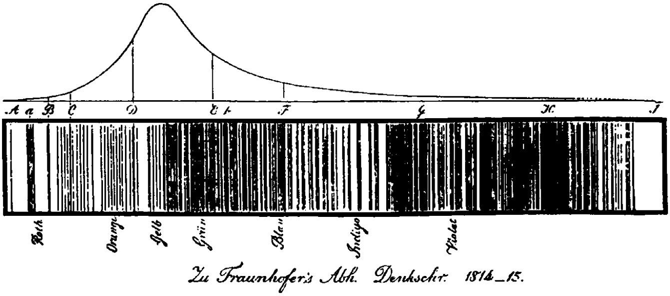

Fig. 1.1. The solar spectrum as recorded by Fraunhofer.

Fraunhofer lines — and labelled the strongest of them with letters. Many of these labels, such as the sodium D lines (see Sec. 6.4) are still used today. Fraunhofer not only recorded the first astronomical spectrum, he recorded the first-ever high-resolution spectrum. Fraunhofer's spectrum was the first to resolve discrete line transitions.

Fraunhofer did not know what caused the dark lines he observed. However he performed a similar experiment using light from the nearby red-star Betelgeuse and found that the pattern of dark lines he observed changed significantly. Fraunhofer concluded correctly that most of those features were somehow related to the composition of the object he was observing. In fact some of the lines were due to the Earth's atmosphere, the so-called telluric lines. For example, the features Fraunhofer marked A and B in his solar spectrum are actually due to molecular oxygen in our own atmosphere.

The first real step in understanding Fraunhofer's observations came in the middle of the 19th century with the experiments of Gustav Kirchhoff (1824–1887) and Robert Bunsen (1811–1899). These scientists studied the colour of the light emitted when metals were burnt in flames. They found that in certain cases the wavelength of the emitted light gave an exact match with the Fraunhofer lines. The sodium D lines, which give sodium street lights their characteristic orange colour, were one such example. These experiments demonstrated that the Fraunhofer lines were a direct consequence of the atomic composition of the Sun.

Any understanding of how these lines came about had to wait until the arrival of the 20th century with the revolution of scientific theory represented by quantum mechanics. The developments of quantum mechanics and spectroscopy have always been closely linked. As it is through the study of spectra that we have learnt of many of the riches in the Universe around us, the development of astrophysics has also been closely linked to that of spectroscopy and quantum mechanics. This book aims to give an introduction to the spectroscopy of atoms and molecules that are important for astrophysics. This book is not a text on quantum mechanics, and indeed, some basic knowledge of quantum mechanics is assumed, for it is not possible to understand or interpret spectra without some understanding of quantum mechanics.

Hearnshaw (1986) gives a fascinating historical view of the relationship between astronomy, spectroscopy and the technical developments in both fields (see further reading).

1.2 What One Can Learn from Studying Spectra

Essentially all information about astronomical objects outside the solar system comes through the study of electromagnetic radiation (light) as it reaches us. This light can contain much detailed information which is only obtained by careful analysis. Generally speaking, one can classify the information obtained by observing light according to the spectral resolution; that is the degree of sensitivity to different wavelengths, used to make the observation. One can classify such observations using the following general categories.

When one looks at the night sky with the naked eye, most astronomical bodies appear white. White light is actually light that is composed of many wavelengths which are not resolved into their different colours. Monitoring white light gives the positions of objects in the night sky. It can be used to construct maps of stars and galaxies. It can also be used to plot the movements of heavenly bodies such as comets through the night sky.

If one looks carefully at some celestial objects, such as the planets Mars and Jupiter, or stars such as Betelgeuse, one can see that these objects are tinged with a certain colour. Using instruments with low resolving power, it is possible to separate the light arriving at Earth into broad band colours. Observing colours tells us something about temperatures. For example, blue stars are hotter than red ones; objects that emit X-rays, such as the solar corona, are very hot, whereas cold objects may only emit light of very long wavelengths such as radio waves.

The most detailed astrophysical information is only obtained from high-resolution studies which involve detecting the light arriving at the earth as a function of its component wavelengths. This allows detailed spectroscopic features to be identified separately from broad band features such as colour. At the highest resolution, such studies not only yield the central wavelength of any feature, often referred to as a line, but also the shape of the feature. Such studies can yield significant extra information and this book is largely devoted to the physical basis of this information and how it can be interpreted.

