Chapter VIII - The Hydrogen Line and Galactic Structure

Horizons have expanded remarkably since the pre-Galileoan days, when the Earth was firmly believed to be the centre of the Universe. Galileo's observations transferred this distinctive role to the Sun, and he seems to have suspected that the Milky Way might be made up of clouds of stars. It was Sir William Herschel however who first saw that the solar system was embedded in a myriad of stars: he tried to determine their structure from star counts in different parts of the Milky Way, on the tacit assumption that the Sun was centrally placed within it. It was left to the Harvard astronomer Harlow Shapley to show that this was not the case, and that the Sun and the whole ~~xxix~~ solar system occupy no such favoured position. We are, in fact, about 30,000 light years, or located one third of its diameter, from the centre (See Chapter page).

Progress in determining the ~~x~~ shape of the Galaxy and distribution of matter throughout it has been aided by the study of other star systems such as the Andromeda Nebula, whose spiral arms were revealed for the first time by the famous telescope which Lord Rosse constructed ~~fxxx~~ for himself around 1845. As telescopes improved it has become clear that the Universe around us is studded with galaxies, many of them exhibiting various forms of spiral structure. Sometimes they may be seen flat-on, sometimes edge-on, or at various intermediate aspects, as is illustrated in Plate .

With the realisation that our Galaxy is merely one of an enormous number of such separate entities which together constitute the Universe came the suggestion that it may also show similar spiral form. That it is a flattened lens or disk-shaped system was clear from a count of stars in various directions. The bright band crossing the night sky which we call the Milky Way indicates the plane, or the <u>long</u>-dimension of the disk; at right angles to this we are looking out through the <u>thin</u> dimensions and stars are relatively scarce. See Plate   . It was clear, too, that the centre of the Galaxy lay in the direction of the constellation Sagittarius, and that the Sun and the solar system are situated at a long way from the Centre. The task of delineating the details of any possible spiral structure, however, xxx looked like being a hopeless task, particularly because the huge clouds of absorbing material which are effectively opaque to light waves severely limit our view in many directions. This is especially so towards the xxxxxxx central regions, where the star population is highest. Something of an optical break-through occurred, however, in the late 1940's when Baade and Mayall, found that the spiral arms in the Andromeda Galaxy, M31, contained most of the emission nebulae as well as the O and B-type stars, i.e. those which are the cosmically youngest. They suggested that these objects might serve as tracers to define the spiral arms within the Milky Way, and in 1951 Morgan and his associates at Yerkes Observatory, following this lead, found that in the solar neighbourhood these objects fall into three groupings which appear to constitute sections of three separate arms. The picture was necessarily a restricted one however because the optical horizon was limited to only a few thousand light years in most directions. A good deal of detail was available within this limited range, but no information at all about the interesting central regions.

It was at this stage that radioastronomy entered the picture with one of its early and major contributions.

At a time when radio waves from space had barely been detected, van der Hulst, xx of the group at Leiden University, which had been particularly interested in galactic structure, predicted (in 1945) that radio emissions should be detectable from hydrogen throughout the Galaxy, as a result of a hyperfine transition which can occur within the hydrogen atom. He foresaw that the availability of a radio line at a precise frequency would provide the possibility of determining velocities in the line light which had proved of such inestimable value to optical astronomers. He saw also that it would give a means of exploring the Universe in depth, because of the much greater penetrating power of radio waves. With their longer wavelength radio waves are able to ooze their way through the dust grains of the absorbing clouds, ~~instead~~ instead of being completely stopped, as is the case for the much shorter waves of light.

The Hydrogen Line

The hydrogen present in the vast spaces between the stars is remote from any source of optical excitation and so is cold, highly rarefied and all the atoms exist in the ground state, i.e. the single electron occupies its lowest orbit. Under these conditions no emission of light is possible. The ground state itself, however, has two levels which correspond to two possible orientations of the spin of the electron and the nucleus. When the directions of the spins are parallel the energy of the atom is slightly greater than when they are opposed. A change from one state to the other is possible and is referred to as a hyperfine transition, or a spin-flip: when the flip is from the parallel to the anti-parallel position a quantum of 21 cm radiation is emitted whose frequency can be measured in the laboratory with high precision. The value to the nearest cycle when both source and receiver are at rest with respect to each other is 1420.405752 MHz. It is impossible to have all the atoms at rest with respect to the observer, however because of their individual motions under the effects of thermal agitation, so the frequencies emitted are varied by Doppler shifts and the line has a definite width instead of being infinitely sharp.

