POLARISATION[†]

V. Radhakrishnan
Raman Research Institute
Bangalore 560 080, India

Introduction

For the first 30 years or so of its existence, Cosmic Radio Astronomy concerned itself with the study of the strength and its frequency dependence of the radio signals arriving from different directions in the sky, paying little heed to the polarisation properties of the radiation. In the next three decades up to the present time there has been an increasing awareness both of the existence and nature of the polarisation in these signals and its importance in providing clues to the physics of the radio emission. With powerful telescope systems now covering the whole radio spectrum and the continual refinement and improvement of the techniques of radio polarimetry, much of our present understanding of objects like quasars and pulsars, for example, has come from studies of their polarisation characteristics.

In the announcements of the General Assembly put out by URSI, Tutorial lectures such as this one are supposed to be aimed at brushing a general picture of the area covered in the last triennium. There is a bit of a problem here as I have been innocent of any involvement in polarisation measurements for somewhat longer than that, in fact for the last seven triennia. I shall therefore confine myself in this talk to describing polarisation in a very general way, telling you about its early and very early history and dwelling on those particular aspects that have intrigued or fascinated me in my attempts to

---

[†] *Text of Tutorial TJ delivered at the URSI General Assembly, Prague, Czechoslovakia, 28 August – 5 September, 1990*

understand this subtle and interesting property of radiation.

As everyone in this audience knows only too well, polarisation is one of the properties that characterise electro-magnetic radiation, the others being intensity, frequency and direction of propagation. The awareness of this property is usually much deeper amongst radio scientists than those who work with light, x-rays, gamma-rays, etc. The reason is simply that the devices we use to transmit or receive radio frequencies have an obvious physical symmetry which governs the nature of the radiation they can accept or emit. Mere visual inspection of the antenna, be it a dipole, waveguide, helix, or whatever, is enough to tell us its polarisation properties, not to mention its approximate frequency of operation as well.

Radiators and detectors of light and higher frequencies - like light bulbs and photo-diodes for example - have no such obvious physical characteristics that govern their polarisation properties. For one thing, the radiators and absorbers of individual high frequency photons are atoms or molecules whose positions and orientations are not precisely determinable even in principle, let alone in practice. More importantly, the objects used to emit or absorb such radiation, whether natural or man- made devices, consist of aggregates of very large numbers of atoms or molecules which in general have random orientations with respect to each other varying from one instant to the next. The net result is that such aggregates can absorb radiation of any conceivable polarisation but when they radiate, the polarisation has an interesting behaviour which I will have more to say about later. The radiation we receive from a variety of celestial objects is of this nature and is commonly called unpolarised radiation.

Among exceptions to the kind of aggregates I have just described are crystals of minerals which occur naturally and have attracted attention through all of history because of their interesting and varied symmetry properties. Their regular outside forms reflect the way in which all the individual atoms have been aligned and locked into their precisely spaced positions around which they execute only minor motions at room temperature. Transparent crystals are such lattices whose structures lead to anisotropy, for example in the propagation of light through them in different directions. And it is to the observation of the reflection of the setting sun in a window viewed through a crystal of Iceland spar that we owe the discovery of polarisation by Malus in 1808, and the name given to the phenomenon by him.[1]

EARLY HISTORY

What Malus had observed was the variation in relative intensity of the two images produced by the crystal as he rotated it. This happened because the image of the sun reflected by the window was already polarised as explained four years later by Brewster who related the degree of polarisation with the angle of incidence and the index of refraction of the reflecting material. It took another four or five years before Fresnel and Young independently gave a theoretical explanation based on postulating a transverse nature for the waves that make-up light. The property of the crystal of Iceland spar that led to all this was that the different planes of polarisation of the transverse vibrations were associated with different velocities of propagation in the crystal. The existence of two refractive indices, or birefringence, was in turn a consequence of the anisotropy of the arrangement of the atoms in the lattice as mentioned earlier.

While the transverse nature of light waves was established this way, the true nature of the vibrations making up the wave remained a mystery till Michael Faraday first established in 1845 the connection of light with electromagnetism using polarisation. The experiment demonstrated that a piece of isotropic glass (incidentally made by Faraday himself) became birefringent when threaded by a strong magnetic field. The direction of the field broke the symmetry and induced the anisotropy, but the two polarisation modes were circulars unlike the Iceland spar case where they were linears. The actual effect that Faraday observed, and which goes by his name, was a tiny rotation of the plane of linear polarisation as it traversed the magnetised glass along the direction of the field[2]. An understanding of the effect in terms of different propagation speeds for the two circular components into which the linear could be decomposed had to await several years and work by others. But Faraday was an intuitive genius who instantly grasped the significance of his discovery and proclaimed with incredible courage that light was in fact electromagnetic vibrations. Happily, he lived to see his intuition put on the firmest mathematical basis by Maxwell who drew much of his inspiration from the work and images of Faraday.

Radiation with wavelengths of interest to URSI were first produced in the laboratory just over a century ago. Inspired by the work of Maxwell and with the incentive of a prize offered by the Berlin Academy for the solution of a problem concerned with Maxwell's theory, Hertz succeeded in producing radio waves in the metre to decimeter range. Apart from measuring their velocity and showing that they could be reflected, refracted and diffracted, he did experiments with polarisation, a phenomenon that until then had only been associated with light. It is no surprise therefore that in describing his experiments he uses phrases like " *with regard to transmitted energy, the screen (which was made of parallel wires) behaves towards our ray just as a tourmaline plate behaves towards a plane-polarised ray of light*"[3].

Coming to wavelengths that have become of increasing interest to Commission-J in recent years, the remarkable experiments of J.C. Bose may not be as well known as those of Hertz. Bose was the pioneer in generating and experimenting with millimetre waves (λ 5mm to 3 cm), and in a paper published in 1895 he describes his measurements of the birefringence (at mm wavelengths) of a variety of natural crystals including tourmaline which Hertz had simulated by a wire screen. Apart from inventing doping, and a variety of solid state junctions, Bose developed wave guides, horn antennas, lens antennas, polarised mirrors, directional couplers and raised microwave polarimetry to the status of an analytical science[4]. An interesting device he used for his experiments was a polariser made with tinfoil between the pages of a railroad time-table compressed and cut to size. For those who do not know, I might mention that this pioneer of microwave physics gave a demonstration of wireless transmission at the Royal Institution of London in December 1896, a year before Marconi's more celebrated (and commercially exploited) wireless transmission demonstrations in the same city.

A DESCRIPTION OF POLARISATION

Any phenomenon can be looked at from many different view points and generally the more ways one can look at it, the greater the insight it provides. In this spirit I shall look at polarisation from the point of view of the information carried by the signal. I shall begin by noting that all man-made radio transmissions can be received by an appropriately polarised antenna and the information so obtained passed along a single cable. This should cause no surprise as the information to be transmitted was taken to the transmitting antenna along a single pair of wires or cable and the information rate was equal to or less than the bandwidth of the signal transmitted. Nature, on the other hand, takes advantage of the fact that there are two degrees of freedom available in transverse vibrations, and packs up to twice as much information into the same bandwidth. To convey all this information therefore, we need two coax cables or pairs of wires leading away from the receiving antenna.

Let me take a common configuration for our antenna, namely two dipoles at right angles to each other, as a way of intercepting electric fields having all possible orientations. If you point such an antenna towards a natural unpolarised source, the fluctuating currents produced in these two oppositely polarised elements will, as is well known, bear no resemblance whatever to each other. What is interesting and deserves to be properly understood is that if we combine the currents from the two dipoles to synthesise a channel of any particular type of polarisation we fancy, there will always be another untapped channel of its opposite polarisation carrying half the incident energy and with totally uncorrelated fluctuations or information. This may appear a trivial statement now, but I can remember a time when there used to be just one receiver on most radio telescopes, and I have heard serious discussions on how to combine two dipoles or helices or whatever so that one could get all the energy from the source into that one receiver to improve the signal to noise ratio. But as I said just a little while ago, this is precisely what one would do in the case of man-made signals. The polarisation of the receiving antenna would be matched to that of the transmitting antenna so that one can recover all the energy, which could be amplified by a single receiver and the information transmitted further along a single pair of wires.

