The only source of information about the universe is the radiation that we receive from various astronomical sources. This article describes some of the methods used by astronomers to analyze this radiation to unveil the mysteries of the universe.

1. Introduction

We are currently in the era of precision cosmology, the science of the universe. We understand the universe as never before. Among the things we understand are star formation and evolution, galactic structure, dynamics and the large scale structure formation and evolution. There are also several mysteries about it for which we do not have a clue yet, the prominent ones being dark matter and dark energy. The fact that we have learnt so much about the universe and are able to measure cosmological parameters to high precision is awe inspiring when we remind ourselves that we are merely passive observers in this game. Unlike in other branches of science like physics, chemistry and biology, where we can do controlled experiments in the laboratory to understand the phenomenon under study, no experiment can be performed on the universe and we have to make do with the radiation/photons that we receive from its different parts. We do receive particles in the form of cosmic rays and neutrinos. But neutrinos being weakly interacting, are very hard to detect and cosmic rays being charged, change their path depending on the magnetic fields and so cannot be directly associated with a particular source. Thus, it is a tribute to human intelligence, ingenuity and spirit that we have been able to unveil the mysteries of the universe to the extent that we have.
The radiation that we receive from the heavenly objects comes in all wavelengths and astronomers use various kinds of telescopes and detectors to gather and analyze these photons. The optical and radio telescopes can be ground based while all others, e.g., the microwave, infrared, X-ray and gamma-ray telescopes have to be necessarily put in space aboard satellites to be able to receive these photons before they get absorbed by the earth’s atmosphere. The development of electronic detectors like the charge coupled devices (CCDs) and subsequent digitization of the spectra and of high resolution spectrographs like the Echelle spectrograph, the commissioning of large 8–10 m class telescopes like the KECK, VLT and Subaru and the launching of several space telescopes for observing in wavebands other than the optical and the radio in the past few decades, have enabled the astronomers to gather data of unprecedented quality and quantity. Availability of high power computers is helpful in analyzing this large volume of data as well as run large simulations. As a result of all this, astronomers have made rapid addition to the knowledge pool about the cosmos.

In general, astronomers make three types of observations: (1) Imaging: essentially taking photographs and then analyzing the distribution of brightness over the surface of the source. (2) Photometry: measuring the total energy emitted by the source over certain wavelength bands by using filters in front of the detectors. (3) Spectroscopy: spreading out the radiation over the wavelength interval permitted by the telescope and detectors. I will be focusing on the use of spectroscopy which is by far the most effective technique among the three mentioned above.

Radiation interacts with matter in basically two ways: scattering and absorption/emission. The scattering cross-section depends on wavelength, the exact dependence determined by the geometry and composition of the
Spectral lines carry information about the material that produces them. Kirchhoff’s laws help us to understand the source of the spectrum.

scatterer, e.g., a molecule or a dust grain. Absorption can be a continuous function of wavelength for non-resonance absorption while for resonance absorption, it is non-zero only over small wavelength regions around the resonance wavelength, resulting in the formation of absorption (and also emission) lines. In addition, the wavelength of the emitted or absorbed radiation gets affected by the velocity of the interacting matter. All these phenomena leave distinct imprints on the incident radiation as it passes through any matter concentration. And it is the astronomer’s job to work backwards from the radiation entering his/her telescopes and learn the conditions in the matter concentrations. In the rest of this article, I will make an effort to make this connection and try to depict various kinds of information that can be obtained by this process.

Kirchhoff gave the three laws of spectroscopy in the nineteenth century which describe the physical conditions for forming different types of spectra. These are: (1) A luminous solid, liquid or dense gas emits light of all wavelengths, i.e., a continuous spectrum. (2) A low density, hot gas seen against a cooler background emits bright lines, i.e., an emission line spectrum. (3) A low density, cool gas in front of a hotter source of a continuous spectrum creates dark lines, i.e., absorption line spectrum. These laws are pictorially depicted in Figure 1, which

Figure 1. Pictorial depiction of Kirchoff’s laws for spectroscopy.
shows digital spectra produced in the three cases.

