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Polarization and its message in astronomy*

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'Light brings us the news of the Universe. Coming to us from the Sun and the stars it tells us of their existence, their positions, their movements, their constitutions and many other matters of interest.'

So said William Bragg over half a century ago. The news of the Universe today is brought to us by electromagnetic radiation spanning an enormous range from kilometre-long radio waves to gamma-rays of TeV energies and more. And it is the *strength* of the radiation at different wavelengths from different directions in the sky that has told us most of what we know about what is out there. But electromagnetic waves are transverse in nature, and hence the *instantaneous* electric (or magnetic) field must have some particular orientation perpendicular to the direction of propagation of the wave. This preferred direction and its behaviour as a function of time form yet another characteristic of the radiation. If at one instant the field is at a particular angle, then at a later time it is likely to be different. In natural radiation, the orientation of the vector displays a systematic variation over the period of the wave, and a random change to a new pattern over a longer time-scale, that of the inverse bandwidth. An understanding of this aspect of electromagnetic radiation began with an observation in 1808 by Malus, who happened to be looking through a piece of Iceland spar at the setting Sun reflected in the windows of the Luxembourg Palace in Paris. The relative intensity of the two images varied as he rotated the crystal, and being a Frenchman I imagine he exclaimed 'Voilà polarization!'. In any case, that was the name he gave the phenomenon.

My first awareness of this property, as of many other things that later earned me a living, was gained from the *Radio Amateurs' Handbook*. It emphatically recommended that the receiving antenna be oriented in the same way as the transmitting one for the message to be received well. It followed from this and more in the Good Book, that two different transmitters and receivers with their antennae appropriately oriented could use the same wavelength or channel without interfering with each other. I used to wonder why this wasn't standard practice to double the use of the densely crowded radio bands until I learnt about the imperfections of antennae, and particularly the strange things that can happen to the polarization of a wave as it is bounced around by objects in its path. Trying to obtain a null on a short-wave station by orienting a hand-held radio receiver inside a building can be an instructive experience.

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My intention, in this lecture, is to give you a personal view of events as I saw them in the development of astronomical polarization studies over the years. Rather than attempting to be comprehensive I have chosen to concentrate on just a few particular examples to illustrate what we have learnt from such studies. And in this choice I have leaned naturally towards those things with which I was familiar.

The most intense astronomical radiation that we receive on earth (about a kW per square metre) is the sunlight we are bathed in all day, at least in some countries. Barring a very feeble amount emanating from sunspot regions, and confined to very narrow frequency intervals, all of this visible radiation is randomly polarized. The meaning of this is that the field vectors have no preferred orientation, or sense of rotation, when averaged over long periods. Minnaert devotes less than 1% of his classic book *Light and Colour in the Open Air* to discussing polarization phenomena associated with the light we live in. And all the cases of polarization that he does discuss, whether they be the appearance of scratches on the window panes of railway compartments, haloes, rainbows or just skylight, refer to the modification of the symmetry of the incident radiation by the geometry of the scattering process involved. Scattered radiation will have a preferred orientation for the vector depending on the direction in which it is scattered. Such radiation is said to be *linearly* polarized. Rainbows are polarized up to 95% but you would never know unless you were told or were as passionate and perceptive an investigator of what we see around us as Minnaert was.

The polarization of skylight is a more widely appreciated phenomenon, particularly since the invention of Polaroid and its incorporation into spectacles to ward off glare. Bees apparently have no problem in detecting this polarization, even without spectacles, and they put this ability to very good use. By performing a complicated dance they convey to other workers in the hive information as to which direction to fly in order to find plentiful sources of nectar. The figure drawn by a colleague of mine purports to depict what might be taking place in a typical beehive. For those not familiar with the jargon, Q and U are polarization symbols whose ratio gives the angle of the preferred direction.

The only other practical application of the polarization of skylight that I have heard of was by the ancient Viking mariners, who apparently made it a navigational aid. They used some form of natural birefringent crystal as a polarization analyser to determine the position of the Sun when it is not directly visible. And I have read a Swedish story of a young Viking who won the hand of his chieftain's daughter by challenging that he could do this without the aid of the traditional *sunstone* kept in the chief's custody, and proving that he could.