This is just another way of saying that all man- made transmissions are a hundred per cent polarised, i.e. they use only half the information capacity of the particular band of frequencies in question. In this way of thinking, strange as it may sound, a signal from a celestial source, which is a hundred per cent polarised such as a Maser for example, has only half the information rate that it could have over the band occupied by the emitted radiation. Stranger still is the fact that both modes can never be used to transmit identical information to achieve redundancy. They will combine to form a new intermediate mode, and clear its orthogonal mode leaving it totally empty, and free for other use.

It follows from the foregoing, that when such a fully polarised signal is picked up by two antennas of opposite polarisation, the responses may have different amplitudes but their information content i.e., the fluctuations in the currents, will be identical. This is another way of seeing the intimate connection between the degree of polarisation of a signal and the coefficient of correlation of the voltages produced in two oppositely polarised receiving antennas. To make these quantities equal, the system response must be matched to the polarisation of the signal, as I shall describe when dealing with the representation of polarisation states to which I turn next.

THE REPRESENTATION OF POLARISATION

As shown in the Figure 1, at any given instant of time T_1, the electric field which has to be perpendicular to the direction of propagation must have some particular orientation. At a time T_2 somewhat later, the electric field could be at some other angle, and polarisation can be defined as a description of the time evolution of this angle. Let me start with a manmade transmission, i.e., a fully polarised signal. Figure 2 shows the different ways in which the electric field could behave as a function of time. It could be in some plane and remain in that plane when we would say it is linearly polarised, or it could go round and round keeping its amplitude constant in which case it is a circularly polarised signal. The more general case of which the other two are merely special cases is elliptically polarised radiation as shown at the top of the picture. To receive all of the energy we must match the polarisation of our receiving antenna to that of the radiation. But if we do not know what it is and were trying to find out, we might use other antennas which are mismatched, and therefore we need to understand the response of an antenna to radiation of a different polarisation.

This is very easy with linear polarisation and linear antennas. We would just resolve the electric fields (because of the angle subtended), and it is easy to see that we would pick up less and less energy as we turn one with respect to the other till when they are at right angles we will receive no energy at all. But say the radiation was left elliptic and the antenna was right elliptic with a different degree of ellipticity. We would then need to do some sort of wretched calculation to find out how much of the energy would be received. One standard way to do this is to use the so called Stokes parameters invented by Stokes of viscosity fame and made popular by Chandrasekhar who used it in solving his difficult radiative transfer problems. The virtue of the Stokes parameters is that they are additive, whatever that means, and in some sense they are the components of polarisation. But at first sight, they may appear weird since three of the four Stokes parameters have a different status from the first one, I, which is the intensity. There is also an apparent lack of symmetry in the expressions for the other three of them. Let us go back to the common antenna configuration of two crossed dipoles. Electric fields in any orientation will be picked up by them since one can always resolve the field into vertical and horizontal components. All the information is there, and all one has to do is to extract it from these two signals. One does this by doing everything one can do, multiplying each by itself, each by the other and adding and subtracting and finally writing down the Stokes parameters (Fig 3).

Of the three quantities which represent the polarised part of the radiation, two are obtained by correlations and one is obtained by subtraction of intensities and this is what I mean by a lack of symmetry. Of course, you will get the right answer to whatever problem you are solving, but I don't think this is a nice way of seeing what you are actually doing. Take a simple straight piece of wire. It describes a direction in space. Put this in the path of radiation perpendicular to the direction of propagation. I find it very annoying that this wire can respond to all four Stokes parameters and if you keep rotating the wire, the best you can do is to reduce this number to three. There must be a better way of looking at this polarisation beast, and in fact there is.

THE POINCARE SPHERE

I refer to the representation of polarisation on a sphere invented by the great Poincaré who has been called the last universalist. This is shown in Fig. 4. The linears are represented on the equator of the sphere, the two circulars are at the two poles and the rest of the surface is taken up by elliptical polarisation of all kinds. Longitude represents the major axis and latitude the ellipticity. It is at once clear from the picture that the representation of polarisation is exhaustive, but its elegance and power will become clear as I go on. The important point to remember is that when we represent the major axis by the longitude and the ellipticity by the latitude, we must always double the angles, and it is quite easy to see why one must do this. It is because of the dipole nature of electromagnetic radiation. If you turn a vertical antenna through 180°, you may have changed the phase, but you would have restored the polarisation to the same state as it was before. Therefore 180° in real space must correspond to 360° on the sphere. If we were dealing with the representation of polarisation of electrons we would not have to do this, and if we were representing the polarisation of gravitational radiation we would multiply the angles by four, simply because the polarisation of the gravitational radiation will repeat itself for every 90° of rotation with, of course, a change of phase as before. The greatest beauty of this representation is its symmetry which is illustrated in figure 5 where we try to answer the question posed earlier of the response of an antenna (or analyser in optics) to radiation of a different polarisation. One simply plots the two points on the sphere, no matter where they are, takes half the angle between them and Cos^2 of this angle will be the fraction of the energy received. In other words, with increasing separation of the two points, the response decreases in a sinusoidal fashion from the maximum when the two points are coincident (polarisation matched), to zero when they are diametrically opposite, in other words of opposite or orthogonal polarisation.

The question of phase is very interesting and I shall come to it a little later. The important thing to note is that the 3 Stokes parameters Q, U and V are along Cartesian axes in this sphere and therefore represent different components of polarisation in this space. Their addivity and symmetry become apparent now in spite of the way they were obtained from the electric fields picked up in two perpendicular directions. The symmetry inherent is best appreciated by noting that instead of linear antennas at right-angles to each other we could have had any two antennas of opposite polarisations to start with. The same operations, namely subtracting their intensities and obtaining their complex correlation would also have provided three other axes also at right angles in the sphere and thus three components in this space of the polarisation "vector". Note that two vectors inclined at 90° in this space do not represent orthogonal states of polarisation.

In the discussion so far, there is no representation for so called unpolarised radiation. It is interesting that I took figure 4 from a book on antenna theory, written undoubtedly by two distinguished members of URSI, where they define polarisation as a property of radiation of a single frequency! There is some truth in this as we shall see shortly, but if this were all there was to the story both you and I could have been spared this Tutorial. The trouble is that in the real world we have radiation which is partially polarised and partially coherent with radiation picked up somewhere else. And it is necessary to understand how signals picked up by antennas which respond to these different radiations are correlated, particularly if one is going to use systems like aperture synthesis to produce maps of the radio sky.

I have already mentioned crystallography twice at the beginning of this talk, and I will do it once again. Understanding the behaviour of light when it passes through crystals, which are birefringent, biaxial, optically active and absorbing is one of the most horrendous problems you can think of in crystallography, and in fact is something that was extremely difficult to understand. It turns out that this problem was completely solved by a young man named Pancharatnam who worked at the Institute where I now work and who died at the very young age of 35. He was trying to understand the behaviour of crystals like amethyst and iolite, and his thesis adviser - a very well known scientist himself - had suggested the problem with the remark that its solution might even throw some light on properties of radiation that had not been properly understood before.