Kirchhoff’s laws form the basis of our understanding of the spectra of astronomical sources. Stars which contain very hot and dense gas emit continuous spectrum, called the black-body radiation, as dictated by the first law above. The shape of their spectral energy distribution (as a function of wavelength) depends only on their temperature. Figure 2 shows the spectra of black bodies at different temperatures. The visible spectrum covers a small range of wavelengths. The temperatures in stars exceed a million degrees at the centre which is the place of nuclear energy generation. The temperature decreases outwards and the energy generated at the centre in the form of $\gamma$ rays flows outwards, continuously getting absorbed and reemitted. The radiation that we receive from the stars is emitted from what is called the photosphere beyond (outward of) which there is little cooler matter and bulk of the radiation can escape unscathed. The small amount of cooler material above the photosphere, in the so-called stellar atmosphere, does cause resonance absorption producing absorption lines as per Kirchhoff’s third law. A typical stellar spectrum

![Figure 2. Figure showing spectra of black bodies at various temperatures. The shape of the spectrum is determined solely by the temperature.](image)
Figure 3. Spectrum of a typical star. The general shape is that of a black-body spectrum with peak around 4200 Å. Comparison with Figure 2 indicates the temperature of the star to be above 5500 K. Absorption lines can be seen superimposed on the continuous spectrum. Source: SDSS web page (http://cas.sdss.org/dr7/en/proj/basic/spectraltypes/stellarspectra.asp)

Physical conditions in stellar atmospheres determine which absorption lines will appear in the spectrum.

is shown in Figure 3 which shows a black-body continuous spectrum superimposed by several absorption lines. The kind of absorption lines that appear depends on the chemical composition of the stellar atmospheres and the physical conditions prevalent there. Cooler stars may have molecules in their atmospheres and produce molecular lines while hotter stars may have ionized atoms producing ionic resonance lines. On the other hand, a nebula which is heated by starlight when seen directly, shows up in emission as per Kirchoff’s second law. A typical nebular spectrum is shown in Figure 4.

Figure 4. Spectrum of a typical nebula. Adapted from: http://www.astro.utu.fi/~cflynn/astroII/9.html
I will discuss how we measure various parameters related to the astronomical sources and also the universe as a whole, using these spectra.

2. Temperature of a Star

As noted above stars in general emit as black bodies and the determination of the shape of the spectrum, by measuring the flux in a few wavebands, directly enables the astronomers to determine the temperatures of photospheres of stars. We thus know that the photosphere of the Sun is at about 5800 K while there exist much hotter and cooler stars with temperatures ranging over a few thousand to 60,000 K.

3. Radial Velocity of Sources

Doppler effect due to the radial motion of the source (or the observer) shifts the wavelength of the photons towards red (i.e., increases the wavelength) or blue (i.e., decreases the wavelength) depending on whether the source is moving away from us or is moving towards us. This is called the redshift or blueshift of the wavelength respectively. Redshift \( z \) is defined by the relation \( \lambda_{\text{obs}} = \lambda_{\text{rest}}(1 + z) \). Knowing the original (laboratory/rest) wavelength of the radiation (e.g., 5890 and 5896 Å for the sodium D lines) and measuring the wavelength of the radiation reaching us, we can calculate the radial velocity of the source. I will describe different kinds of information obtained from radial velocity measurements.

3.1 Measurement of the Masses of Binary Stars

Binary stars are a pair of stars gravitationally bound to each other, revolving around their centre of mass. The lines due to individual stars keep shifting positions in the observed spectrum as the radial velocity of the stars with respect to us changes due to their orbital motion. If the plane of the orbit lies exactly along the line of sight, the measurement directly yields their orbital velocities.
they can be resolved visually and the parameters of the orbits can be measured, the application of Kepler’s laws leads to the measurement of their masses in the same way as that in measurement of the masses of planets in the solar system.