This has to do with the little-known but definite ability of the unaided human eye to detect linear polarization in light. All of us here can do this, but you may need a little practice staring through a sheet of Polaroid at a bright background and learning to recognize a fleeting yellow and blue form. It looks like a yellow bug with blue wings, it is called Haidinger's brush, and it is formed in the eye. With more practice you can discern this form in skylight and determine the direction of the Sun even if it is clouded over. But in the present-day social climate you are unlikely to win the kind of prize that

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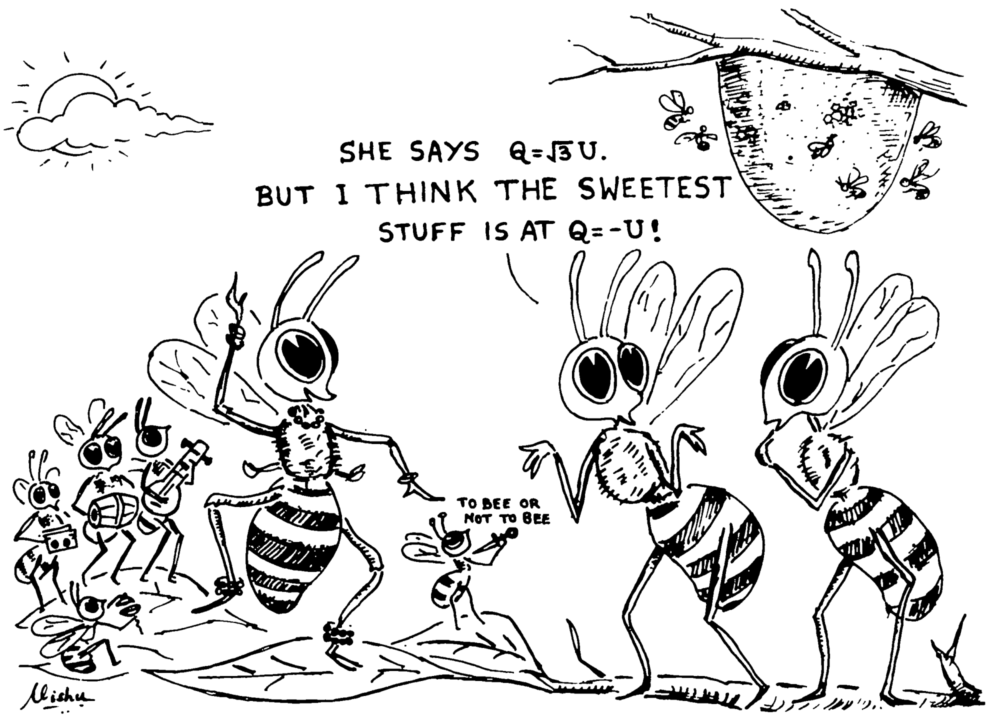

the young Viking did. One wonders incidentally if the presently marginal human faculty also owes its origin to the *existence* of polarization in skylight, and if it perhaps served a function in the hunting or food-gathering habits of an earlier stage in our evolution.

Returning to astronomy, almost all the radiation from celestial sources at wavelengths shorter than a centimetre or so is also of thermal origin. The electrons or atoms or molecules responsible describe chaotic motions and their radiation is randomly polarized. Starlight was found to be weakly polarized by Hiltner in the middle forties but this was subsequently understood to be also a propagation effect. It was identified as due to scattering by elongated particles of interstellar dust subjected to an alignment force, presumably a galactic magnetic field. If, now, there were a radiation mechanism that reflected the strength and direction of this hypothetical magnetic field, such radiation should be *intrinsically* polarized. The extra information the wave would carry is the signature of the emission mechanism and the orientation on the sky of the magnetic field. Remarkably, such a candidate appeared on the scene just around this time, but from the new and emerging field of radio astronomy.

The cosmic radio radiation discovered by Jansky in 1933, first mapped by Reber in 1944, and studied intensively by many in the post-war years, clearly had a non-thermal component from its spectrum, but its origin was at first obscure. Alfvén and Herlofson suggested in 1950 that such radiation could be produced by relativistic electrons gyrating in a magnetic field – the synchrotron mechanism. Very soon thereafter, Kiepenheuer suggested that it was cosmic-ray electrons trapped in the galactic magnetic field that produced the non-thermal halo component of the galactic radio emission. Because the acceleration of the particles would be perpendicular to the

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magnetic field, the radiation should be linearly polarized in the same direction. The detection of polarization in this radiation would provide the strongest support for the proposed synchrotron mechanism of cosmic radio emission, and Razin in the Soviet Union, where the theory had received its greatest development by Ginzburg and others, did make an attempt which indicated a positive result. The observational difficulties were considerable, however, and subsequent attempts by others to repeat these pioneering Soviet efforts unfortunately failed to confirm Razin's results.