PANCHARATNAM'S EXTENSION

Pancharatnam solved this problem, and many others, with the help of the Poincaré sphere by making one important addition to it and proving a number of elegant theorems[5]. The addition was a master stroke, and it was to make the radius of the sphere=I, the first Stokes parameter which corresponds to the total intensity. This is illustrated in Fig. 6, as also the representation of unpolarised radiation, partially polarised radiation and totally polarised radiation. The vector S is called the Stokes vector and its length divided by the radius of the sphere represents the degree of polarisation of the signal. This makes self evident, as you see, the proof of the fact that $\sqrt{Q^2 + U^2 + V^2} \leq$ I, which is something that looks like a big deal in earlier treatments. The new rule for calculating the intensity of any signal picked up by an analyser or antenna which subtends a certain angle with the direction of the Stokes vector is Cos^2 half the angle as before, plus one half of a "zero component" which represents the unpolarised radiation. The value of this component would be truly zero if the radiation were totally polarised, equal to the radius of the sphere for totally unpolarised radiation, and the bit between the tip of the Stokes vector and the surface of the sphere in the case of partially polarised radiation.

The important thing to appreciate here is that any analyser or antenna will always pick up one half of the value of the zero component, and for those, like me, who need a picture to understand unpolarised radiation it is as follows. I started off by saying that polarisation is the time evolution of the electric vector which can only have one orientation at any instant of time. The evolution goes differently for different timescales and the first thing to understand is that for times of the order of the period of the radiation, the evolution has to be one of the three cases shown in Fig. 2. That is, the radiation has to be either linear or circular or in general elliptic. The reason for this is that when the radiation has a certain bandwidth Δf, the rate at which you can receive information is only on a timescale which is 1/Δf and, therefore, the polarisation, the phase and the amplitude have all to remain constant for this timescale.

If Δf is a small fraction of f as is often the case, there will be many many cycles when in fact nothing whatever changes. The meaning of this is as follows. If you look at the electric vector at any instant of time it will have a certain direction which is, of course, perpendicular to the direction of propagation. If you look at its behaviour over several cycles for a time which is short compared to 1/Δf, which is called the coherence time of the radiation, it will be 100 per cent polarised in some particular state which is in general elliptic. Over the period of a coherence time, the polarisation will gradually change to something else in a random fashion. If you look at the radiation for a long time, the Poincaré sphere will be covered in a random walk fashion leaving an average value for the polarisation which will tend to zero as the number of samples we have tends to infinity. In the case of partially polarised radiation, the sphere will be covered in a non-uniform, or biased, fashion leading to a resultant Stokes vector that is non-zero.

It is now easy to visualise, using the rule for angles given before, why an antenna of any polarisation will pick up one half of the available energy in unpolarised radiation, or the zero component, when you integrate over a long time. But there is one more important step, however, to appreciate why oppositely polarised antennas have uncorrelated fluctuations when they are looking at natural or other unpolarised radiation. If you think of the successive states of polarisation that the radiation has in successive coherence times, it is clear that it will sometimes be closer to one antenna, and sometimes closer to the other; and therefore if one of them picks up more radiation, the other must pick up less. And indeed one might expect an anticorrelation between these fluctuations for just this reason. What happens is that the intensity of the radiation is also fluctuating in a random way, and while in each coherence time the Stokes vector will reach all the way to the surface of the sphere, the radius of the sphere itself undergoes oscillations in coherence times and this is such as to precisely decorrelate the signals. It is a bivariate Gaussian distribution if you like such terms. Over a long time we get the radius converging to the mean value and the Stokes vector in the middle tending to zero. We can visualise thus an intimate connection that exists between partial polarisation and the frequency spread (bandwidth) of the radiation.

We have just seen how unpolarised radiation produces uncorrelated fluctuations in all pairs of oppositely polarised antennas. Interestingly, partially polarised radiation can produce totally uncorrelated fluctuations in non-oppositely polarised antennas. And this property can be used to form the basis of an accurate null method for the measurement of very small values of partial polarisation[13].

SOME APPLICATIONS

I just mentioned above an interesting property relating to partial polarisation and the incoherence of signals picked up by non-oppositely polarised antennas. In fact, it can be shown that for any antenna of a given polarisation exposed to radiation of any given polarisation, there is always another antenna with a different polarisation that will pick up a signal uncorrelated with that of the first. And the determination of the polarisation of the second antenna is a trivial geometrical construction in the sphere as shown in Fig. 7, and an excellent example of the power of this method in solving problems in polarisation. This construction is always valid including the limiting cases of unpolarised and fully polarised radiation.

As an example of a problem relating to sources rather than antennas, let there be two partially polarised sources within the beam of the telescope and we wish to know what will be the net polarisation of the combination taken together. We just draw two spheres, one for each of the sources, each with its own Stokes vector which may be pointing in any direction whatever. To know what we would measure if both were combined, we merely add the radii of the spheres to make a new one, and we add the two Stokes vectors vectorially. If they were pointing in opposite directions and were equal in magnitude then it is easy to see that the resultant Stokes vector would be zero. In other cases the resultant Stokes vector will give you both the fractional polarisation and its particular state.

In the foregoing example, I assumed that the two radio sources were incoherent as would be case for real radio sources separated in the sky. But, if you wish to add coherent polarised beams, phase comes into the picture. As everyone is familiar in connection with understanding Faraday Rotation, one thinks of the observed linear as the resultant from summing two coherent circulars of opposite sense, where the changing phase difference between the two opposite circulars results in a change in the orientation of the resultant linear. On the Poincaré sphere, in this particular case, one would represent the two input polarisations as poles, with the resultant lying along the corresponding equator, and going round it as you change the phase between the two inputs. And because of the symmetry of the sphere this will be true whatever the two opposite input polarisations, elliptics in general. If the relative intensities of these two coherent beams were not equal, the resultant will lie on a locus which now shrinks from being a great circle to a small circle centred on and closer to the stronger of the two beams.

As an example of a difficult problem where the Poincaré sphere again lets you see the answer very easily is polychromatic polarisation. I refer to a topic which, to my knowledge, was first discussed in the literature by Pancharatnam, i.e., the situation where the polarisation across a band changes as a function of frequency. The conventional Stokes parameters are inadequate to deal with this situation and have to be replaced with Stokes spectral functions which Pancharatnam introduced. A familiar and simple case in Radio Astronomy is once again Faraday Rotation which can cause an apparent depolarisation due to change in orientation of the linear within the band of reception. Instead of a single Stokes vector from the centre of the sphere, we now have a spread of such vectors and because you are trying to do a vector addition in this polarisation space, it is trivial to see that the answer will be given by a fourier transformation. The amplitude will give you the net fractional polarisation and the phase will give you the state of polarisation of the resultant whatever the plane in the Poincaré sphere on which these vectors are spread out.

On the subject of the phases of polarised radiation, the most remarkable discovery made by Pancharatnam during his investigations was that two beams which are in phase with a third need not be in phase with each other. This is illustrated in figure 8(b), where you see two linears which are in phase with each other. If you take the one on the left, it is in phase with the circular above it, because they will both reach a maximum at the same time and therefore give the greatest contrast when they interfere. But this circular would have to be shifted in phase as shown to the right before it could be considered to be in phase with the linear on the right hand side. By such arguments, Pancharatnam proved that if you took the polarisation of any radiation round a closed path on the Poincaré sphere such as shown in figure 8(a), you will end up with the same polarisation, but it would now have suffered a phase change equal to half the solid angle subtended by the path. We already encountered unwittingly a special simple case of this phenomenon when discussing the rotation of a dipole antenna by 180° (the closed path in this case being the equator) leading to a phase change of 180° (half the solid angle of a hemisphere). Pancharatnam's result obtained in the fifties has now been identified with a phase factor in a quantum mechanical context derived about ten years ago by Michael Berry of Bristol and on which subject hundreds of papers have been written since then[6]. I could go on and on about the Poincaré sphere, but before I stop let me make just one statement about how powerful, or convenient if you will, I have found its use. You could sit down with a globe in front of you, put some chalk marks on it and simply by inspection and without a line of derivation write down the response of an interferometer with arbitrarily polarised antennas to a distribution of arbitrarily polarised radiation[7].