The chance of a spin-flip occurring spontaneously is governed by probability considerations and is extremely low - only about 2.85×10^{-15} per second. An atom in the higher energy condition (with spin orientations parallel) is likely to remain there on the average, for about 11 million years before ipping spontaneously into the alternative lower energy state. espite this low probability of occurrence and the low density of hydrogen atoms in interstellar space enough transitions are taking place at any instant to produce 21-cm radio emissions that are easily detectable with modern radio telescopes, even from galaxies well outside the Milky Way. The relative numbers of atoms in the two possible conditions of the ground state are a function of the spin or excitation temperature, which is essentially determined by collisions between atoms; when this is the dominant factor the spin temperature is effectively equal to the kinetic or "ordinary" temperature of the gas cloud. This is generally of the order 100°-125°K, but may fall as low as 50°K in some particularly cold regions of space. The brightness temperature of the continuous background emission at a wavelength of 21 cms rarely exceeds about 30°K so the clouds of neutral hydrogen appear bright in emission. Point sources may, however, be bright enough to reveal the presence of clouds in the foreground by absorption lines at the hydrogen line frequency.

The Leiden group set out to follow up Van der Hulst's prediction but were forestalled in their discovery of the hydrogen line by a fire which destroyed their first receiver in 1950. The first successful detection of 21 cm signals was carried out by Ewen and Purcell at Harvard in 1951, who reported an antenna temperature of 25° over a section of the Milky Way. This result was confirmed shortly after by Christiansen and Hindman in Sydney and by Muller and Oort in the Netherlands. Thus was forged a unique tool for pulsing regions of space where neutral hydrogen is the predominant constituent but can never be studied optically.

Mapping the Spiral Structure

Radio astronomers were quick to appreciate the possibilities held out from a detailed survey of the distribution of the H-line emissions, and two groups in particular set out to carry out the necessary observations one at the Radiophysics Laboratory in Sydney and the other at the Leiden Observatory in the Netherlands. The basic observational problems are increased in the case of line emissions by the need to search in frequency as well as in two coordinates of position in the sky, and by the fact that the signal intensity is low. It is consequently xxxxxxxx essential to use highly stable receivers of low-noise performance, since the signal intensity is commonly below that generated by circuit noise. It is necessary also to eliminate the contribution to the signal from the continuum emission at the line frequency: this is usually done by comparing the intensity at two frequencies, one within and the other outside the band over which hydrogen line emission is expected. In practice these comparison frequencies are 1.5-2.0 MHz apart, and switching between them is done at a rapid rate, so that gain variations in xx the receiver will be largely cancelled out, with consequent improvement in stability. A profile of the emission at a point in the sky is obtained by recording the intensity as the receiver is tuned over the appropriate frequency range, or alternatively, by providing a number of narrow-band filters which together span the desired range, so that the profile is obtained directly from the intensity recorded by the filters. A remarkable feature of these observations is the complexity of the profiles observed in some directions, where many peaks in the curve indicate that signals are being received from a number of clouds moving with different radial velocities. This could be due to local turbulence, or more probably, to the fact that they are located at different distances from us - see for example Figs. . In other directions the cloud structure is obviously much less complex: in these figures the signal intensity has been plotted in terms of radial velocity, derived from the difference between the observed frequency and the known rest frequency (1420.40575 MHz) i.e. the Doppler shift.