Apart from the diffuse halo component, several so-called discrete sources of radio emission had also been discovered. John Bolton in 1949 made the first ever identification of such a discrete radio source, Taurus A, with an optical object. It was the Crab nebula, the visible remnant of the famous supernova of 1054 observed and recorded by the Chinese. The optical radiation from this nebula had already been noted to contain a diffuse component whose spectrum was featureless and whose origin was unknown. Shklovsky, the great Russian astrophysicist, advanced the bold hypothesis that both the radio and diffuse optical emission were due to the synchrotron mechanism. If this were so then, as pointed out independently by both Gordon and Ginzburg in the Soviet Union in 1954, the optical radiation should be polarized. And in the same year this was detected by Dombrovsky and by Vashakidze, also from the Soviet Union. Subsequent work by Oort and Walraven beautifully confirmed these early findings, and provided us with the first map of the magnetic field inside a distant astrophysical object.

Very soon thereafter, two more radio sources were identified with extragalactic nebulae, or galaxies as we would call them now. One of these was Virgo A, identified with the peculiar galaxy NGC 4486, better known as M87, in whose central and brightest region Baade and Minkowski had found a striking jet-like feature at optical wavelengths. Its spectrum showed no lines either, and once again Shklovsky suggested that, as in the case of the Crab nebula, the optical emission from the jet was due to synchrotron radiation from relativistic electrons. One should therefore expect the jet emission to be polarized, and this was shown to be indeed so by Oort and Walraven, and by Baade, both in 1956. Thus, the most crucial evidence in support of the existence of the synchrotron mechanism in both galactic and extragalactic radio sources was the detection of its *polarization*. But it was extraordinary that the only two known polarized emitters in the sky were in the optical, although they owed their detection to their associated radio properties. The implications of this took quite some time to be appreciated, and I will return to this point a little further on.

The outstanding pioneers in the search for polarization in radio sources were Cornell Mayer and his group at the Naval Research Laboratory (NRL) in Washington, D.C. They found the first one in 1957, and it was none other than the Crab nebula, which has continued over the decades to hold its place as the most remarkable single object in the sky. Unlike the extragalactic non-thermal sources, its spectrum is relatively flat and the flux does not fall off as fast with increasing frequency. The NRL group had pioneered radio astronomical observations at very short wavelengths, and they showed that at $\lambda \sim 3$ cm the radiation from the Crab nebula was substantially polarized (8 per cent), at a position angle close to the average

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optical direction. But from then on, for the next five whole years, an incredible situation persisted. Hundreds of radio sources, both galactic and extragalactic, had been discovered, the spectra of most of which clearly indicated that they were non-thermal, and in all probability synchrotron radiators. But not one of them was detectably polarized, excluding, of course, the always-extraordinary Crab nebula.

The longest wavelength at which polarization in this object had been measured was around 10 cm with a value of 3–4%. Some attempts at 20-cm wavelength had only placed a limit of around 1%, but there seemed good reason to doubt that the instruments used could reach such a limit with confidence. Convinced that all synchrotron sources must show polarization, and that an improvement in measurement techniques should lead to success, my colleagues and I made the most strenuous efforts at the Caltech Observatory, where I happened to be working at the time. If I might digress a little I would like to describe some incidental aspects of this exercise. I for one suddenly discovered that my mainstay, the *Radio Amateur's Bible*, could not see me safely through this lot, and it appeared unavoidable that I should learn about those strange things called Stokes parameters. The place to learn about them (in those days) was of course Chandrasekhar's classic treatise on Radiative Transfer, where the mathematics of how to deal with it all was laid out in detail. This was fine if you were one of those who loved equations. Also if you didn't mind that the simplest antenna – a single straight piece of wire – could respond to all four Stokes parameters, although they were supposed to represent different aspects of the radiation! Worse, there was no way in which you could orient the wire (or rotate your coordinate system) to get it to respond to *less* than three of the four Stokes parameters. I needed another way, preferably pictorial, to look at this difficult problem, and see the answer, so to speak. Fortunately, it turned out that there was one.