In all of this discussion, I have talked about radiation as if it alone were the culprit, while the antennas used to receive the radiation were perfect and could be represented by single points on the Poincaré sphere. People who actually make polarisation observations know that nothing could be further from the truth. In fact, almost any antenna except a single straight piece of wire far out in empty space has a polarisation response which varies as a function of direction. This has many very interesting aspects, but it has been generally treated more as an engineering problem or nuisance, and much success has been achieved in minimising the consequent complications in the measurement of polarisation in radio astronomy.

THE ORIGIN OF POLARISATION

I would like to turn now to saying something about the origin of polarisation in the radiation from astronomical bodies, which by definition are far away and big in size. They are therefore large aggregates almost all of them with violent internal motions. The radiation from such aggregates should therefore be expected to be randomly polarised as I have described. To have any polarisation at all there must be something to break the symmetry and lead to a preferred direction or sense of rotation. Except in some odd cases (e.g., solid bodies like the moon, where the thermal radio radiation from the limb is polarised due to reasons associated with Brewster's law and thermodynamics), the symmetry breaking agent is almost always the magnetic field which Eugene Parker has called "*the radical element responsible for the continuing thread of cosmic unrest*". The strength of this field whose presence leads to the observed polarisation of the radiation varies over an extraordinary range of about 19 orders of magnitude. In the interstellar medium we have atomic and molecular clouds with fields of the order of microgauss and milligauss respectively. In the radiation belts of Jupiter, which incidentally was the second radio source to be found polarised and which remained the most strongly polarised source for many years, the field strength is of the order of 1 gauss. Magnetised white dwarfs have fields of the order of a million gauss and this figure climbs up to a dizzy 10^{13} gauss around pulsars which are always polarised and where the characteristics of the polarisation have played an important role in providing clues to the emission mechanism. At first sight it seems surprising that fields with such an enormous variation in intensity can all leave a clear signature on the radiation produced in these sources. But I think the reason is simply because we are always dealing with plasma whose particles have an energy such that their motion can be influenced by the ambient field, which is very often the confining agent.

Even so, the earliest of astronomical polarisation measurements had to do with something else that broke the symmetry, and I would like to tell this story as it is historically interesting. As illustrated in figure 9 the scattering of even unpolarised radiation can lead to polarisation depending on the direction from where the radiation is viewed. Daylight is the most familiar terrestrial example of polarisation due to scattering, but its quantitative distribution over the sky in the presence of multiple scattering is an extremely complicated matter. It was solved by Chandrasekhar and Elbert in 1951[8] using the methods he originally derived to understand scattering in the atmospheres of stars, to which my story relates. Because the atmospheres of early type stars are completely ionised there is reason to expect Thomson scattering and the problem Chandrasekhar set himself was to calculate the amount of partial polarisation due to scattering in the atmospheres of such stars. It was in searching for a representation of polarisation which could cope with multiple scattering that he discovered in the papers of Stokes[9], the parameters that are named after him and which we all use regularly. The result of Chandrasekhar's calculations, rightly considered a mathematical tour de force, was a prediction of polarisation of approximately 11 per cent from the limb of early type stars, with a circumferential distribution because of the symmetry of the star (figure 10a).

The average polarisation of such a star would, of course, be zero, but it occurred to him that if one could observe the partial eclipse of an early type star by a late type one in a binary system (figure 10b), there should be times when some polarisation should be measurable. He suggested this to his colleague Hiltner who undertook to make these measurements together with Hall, and as Chandrasekhar himself has described in a recent article, "*the first binary star they observed did indeed show a polarisation during the last phases of eclipse; but contrary to prediction the degree of polarisation did not change with phase and it persisted even after the eclipse. Hiltner and Hall had discovered interstellar polarisation instead!*[10]".

An explanation of the observed polarisation in terms of preferential scattering and absorption by elongated dust particles in the interstellar medium, whose dynamics are governed by a magnetic field was subsequently provided by Davis and Greenstein[11]. The implication was that there was indeed a galactic magnetic field, and the uniformity of the polarisation over large areas of the sky found by Hiltner and Hall further indicated that the field tended to have a reasonably large scale structure. Thus, an observation to look for the effect of scattering in the atmospheres of early type stars resulted in the discovery of the galactic magnetic field.

THE POLARISATION OF RADIO SOURCES

As the galactic background radio nonthermal radiation was hypothesised to come from cosmic ray electrons gyrating in the galactic magnetic field, one should expect the radiation to be polarised. Given a reasonably uniform field as the optical observations had suggested, and the theoretical expectation of up to 70 per cent polarisation for synchrotron radiation, there should be no difficulty whatsoever in detecting this polarisation. The large number of nonthermal radio sources that had been discovered both within the galaxy and outside it like supernova remnants and radio galaxies were also believed to emit by the same mechanism, and they too should therefore be polarised. But simple minded attempts to detect this polarisation were totally unsuccessful. So began a struggle in the late fifties to detect this elusive polarisation and it took about five to six years to really understand what was going on and why in fact it had been so difficult to detect any polarisation. It was only in 1962 that Westerhout and colleagues succeeded in detecting polarisation in the galactic background radiation, at a wavelength of 75 cms[12].

The pioneers in the exercise to find polarisation in discrete radio sources were Connie Mayer and his colleagues working at the Naval Research Laboratory, Washington, DC. They had already pioneered radio observations at very short wavelengths, in the range 1-3 cms, which are commonplace today but which at that time were considered almost crazy. In fact, one very distinguished radio astronomer when visiting the Naval Research Laboratory asked them why they were wasting their time looking at frequencies where the radiation should obviously be very weak or impossible to detect, and he wasn't talking of polarisation either. In the event, the NRL group did discover polarisation, first in the Crab Nebula and later in Cygnus, the extragalactic source which in many ways is a prototype, in Centaurus - a famous southern galaxy and also Cassiopeia A, the strongest source in the sky and a supernova remnant. The amounts they measured were in the range of 1-10 per cent of linear polarisation, whereas very careful attempts at longer wavelengths around 21 cms on these same sources had indicated much lower values or limits. A highly disordered magnetic field could be one possible explanation for the low percentages of average polarisation, but the fact that at short wavelengths one measured substantially higher amounts was clearly indicative of something that was frequency dependent. We go back once again to the effect discovered by Faraday and the figure 11 illustrates what happens to polarised radiation as it passes through a region containing both magnetic field and thermal electrons gyrating in them. If the Faraday rotating medium is external to the region of generation of radiation, then the polarisation gets turned around by different amounts for different frequencies, and observations over a given bandwidth will indicate an apparent reduction in the percentage of polarisation because of the spread of the vectors within the band. But this is not really depolarisation in the sense I discussed at length, as it is possible both in a thought experiment, and with the right kind of apparatus to rotate these vectors back by the same amount to align them all to give a high percentage of polarisation. The information rate in the band remains the same as before. On the other hand, if the rotating medium were actually mixed with the region of generation, than we tend to get true depolarisation as illustrated in the lower part of figure 11. And nothing can be done to recover the polarisation. In the first two cases, i.e., a disordered field, and that of Faraday rotation external to the medium, observations with sufficient resolution both in angle as well as in frequency should recover the full polarisation. It thus became clear in the early sixties that future progress would have to await instruments which had high sensitivity and high resolution both angular and spectral. All this has happened now and in the last part of my talk I shall discuss two examples which show precisely the effects that I have discussed and how beautifully they have been sorted out now.