3.2 Detecting Extrasolar Planets

Doppler effect is also used as one of the methods to detect extrasolar planets. This method relies on measuring the radial velocity of the parent star as it moves around the common centre of mass. Very high accuracy in wavelength measurement has been achieved and radial velocities of stars can now be measured up to a few m/s. Massive planets moving close to parent stars, planets around low mass stars and planets whose orbits lie close to the line of sight can produce measurable radial velocities of the parent stars and thus can be detected through such measurements. This has been the most successful method for detecting extrasolar planets and has so far yielded more than 500 detections.

3.3 Dark Matter

Doppler effect, which is basically used to study the dynamics of a system, has been the key tool to detect dark matter. In 1933, Fritz Zwicky measured velocities of galaxies in a cluster of galaxies which is a gravitationally bound system. He could measure the total mass of the galaxies in the cluster by measuring the total light emitted by them and by assuming a mass to light ratio similar to that of the Sun. The velocities of some of these galaxies, as measured using Doppler effect, were higher than the escape velocity of the cluster as calculated from its total visible mass. The requirement of the stability of the cluster made Zwicky postulate the presence of some kind of matter which does not interact with radiation and would be dark and unobservable, but can provide gravitational attraction and can raise the value of the escape velocity. The presence of this so-called dark mat-
ter was confirmed inside spiral galaxies in the seventies, again using Doppler effect when astronomers measured the velocity of rotation of these galaxies as a function of radial distance from their centres (the plot known as the rotation curve). This revealed that the mass inside a given radius of a galaxy monotonically increases way beyond the radius of the visible disk of the galaxy. Ample evidence for dark matter has been collected from observations of rotation curves using the 21 cm hyperfine transition line emitted by neutral hydrogen gas clouds which continue to be present at large distances from the galactic centres beyond the visible disk. A typical rotation curve is shown in Figure 5 which also shows the expected rotation curve if one assumes most of the mass in the galaxy to be in the form of stars. Laboratory experiments are being carried out to directly detect dark matter particles but have not been successful so far.

4. Magnetic Field

Zeeman effect splits atomic resonance lines into multiple components, the magnitude of the split depending on the strength of the magnetic fields. This is used in measuring the field, e.g., in sunspots (shown in the left panel of Figure 6). The field in these dark regions on the surface of the Sun is strong \( \sim 2500 \) Gauss, i.e., more than tens of thousand times stronger than the field on...
Figure 6. Left panel shows the photograph of sunspots; Source: http://www.windows2universe.org/sun/images/sunspots_big_jpg_image.html

Right panel shows the spectrum obtained by placing a slit (vertically) across a sunspot. Splitting of lines due to Zeeman effect is maximum at the centre of the sunspot where the magnetic field is expected to be maximum.

Zeeman splitting of lines has been measured in Sun and also in other stars.

Studies of absorption lines yield the abundances of species.

5. Chemical Abundances

The strength of a resonance absorption line depends upon the number of atoms/ions/molecules of the species crossing the line of sight between the source and the observer (i.e., responsible for producing the line). In situations where this number is not too small or too large (these values depend on the species), it also depends on the velocity dispersion of the particles. Using multiple lines of the same or different species, both the velocity dispersion and the concentration of the species can be determined. Usually, a given element exists in several ionic states and to get the abundance of the element one has to measure the concentrations of all the ions. This is not always possible (as the lines produced by some ionic states may not lie in the observational window) and theoretical models are often constructed to estimate the total abundance of the species from the abundances of observed ions.
A new element was first discovered in 1868 in the spectrum of the Sun and was appropriately named Helium. This was discovered on the earth much later, in 1875. Similarly, a green line in the spectrum of the solar corona (the outermost hot portion of the Sun having temperatures of a million degrees), first seen during the total solar eclipse of 1869, did not correspond to that of any of the known elements on the earth and was believed to be due to a new element which was named Coronium. It was much later, in 1930 that the line was found to be due to highly ionized Iron ions which survive at the high temperatures prevailing in the corona.