To interpret an astronomical spectrum, one needs considerable knowledge of atomic and molecular physics. This knowledge usually comes from laboratory studies which provide the basic physical parameters necessary for understanding the astronomical spectrum. There is a direct relationship between these physical parameters and the astronomical information that can be obtained by observing spectra. Thus for any line observed in an astronomical spectrum, one can potentially use laboratory data to extract the following information.

The **composition** of the object being observed can be inferred by knowing which atom (or ion or molecule) produces the observed transition.

The **temperature** and other physical conditions can be deduced from assigning the actual transition being observed to precise energy levels in the atom. Transitions take place between many different states in a particular atom. Knowing which states are involved gives direct information on the degree of excitation of the system. This can be used to determine the physical conditions, such as the temperature or density of the environment local to the system.

The **abundance** of the species undergoing the transition can only be determined if the intrinsic strength of the transition being observed is known. Line strengths can be hard to determine in the laboratory. Astronomically, the strength of a transition is directly related to the number of atoms undergoing the transition under suitable conditions of optical depth (see below). Knowledge of the intensity of transitions is therefore important for determining the abundance of any species.

Motions of the species being observed relative to the earth, or indeed the whole region containing the species, lead to a shift in the wavelength of the line; this shift is known as the Doppler shift. The Doppler shift is the change in the line position from the position measured in the laboratory. This shift is given by the Doppler formula,

$$\frac{v}{c} = \frac{\Delta\lambda}{\lambda}, \tag{1.1}$$

where v is the velocity of the source in a direction away from us, $c = 2.99792458 \times 10^8\,\mathrm{m \cdot s^{-1}}$ is the speed of light, λ is the rest wavelength of the transition and $\Delta\lambda$ is the change in wavelength, known as the *Doppler shift*. Application of this formula requires laboratory measurement of the rest wavelength to high accuracy. Formula (1.1) is for non-relativistic motions. When an object is moving towards us, the transition is shifted to shorter wavelengths ('blue-shifted'), and when the object is moving away from us, it is shifted to longer wavelengths ('red-shifted'). It was through the monitoring of Doppler shifts of spectra of hydrogen atoms that allowed Edwin Hubble (1889–1953) to show in 1929 that our universe is uniformly expanding and so started from a single point or Big Bang.

The **pressure** or density of the environment local to the species undergoing the transitions can be monitored by observing the line profile. Such observations require particularly high resolutions. Spectral lines are broadened by collisions between species; the more frequent these collisions are, the greater the broadening. This process is called 'pressure broadening'. Lines are also broadened by the thermal motions according to the Doppler formula. Doppler broadening arises because hot species move about faster than cold ones. Both of these reveal information about the physical environment of the species being observed. However, the combined effects of pressure and temperature on the line profile can only be resolved using ultrahigh resolution observations.

Any **magnetic field** present can be monitored as certain spectral lines will be split into more than one component. Energy levels of states which possess angular momentum are split in the presence of a magnetic field. The result is that a single transition can become two or more distinct transitions. The degree of separation between these component lines depends directly on the strength of the local magnetic field. Such splittings, if observed, can therefore provide a measurement of this field.

The information obtained from such observations is the key to most astronomical knowledge. However, to interpret any astronomical spectra requires detailed information about the intrinsic properties of atomic spectra. For each atom or ion or molecule being observed, one needs to know:

(1) Its important spectral lines: these are often summarised using figures called Grotrian diagrams (see Sec. 5.4).
(2) Its energy level structure: also summarised on Grotrian diagrams.

(3) The intrinsic line strength of the transition(s) being observed.
(4) The precise rest (i.e. laboratory) wavelength of any transition observed.

Additional information is required to interpret pressure broadening of spectral lines and splitting in magnetic fields, however these topics will not be pursued in this book. Understanding and use of all this detailed spectroscopic information requires considerable knowledge of quantum mechanics.

At all wavelengths there are observed spectral lines which have yet to be identified (see for example Figs. 6.8 and 7.6). A particularly long-running current example are the diffuse interstellar bands or DIBs. This means that laboratory astrophysics, the study of astrophysical processes in the laboratory, based on either experiment or theory (or both), remains an active area of research.

Problems

Answers to problems are given at the end of the book.

1.1 While observing stars in a distant galaxy, Edwin Hubble observed discrete line emissions at 411.54 nm, 435.50 nm, 487.75 nm and 658.47 nm. There are H-atom transitions with rest wavelengths of 410.17 nm, 434.05 nm, 486.13 nm and 656.28 nm. Verify that these lines are all Doppler-shifted by the same amount. What is the speed of the distant star relative to earth? Is it moving towards us or away from us?