The apparent lack of detectable polarisation at decimeter wavelengths led to a considerable refinement of techniques of polarimetry. Using a sensitive interferometric null method, it was possible to show that the integrated polarisation from Cassiopeia A at 21 cm was less than a quarter per cent[13]. But observations by Mayer and Hollinger in 1968 at a wavelength of 1.5 cms and with a beamwidth of 1.7 minutes of arc revealed a surprising result[14]. The source was polarised in a beautifully symmetrical way with the electric vector circumferential and the polarisation almost zero at the centre of the source. The degree of polarisation was about 4.5 per cent around the ring of polarised radiation and the remarkable symmetry of its distribution explained the failure to observe any polarisation using lower resolution as in the longer wavelength measurements I just mentioned. It is a tribute to the perception of these early investigators that they recognised that the unexpected result of a radial component of magnetic field in the source,

> "*suggests that the magnetic field has been carried out with the expansion of the supernova envelope, and we observe polarised radiation associated with a component which has been stretched out in the radial direction during the expansion of the shell. One possibility which would seem to agree with the observations is a disordered magnetic field which has formed a radial component during the expansion*

but which remains disordered when viewed along radius vectors".

RECENT ADVANCES

The astrophysical interpretation of Mayer and Hollinger based on a radio map with a mere 16 beam areas within the source has been beautifully vindicated by the remarkable VLA† images that were shown yesterday by Dr. Ekers in his General Lecture. Painstaking work spread over several years by Rick Perley and his colleagues with the largest and most powerful synthesis radio telescope in the world today went in to make that image with sixteen million picture points in it, representing the most detailed radio image yet constructed. Among numerous other details it reveals conical extensions of the circular outline of the supernova remnant. These have been interpreted as more slowly expanding material from deeper within the star breaking through the shell, which has decelerated sufficiently from sweeping up surrounding interstellar material. A similar picture of the linearly polarised emission shows the overall radial field referred to earlier but also local departures showing tangential and turbulent fields just at the conical extensions. Such pictures show changes in their details over time-spans as short as a year and make it possible to recognise processes that shape such supernova remnants; they lend strong support to current theories that the fields are built up through turbulent action near the expanding boundaries of the shell[15].

I turn next to Cygnus A, the second strongest source in the sky at low frequencies and whose distance determination by Baade and Minkowski in the early fifties was the first decisive indication of the potential of radio astronomy to probe large volumes of the observable universe. Cygnus A is the prototype

---

† *It is a part of the National Radio Astronomy Observatory of the U.S.A., operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation*

of the double-lobed radio source with an optical galaxy in the middle feeding the lobes by a jet. The NRL measurements of 20 years ago had revealed that the lobes were polarised at different angles and that the Faraday rotations in their directions were too large to be caused by the ISM in our own Galaxy and thus had to be associated with the source itself[14]. Perley and his colleagues have made observations over several years with the VLA and combined them to produce a number of extraordinary images with sub-arc second resolution. These images reveal incredibly fine details, including filamentary structure in the two lobes[16].

As the mapping of the field direction requires the determination of the intrinsic polarisation angles, this involves correctly allowing for the rotation measures, which, as I said before, were known to be large and the cause of confusion and ambiguity in interpreting earlier measurements over the years. This problem has finally been sorted out and images produced displaying enormous rotation measures which vary from -4000 to +3000 rad/M^2 over the face of the source[17]. The achievement in this exercise can be appreciated by noting that the gradients in the rotation measures in both lobes commonly exceed 300 rad/M^2 <u>per arc second</u> and that this number is typical of the <u>maximum</u> RM encountered due to passage even through the whole plane of our Galaxy.

Most remarkably, there is no evidence for internal depolarisation in spite of these high RM values. In fact, there are regions where the linear polarisation actually reaches 70 per cent, the expected maximum for synchrotron radiation. The operative Faraday screen must therefore be <u>outside</u> and in <u>front</u> of the radiating region. The implications of this are many and important and have been discussed in many papers in the literature[18]. The only point I wish to make here in conclusion is that the effect discovered by Michael

Faraday, a thread running through all of this talk, is now providing a third dimension to studies of distant objects in the universe.

ACKNOWLEDGEMENTS

I thank several colleagues for a critical reading of the manuscript, suggestions for improvement and help with the illustrations.

References

1. *The Universe of Light*, Bragg, W., Dover Publications Inc., New York, reprint (1959).
2. *Experimental Researches in Electricity - Nineteenth Series,* Faraday, M., Philosophical Transactions of the Royal Society of London, Part 1, P1 (MDCCCXLVI).
3. *Electric Waves - being researches on the propagation of electric action with finite velocity through space,* Hertz H., Tr. by D.E. Jones, Macmillan, 1893 and Dover, (1962).
4. *Collected physical papers,* Bose, J.C., London, Longmans, Green & Co. (1927).
5. *Collected Works of S. Pancharatnam,* Oxford Uni. Press (1975).
6. *The interference of polarized light as an early example of Berry's Phase,* Ramaseshan, S. and Nityananda, R., Curr. Sci., **55**, 1225 (1986).
7. *On measurement of polarization distributions over Radio Sources,* Morris, D., Radhakrishnan V. and Seilstad, G.A., Astrophy. J., **139**, 551 (1964).
8. *Polarisation of the sunlit sky,* Chandrasekhar, S. and Elbert, D., Nature **167**, 51 (1951).
9. *Mathematical and Physical papers,* Stokes, G. G., Cambridge, CUP, **3**, (1904).
10. *Radiative transfer - a personal account,* Chandrasekhar, S., Proc. Symp. on Principle of invariance and its applications, Byurakan, Oct. 26-30, 1981, Yerevan, Publ. House of the Armenian Acad. of Sciences, 521 (1989).
11. *The polarization of starlight by aligned dust grains,* Davis, L.Jr., and Greenstein, J.L., Astrophy. J., **114**, 206, (1951).
12. *Polarization of the galactic 75-cm radiation,* Westerhout, G., Seeger, C.L., Brouw, W.N. and Tinbergen, J.A., Bull. Astron. Inst. Neth., **16**, 187, (1962).
13. *Tests for linear polarisation in the 1390 Mc/s radiation from six intense radio sources,* Morris, D. and Radhakrishnan, V., Astrophys. J., **137**, 147 (1963).

14. *Polarised brightness distribution over Cassiopeia A, the Crab nebula, and Cygnus A at 1.55-cm wavelength,* Mayer, C.H. and Hollinger, J.P., Astrophys. J., **151**, 53 (1968).
15. *Physical process which shapes Cassiopeia A,* Braun, R., Gull, S.F. and Perley, R.A., Nature **327**, 395 (1987).
16. *The Jet and filaments in Cygnus A,* Perley, R.A., Dreher, J.W. and Cowan, J.J., Astrophys. J., **285**, L35 (1984).
17. *The Faraday rotation of Cygnus A: Magnetic fields in cluster gas,* Dreher, J.W., Carilli, C.L. and Perley, R.A., Astrophy. J., **316** 611 (1987).
18. *Discovery of the bow shock of Cygnus A,* Carilli, C.L., Perley, R.A. and Dreher, J.H., Astrophys. J., **334**, L73 (1988)