6. Expansion of the Universe and the Big Bang Theory

Around 1928, Hubble measured the velocities, using Doppler effect, and distances to several nearby galaxies. He discovered that not only all galaxies are receding away from the Milky Way, but the velocity of recession is directly proportional to the distance of the galaxy from us; this relation is named Hubble’s law after him. The only way this phenomenon can be explained assuming an isotropic and homogeneous universe is to assume that the fabric of the universe (i.e., space) itself is expanding making every galaxy recede from every other galaxy (similar to dots on a balloon in which air is being pumped) naturally giving rise to the Hubble’s law. With this observation and Einstein’s theory of general relativity, flourished the science of the formation and evolution of the universe which we call cosmology. At this point it is necessary to point out that even though the wavelength of the radiation coming to us from distant galaxies and other sources changes, the change cannot be really ascribed to Doppler effect. It is actually due to the expansion of the space and thus change in physical scales with time, the effect being exactly similar to the Doppler effect.
The expansion of the universe and the constant recession of galaxies tells us that the galaxies must have been closer together at earlier times and that there must have been an instant of time when the entire universe was confined to a space point. It must have started expanding due to some explosion and has continued to expand till date. This is the big bang theory of the universe according to which, the very early universe had very high temperature and density and consisted only of radiation and elementary particles. As the universe expanded, it cooled due to the lack of further input of energy and slowly the structures that we see today were formed. In the first 200 seconds in the life of the universe, the temperature and density were sufficiently high for nuclear reactions to take place. The light elements H, D, He, Be, B formed at that time. All the heavier elements formed later inside stars and were thrown out into the interstellar space during stellar explosions. According to this theory, the chemical abundances of heavy elements in galaxies have been increasing with time, each generation of stars chemically enriching the interstellar medium further.

7. Quasar Absorption Lines as a Tool in Understanding the Universe

Quasars are very bright objects with luminosity which can be more than tens of thousand times the luminosity of an individual galaxy and having sizes of about the size of the solar system. They are believed to be galaxies which harbor super massive (with mass around a million times the mass of the Sun) black holes at their centres. Accretion of matter onto this black hole produces enormous amount of energy in a very small region of space. For our purpose here, quasar serves as a bright background source of light against which we are able to view the material lying between it and us through the absorption lines that this material produces in its spectrum in accordance with Kirchoff’s third law (see Figure...
1). Thus, absorption lines in the spectrum of a quasar (shown in Figure 7) offer an indirect way of studying the intergalactic medium as well as interstellar medium of galaxies lying along the way. As quasars are very bright, they can be seen up to large distances (high redshifts) and enable us to study the intervening gaseous material up to those distances.

As large distances imply long travel times for photons before they reach us, the light that we receive from a far away quasar at the redshift of, say, 5 would have left the quasar about 12 G Yr earlier so that we would be seeing the quasar as it was that many years back (look back time). We would have to wait for another 12 G Yr to see what the quasar is actually looking like at the present time. Similarly, the absorption lines that we see at the redshift of, say, 3 would have been produced by gas in an intervening galaxy when the universe (and the galaxy) was 11 G yr younger. Larger the redshift of an object that we are observing at present, larger is the distance of that object from us and larger is the look back time. Thus, the quasar absorption lines not only allow us to see the distant universe, they also enable us to see the universe as it was at different stages during its evolution.
all the way back to when it was a few million years old. I will describe a few measurements which are made by using these lines.

8. Fine Structure Constant

The fine structure constant \( \alpha = \frac{e^2}{\hbar c} \), where \( e, \hbar \) and \( c \) are respectively the electron charge, \( \frac{1}{(2\pi)} \) times the Planck’s constant and the velocity of light) has a value of \( 1/137 \) as measured in the laboratory. However, there is no reason why its value should have been exactly the same since the beginning of the universe. In fact there are theories of high energy physics which allow the variation of its value over the history of the universe. Using quasar absorption lines, it has been possible to measure the value of \( \alpha \) over the time period of billions of years as described below.