The first maps of the Galaxy which gave a clear indication of its undoubted spiral structure were the result of combining observations made by Dutch and Australian radioastronomers. A more recent determination of the structure of the outer regions is given in Fig. , in which the left hand half of the picture is based on observations of regions which are visible from Sydney and the right hand half on data from Leiden. Determination of the shape of the spiral arms from the deduced radial velocities is dependent upon being able to convert the observed Doppler displacements into distances from the Galactic centre. Observations of the motions of visible stars and gaseous nebulae indicate that everything in the Galaxy is rotating in slow majesty around a common centre. Plausible models have been deduced which relate velocity in orbit to the distance from the centre, and with the aid of these models, in particular that developed by Maarten Schmidt while at Leiden, the observed radial velocity with respect to the Sun can be converted into a distance from the centre of rotation. The much greater power of radio-waves to penetrate the absorbing dust clouds makes virtually the full depth of the Galaxy available for exploration and the resulting picture leaves no doubt that we are living in the midst of a spiral nebula; if we could view it from far enough away it would probably resemble , shown in Plate The information available from hydrogen line studies is, in fact, so much more comprehensive than that from optical observations that it has been used to define a new position for the centre of the Galaxy differing from the previously accepted position by several degrees. The new system of galactic co-ordinates based on ± 21 cm hydrogen line measurements was adopted in 1960, following the recommendation of a Commission of Dutch and Australian astronomers. This is perhaps the first time on which an important astronomical decision has been based on radio evidence.

The blank sectors in the map of the Galaxy shown in Ezf Figure represent x areas where no reliable indication of distance can be given because the orbital velocity is at right angles to the line of sight, i.e. the Doppler shift is nil and the method of deriving distance breaks down. The

Galaxy seems to be a fairly tightly wound spiral, with arms which are nearly circular in form, and with no clearly marked tendency to either trail or lead the direction of rotation. There appears to be a very bright central nucleus, as for the Andromeda nebula from which two major arms emerge, but details of structure in the central regions are still very sketchy: these regions are completely screened to light waves, so there is no optical picture to help in the interpretation. Some indication of the complex structure near the centre is given by Figure · which is derived from a survey at 3 cms carried out by Hill with the Parkes 210-ft Radio Xxx Telescope: it reveals at least four small sources aligned in the galactic plane.

The radio observations also reveal thaxx that remarkable and unexpected expansion is taking place throughout the central regions, with velocities reaching up to 200 km/s in some regions. This leads inevitably to loss of hydrogen from the centre at a substantial rate, of the order of one solar mass per annum, which would lead to depletion of the hydrogen in a time very short compared with the age of the Galaxy. There must, therefore, be some means by which this is replenished; it comes presumably from the halo which surrounds the Galaxy. Almost at the very centre the observations show the existence of a disk with high xx rotational velocities, up to 265 km/sec. This is associated with a radio source whose non-thermal spectrum indicates synchrotron origin, and hence the presence of rather strong magnetic fields. About 3000 parsecs from the centre a feature known as the 3 kiloparsec arm occurs where the hydrogen concentration is high. Two sections of the arm are defined from the profiles: they participate in the rotation at the normal speed of 200 km/sec and also have an expansion velocity of 50 km/sec. A possible structure for the central regions is indicated in Fig. .

The distribution of the neutral hydrogen in the galactic plane can be determined by scanning across the plane of the Milky Way. It is found to be concentrated in a very thin disk whose thickness is of the order 200 parsecs, i.e. less than one per cent of the diameter. The hydrogen layer is extremely flat in the central regions and almost out to the Sun's distance from the centre, and it is this plane which has been used as a primary reference plane in defining the new system of galactic latitude and longitude introduced in 1960. Systematic distortion of the layer occurs in the outer parts, with positive deviations of several hundred parsecs on the northern side of the line joining the Sun to the centre, and negative deviations on the southern side. A cross section through the Galactic centre normal to the Sun-centre line is shown in Fig.

The maximum downward deflection occurs at the galactic longitude of the Large Magellanic Cloud and the possibility of a tidal effect was considered as a possible cause. The observed deflection is too great by several orders of magnitude to be accounted for as a gravitational tide, however, and some other forces must be responsible: studies of interaction between galaxies have shown that the observed structure cannot always be accounted for by gravitational effects alone.

Observations of the non-thermal radio emission at high galactic latitudes indicate that the Galaxy is embedded in a tenuous halo of gas, of diameter 20-25 kiloparsecs. The Andromeda and other galaxies are observed to be surrounded by a similar gaseous halo, and the existence of such a medium is in fact basic to theories of galactic magnetic fields. An upper limit to the density of neutral hydrogen within the halo is about 10^{-2} per cm^3, so very refined techniques are needed to detect it; at this stage it is not known whether it occurs in concentrated clouds, or is uniformly distributed.