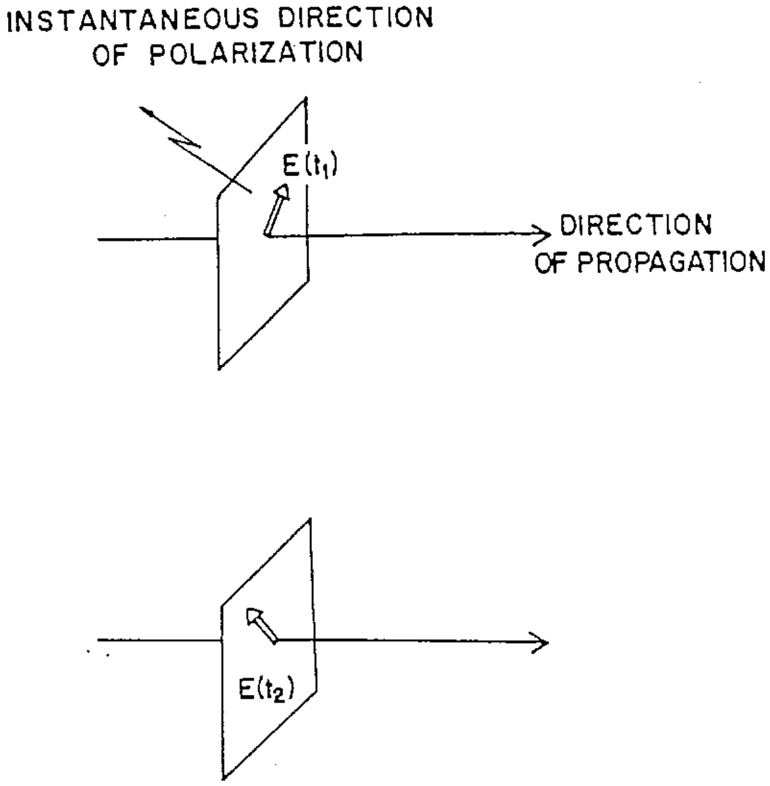

Fig.1: The electric field as a function of time.

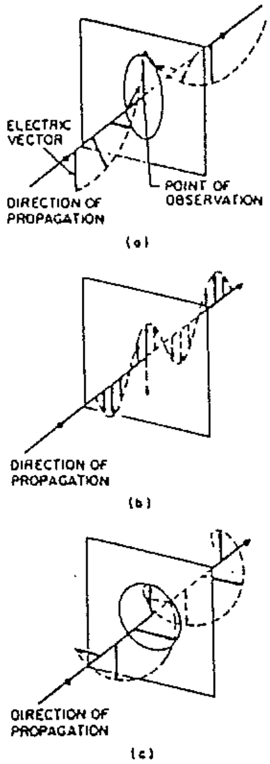

Fig.2: Diagrammatic illustration of waves of various polarisation. (a) Elliptical polarisation. (b) Linear polarisation. (c) Circular polarisation (right-hand).

$$I = <(E_x)^2> + <(E_y)^2>,$$

$$Q = <(E_x)^2> - <(E_y)^2>,$$

$$U = 2<E_x E_y> \cos\delta,$$

$$V = 2<E_x E_y> \sin\delta.$$

Fig. 3: STOKES PARAMETERS. The subscripts give the directions along which the components of the electric vector are taken and δ is the difference in phase between these components.

Fig.3: The Stokes parameters.

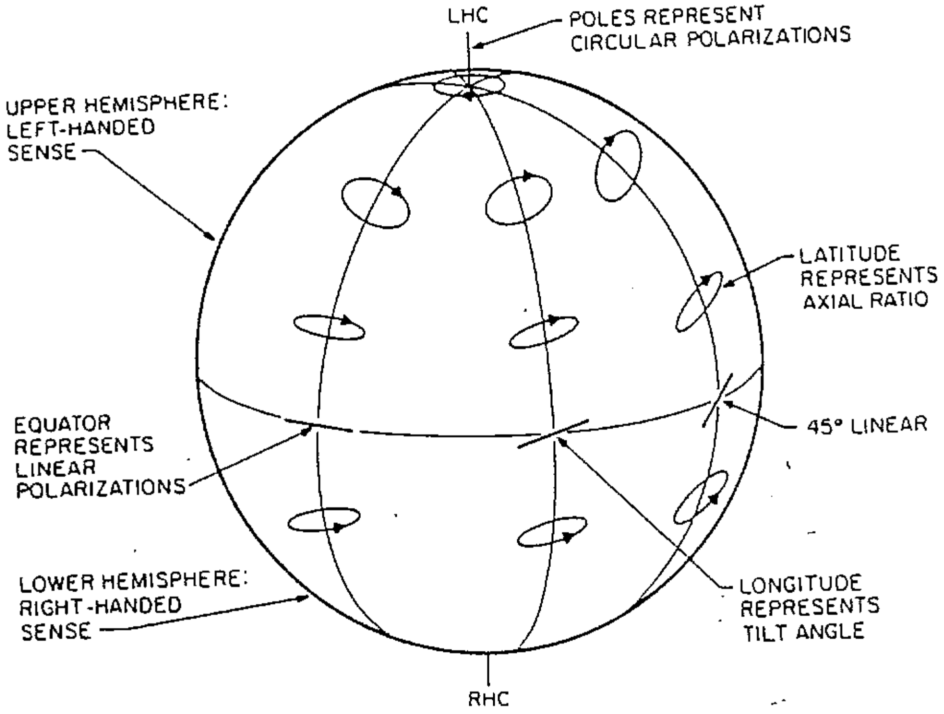

Fig.4: Polarisation states on the Poincaré sphere.

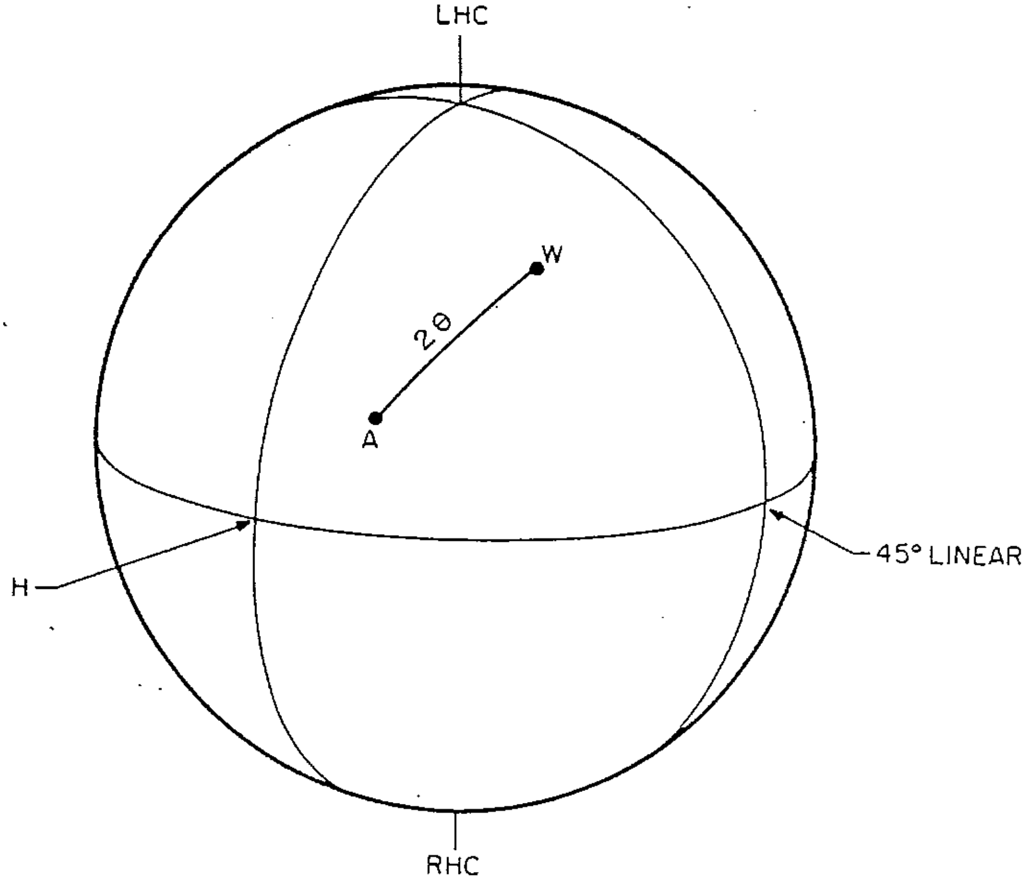

Fig.5: Receiving polarisation of an antenna (analyser) A and polarisation of an incident wave W. The fraction of energy received is $Cos^2\Theta$.