Quantum mechanical models of atoms and molecules tell us that the separations between the energy levels of these systems depend on the values of fundamental constants like the fine structure constant. For example, the wavelengths of the lines of Fe II (singly ionized iron) emitted or absorbed at an earlier time in the life of the universe would not be same as the wavelengths of similar lines produced in the laboratory at present if the value of the fine structure constant has changed in the meantime. This effect will be over and above the change in wavelength due to the \( (1 + z) \) factor (due to redshift) caused by the expansion of the universe. An accurate measurement of wavelengths of the quasar absorption lines produced by galaxies at high redshifts and their comparison with the laboratory values today can thus give us direct information about the variation in the value of the fine structure constant over time-scales of the order of billions of years.

The task is not as easy as it sounds. There are several reasons for this. The first and foremost is that the total change in wavelength can be easily mistaken as be-
ing a redshift effect. Thus if the actual redshift of the galaxy producing quasar absorption lines is 3 and the change (say increase) in wavelength due to the difference in the value of the fine structure constant is 1 Å, one can (wrongly) conclude the redshift to be slightly higher than 3 (by $2 \times 10^{-4}$ for a line having wavelength of about 5000 Å) and not learn anything about the variation in $\alpha$. However, we are helped by the fact that even though the effect of redshift on the wavelengths of lines is uniform (wavelengths of all lines change by a factor of $(1 + z)$), different lines are affected differently by the change in the value of $\alpha$. For example, the wavelengths of doublet lines of Mg II (wavelengths 2796 Å and 2803 Å) are highly insensitive to the change of the value of $\alpha$ while those of the Fe II multiplets are highly sensitive. Thus, the Mg II lines in the observed high redshift absorption system can be used to determine the actual redshift of the system and the observed wavelengths of the Fe II multiplets can be used to detect any change in the value of $\alpha$.

This method and its variants have been used and the latest results show no evidence for variation in the value of $\alpha$, though one group of astronomers has claimed the value to be space dependent.

9. Chemical Evolution of the Universe

According to the big bang theory, the chemical abundances of heavy elements in the universe has been increasing due to nucleosynthesis inside several generations of stars in galaxies, each generation adding heavy elements in the interstellar medium. This fact can be verified directly by measuring the chemical abundances of elements in galaxies at different times in the life of the universe. As seen above this is possible by measuring abundances using quasar absorption lines at different redshifts which correspond to different times in the life of the universe. This has been done and there ap-
pear to be clear evidence for a monotonic increase in abundances over the past ten billion years.

10. Temperature of the Cosmic Microwave Background Radiation (CMBR)

CMBR is the left-over radiation from the big bang which has retained its black-body shape but has cooled from the extremely high temperatures at very early times to 2.7 K at present. It was discovered in 1965 by Penzias and Wilson for which they received the Nobel Prize in 1978. This is one of the sound evidences for the big bang theory. According to this theory, the CMBR temperature depends on redshift as \((1 + z)\). The temperature of the CMBR at redshifts of \(\sim 2-3\) has been measured through the effect it has in exciting the CO molecules to higher rotational states from the analysis of absorption lines from these states in the spectra of quasars. The measured values are fully consistent with the expected redshift dependence.

11. Summary

In this article I have tried to present some of the basic methods that astronomers use to understand different aspects of the universe by analyzing the radiation received from various astronomical sources. I have only concentrated on spectroscopy and the line radiation and there also I have touched upon only a few aspects so as to give a glimpse of the information-gathering process that the astronomers employ. I hope I have been able to give some insight into the exciting field of the science of the universe to the young readers. This is a very promising time for astronomers. Several new, large facilities are being set up and there is going to be an unprecedented wealth of data leading to new discoveries and a deeper understanding of the universe. India is also likely to participate in several of these mega projects and there will be plenty to explore for the young minds taking up a career in the subject at this juncture.

Suggested Reading