External Galaxies

The sensitivity of modern radio telescopes is such that 21 cm hydrogen line signals can be picked up from sources which lie well outside our own Galaxy. The Magellanic Clouds were the first external systems in which the 21 cm line was observed (by Kerr, Hindman and Robinson in Sydney in 1954); H-line emission has since been detected from approximately 100 external galaxies. These systems mostly exhibit some form of spiral structure: only one elliptical system has been observed to emit the 21 cm line. In many instances profiles taken at different points across a nebula reveal different Doppler shifts, from which its recession as a whole can be determined and sometimes its relation as well. The galaxy with the largest velocity of recession so far detected from H-line xx measurements with the Parkes telescope is NGC 4501, which is receding at a speed of 2120 km/sec (corresponding to a received frequency of 1410 MHz). Plate shows a photograph of the Galaxy NGC 300 with some relative Doppler shifts indicated, from which it is clear that the system as a whole is receding at a speed of 140 km/sec, and xxixxixg rotating as it goes.

The integrated 21-cm energy received from a galaxy provides a measure of the total amount of hydrogen in the galaxy, while the internal motion revealed from differential Doppler shifts allows the total mass of the system to be determined. Thus, from these results the relative proportion of neutral hydrogen can be determined for different types of galaxies.

The Magellanic Clouds

These twin assemblages of stars, easily visible to the unaided eye on moonless nights as hazy patches, distinct from the Milky Way, not far from the south celestial pole, were named after the explorer Ferdinand Magellan who mentioned them in the log of his voyage in which the globe was circumnavigated for the first time. They are the closest of the external galaxies but are too far south to be reached by the world's largest optical telescopes, and consequently have not been studied in detail until relatively recently. They are only about 180,000 light years away, i.e. at about one-tenth the distance of the Andromeda Nebula, and thus present unique opportunities for studying the birth and evolution of stars in relation to the structure and dynamics of the system to which they belong.

Both the Large and the Small Clouds were originally regarded as irregular galaxies, without the spiral or regular structure so evident in other external systems. An increasing body of evidence, particularly from studies of the 21-cm hydrogen line xxxxxxxx emission has produced a clear picture of their rotation and their spiral structure. The rotation curves derived for H-line Doppler shifts are shown in Fig. The Large cloud offers an ideal opportunity to study the distribution of neutral and ionized hydrogen in relation to the xxxxx distribution of young stars. From a detailed xxxx study of 21-cm emission with the Parkes 210-ft radio telescope McGee and Milton found the neutral hydrogen to be largely situated in some fifty two large complexes of average diameter 2000 light years and mass some four million times that of our Sun. These vast clouds of gas curtain most of the young stars and are the nurseries where new stars are born: combination of the radio data with optical studies of the Large Cloud is providing a comprehensive picture of the early stages in the life of stars. It also reveals that the Large Cloud has extensive structure characteristic of a fairly typical barred spiral of type SBC. Two enormous spiral arms emerge from either end of the bar of stars which is a feature of the system, and wind around on the north and south sides in the plane of the sky. In addition two shorter arms also emerge from the ends of the stellar bar, but are inclined at an angle of about 20° to the former system. Plate shows a picture of the spiral arms superimposed on a Mount Stromlo photograph of the Large Cloud.

The total mass of the Large Cloud deduced from the rotation and random motion of the hydrogen clouds is about 6×10^9 times that of the Sun, while the total mass of the neutral hydrogen is deduced to be 5.4×10^8 solar masses. The neutral hydrogen thus ~~xmaxxitwaxxx~~ constitutes about 9 per cent of the total mass of the system, as against about 1.5 per cent for our Galaxy. The Magellanic System is thus at an earlier stage in its evolution.

Hydrogen between the Galaxies

Information on the density of intergalactic space would be of great cosmological importance and a number of attempts have been made to detect neutral hydrogen, both in emission and in absorption. Some of the best work has been carried out by Robinson et al. with the Parkes 210-ft radio telescope. No trace of the 21-cm hydrogen line in emission was observed, but it was detected in absorption in a cluster of galaxies in the constellation Virgo, suggesting that gas clouds are common in this group of galaxies. Traces of absorption were also found in the spectrum of the radio source Fornax A, and this was attributed to general intergalactic hydrogen, with an upper limit to its density of about 9×10^{-6} atoms per cm^3.