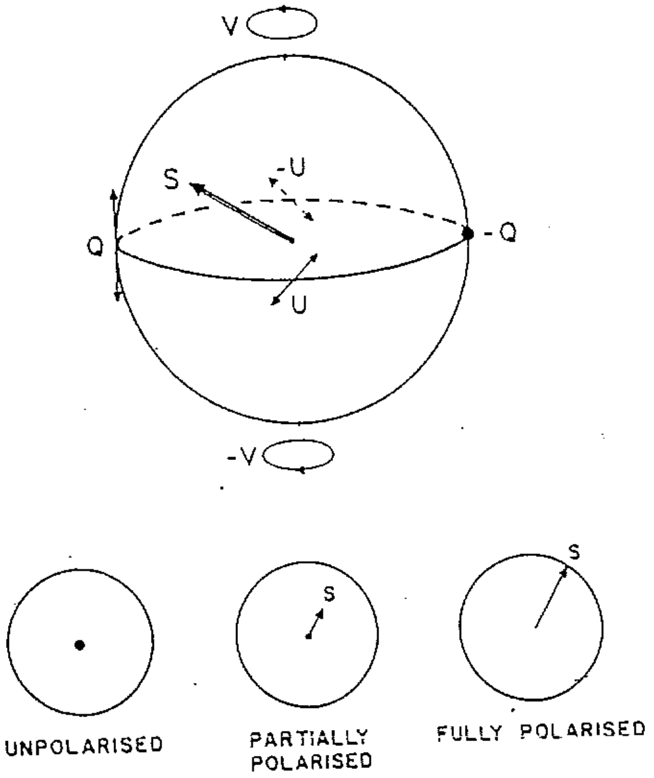

Fig.6: (a) The representation of partial polarisation through Pancharatnam's extension of Poincaré sphere. The radius of the sphere=I, the first Stokes parameter. The vector S is called the Stokes vector, and its length S=$\sqrt{Q^2+U^2+V^2}$. (b) The implied zero vector is indicated here by the dot at the centre and has a value = I-S.

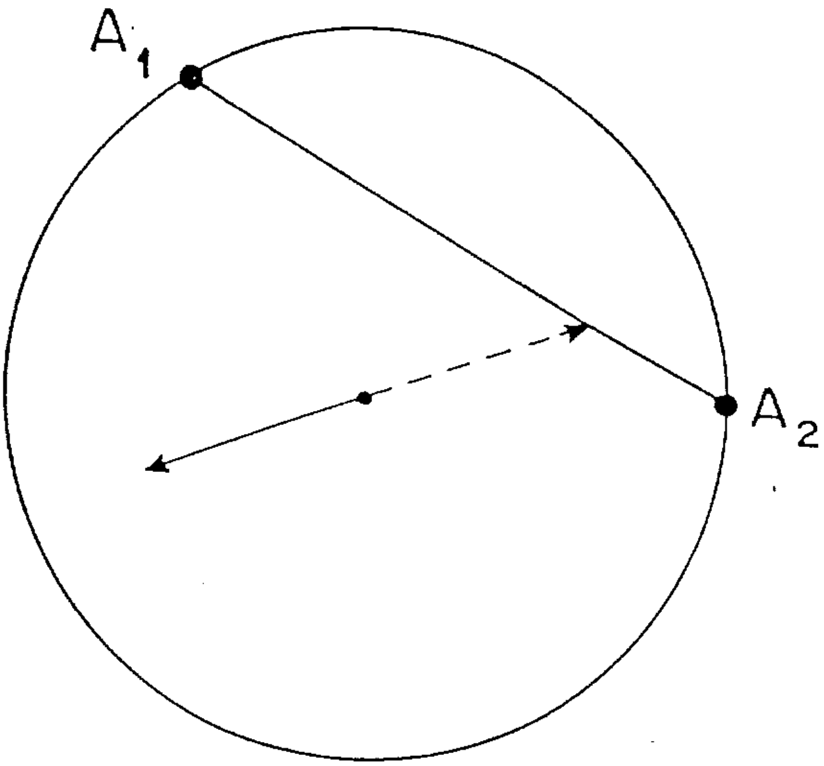

Fig.7: Resolving radiation into incoherent components. Let A_1 be any point on the sphere representing the polarisation of antenna one, and the Stokes vector the representation of the radiation. The figure shows the great circle through A whose plane contains the Stokes Vector. A_2 is the intersection of the line joining A_1 and the tip of the reflected Stokes vector with the great circle, and gives the polarisation of antenna two whose signals will be uncorrelated with those of antenna A_1. This construction is valid whatever the degree of polarisation.

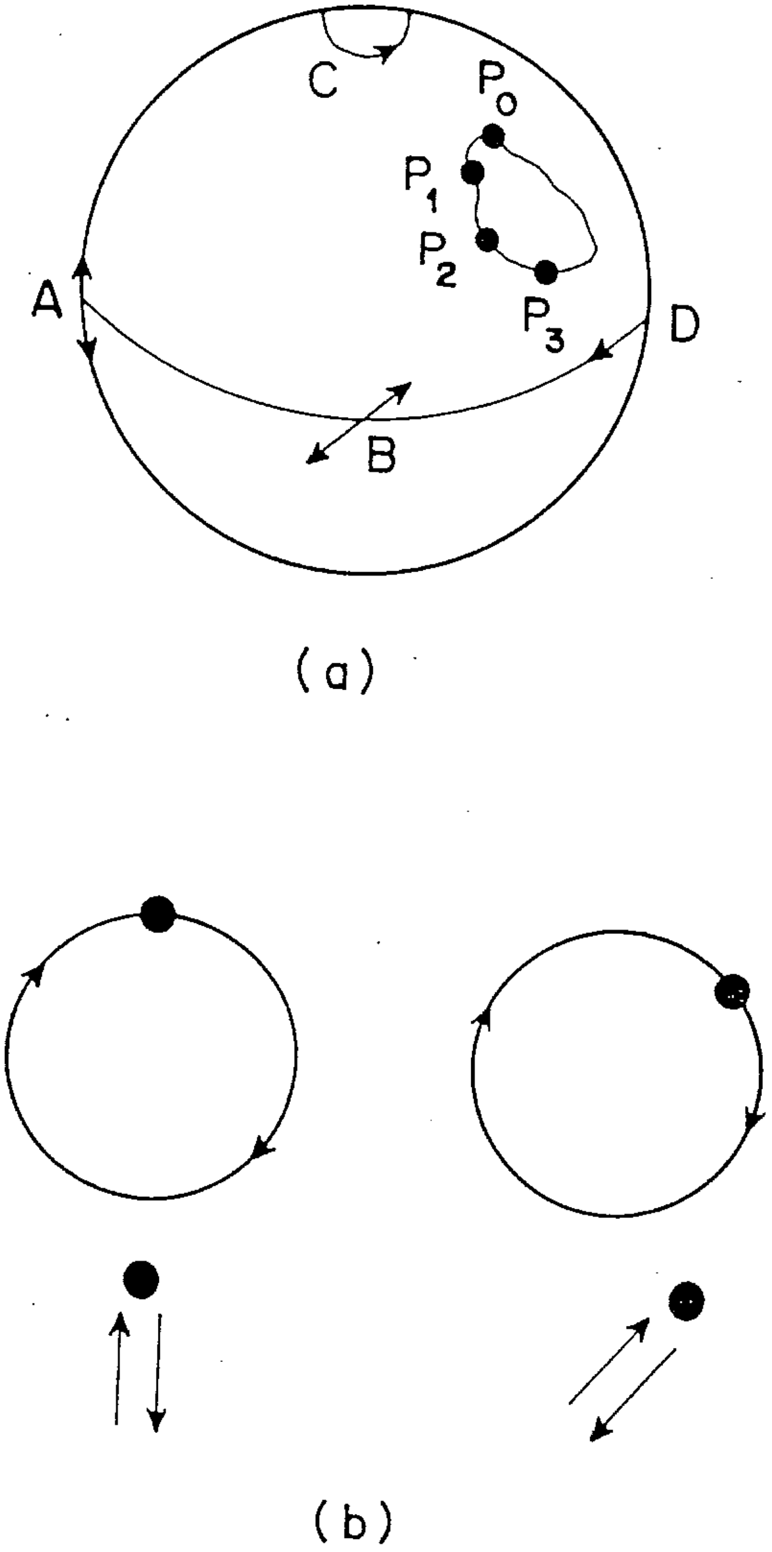

Fig.8: (a) The Poincaré sphere representation of the states of polarisation. C is a circular state, represented at the pole, while A, B and D represent linear vibrations respectively oriented vertically, at 45°, and horizontally. (b) The lower half of the figure shows two linear states inclined at 45°. The filled circles indicate a situation when the two linear vibrations may be said to be in phase. The result of analysing these two states with a circular analyser is shown just above. The phase difference between the circulars is now 45°.

(a) If radiation polarised initially in the state P_0 is passed through analysers in states P_1, P_2, P_3 and back to P_0, it would have suffered a phase change equal to half the solid angle subtended by the path P_0, P_1, P_2, P_3, P_0.

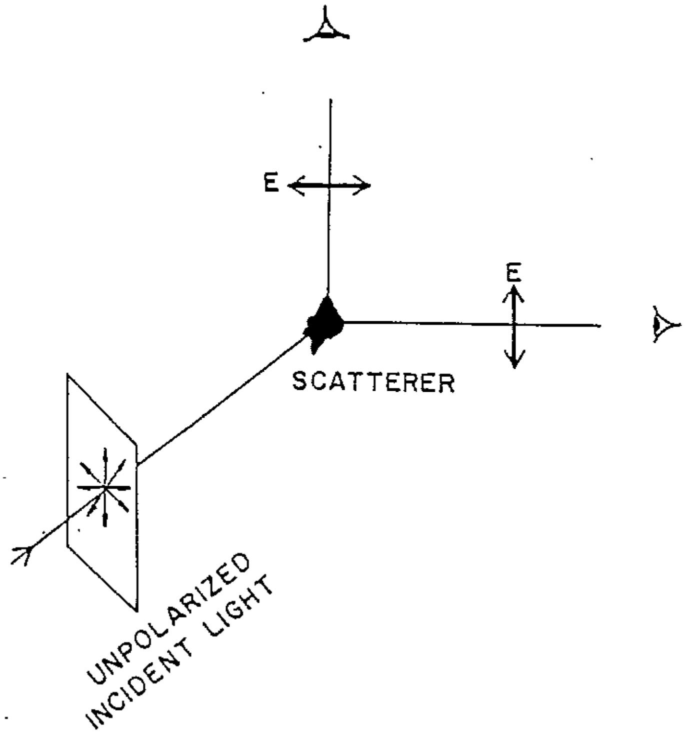

Fig.9: The polarisation of scattered radiation. When viewed at right angles to the incident radiation the scattered fraction will be fully linearly polarised with the electric vector perpendicular to the two directions.

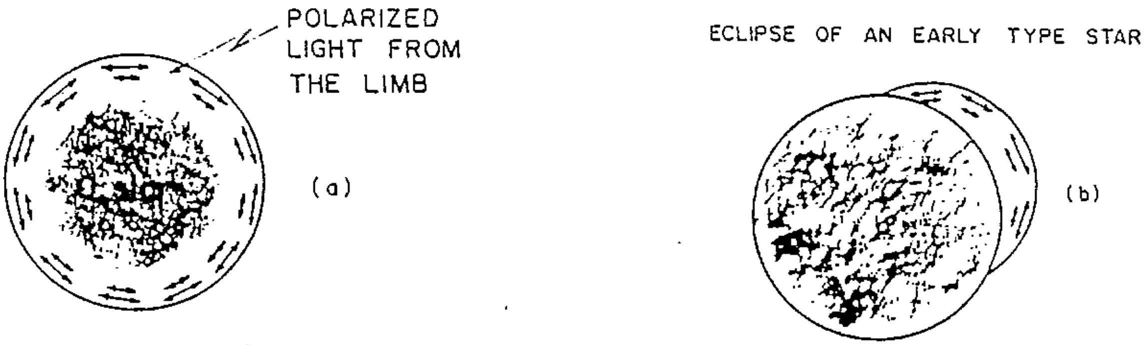

Fig.10: Chandrasekhar's prediction of the limb polarisation of an early type star. (a) The average polarisation will be zero for an unresolved star. (b) When partially eclipsed by a late type star, the average polarisation will be nonzero at ingress and egress.

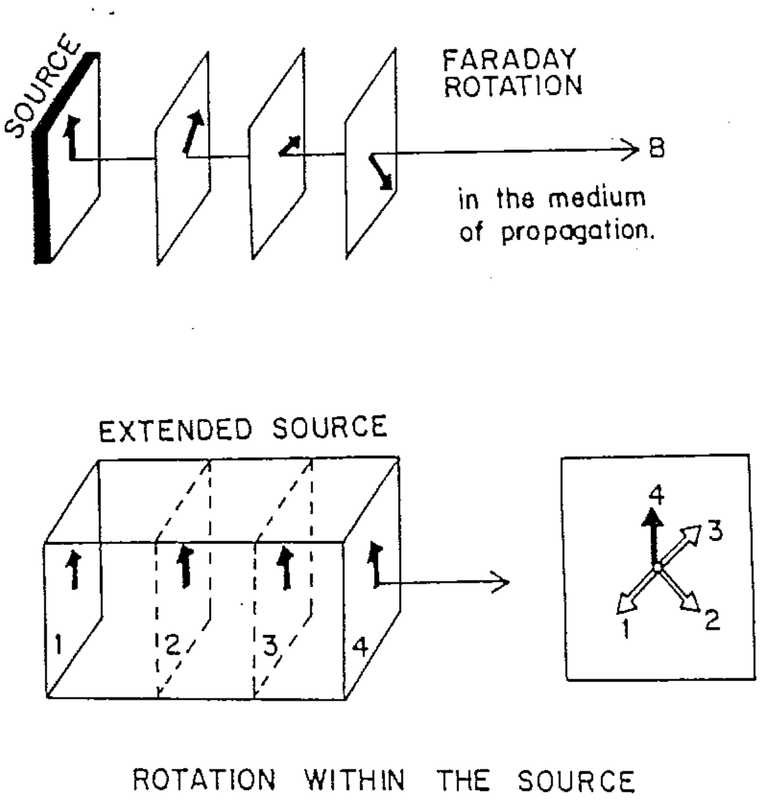

Fig.11: Faraday rotation occurring in a medium outside the source turns the plane of polarisation through angles proportional to λ^2 but does not affect the true degree of polarisation. Rotation within the emitting region leads however to the incoherent addition of Stokes vectors in different orientations and thus to true depolarisation.