It is described in a series of papers on the generalized theory of interference which form part of the doctoral work of Pancharatnam, a former student of the Institute where I now work. The papers I refer to are in his collected works, published by the Oxford University Press some years after his premature death in 1969 while he was still a Research Fellow of St Catherine's College. To deal with the complex polarization phenomena encountered in crystals involving double refraction, absorption, optical rotation, and partial coherence, he used and extended the geometric representation of polarization states on a sphere due to none other than Poincaré. Elegance and simplicity characterized his approach and his theorems and methods provide a powerful way of dealing, not only with radiation in different states of polarization, but also with antennae (which are merely analysers) and interferometers, and their responses to arbitrary states of incident radiation. Speaking for myself, not only did these methods make it almost trivial to understand what would happen in even a complicated situation, but they revealed a certain beauty and aroused an enduring fascination for the subject of polarization in general.

As an example of the power of this method and the insight it provides, one of Pancharatnam's surprising results may be mentioned. He showed that two beams of polarized radiation which are in phase with a third beam need *not* be in phase with each other! This led him to conclude that a phase change

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must result from describing a closed curve on the Poincaré sphere equal to half the solid angle subtended by the curve at the centre. This result, derived in the fifties, has now been identified with a phase factor derived a decade ago in a quantum mechanical context by Michael Berry of Bristol. (If I may be permitted an aside, the very large number of publications sparked off by Berry's work prompted someone to call it the *phase that launched a thousand scripts*.)

Returning to antennae, the immediate result of our efforts was the development of an interferometric null technique which provided an order of magnitude improvement, and we were able to measure with confidence the polarization of the Crab nebula at $\lambda \sim 20$ cm as $1{\cdot}5 \pm 0{\cdot}2\%$. But what was staggering was that the three other strongest non-thermal sources in the sky – Virgo A, Cas A and Cygnus A – were polarized *less* than a third, a fourth and a *fifth* of a per cent respectively! (The theoretical maximum, under normal conditions, expected from synchrotron radiation is around 70%.) I cannot forget the major mystery these extraordinary low limits posed at the time, particularly considering that the optical counterpart of Virgo A had been found to be polarized as described earlier. I remember trying to get five minutes time at the 1961 IAU General Assembly in Berkeley to communicate our mostly negative, but nevertheless mystifying observations just made. However, the radio astronomers there (as many to this day!), were more concerned with heated arguments about number counts versus flux density and such issues. Looking for radio polarization was clearly a waste of time they felt, as had been established by earlier attempts! But, in fact, things were just about to take off.

The breakthrough came the next year, in 1962, when, on the one hand, Mayer *et al.* found that two important extragalactic sources, Cygnus A and Centaurus A, were polarized several per cent at $\lambda \sim 3$ cm, and on the other hand Westerhout *et al.* in Holland detected polarization in the galactic background radiation at $\lambda \sim 75$ cm, which could not be attributed to spurious effects. The spell had been broken, and within weeks the bandwagon was rolling. A flood of reports poured in claiming practically every direction in the Galaxy and every strong non-thermal source to be polarized, whether or not the particular telescope used was capable of such a measurement and the observer capable of telling one Stokes parameter from another. By the time of the next IAU General Assembly at Hamburg in 1964 the measurement of polarization in radio sources had become an industry. While many were busy adding to the list of sources in which some polarization could be detected, there were also a few trying to understand the implications of the observed low values. In any event, when the dust finally settled, the several reasons for the failure of our and other previous attempts appeared obvious in retrospect.

Firstly, in the design of radio telescopes and particularly feeds for them, little or no thought had been given to their ability to measure polarization, and this resulted in large instrumental effects. Secondly, the systematic or random changes in the direction of the magnetic field within a radiating region could drastically reduce the net polarization when the source was unresolved and contributions from its different parts were averaged together, as in our measurements of the integrated radiation from the three

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strong sources. Hiltner showed that polarization exists at all orientations in the Crab and varies in amount from zero to almost 60% over the face of the nebula. In the case of M87, Baade found up to 30% polarization in the jet, but also that it was broken up into knots polarized at considerable angles to each other. And lastly, there was the result of an effect discovered by Faraday and named after him, that radiation traversing a medium threaded by a magnetic field has its plane of polarization rotated by an amount proportional to the square of the wavelength. The constant of proportionality, which depends on the longitudinal field strength and the medium traversed, is called the rotation measure. In the present context, the medium is the ionized gas in interstellar space or within the radio source itself and the magnetic field is that present in these regions.

If the rotation takes place *outside* the source, different wavelengths appear to be polarized at different angles, but this can be measured and allowed for. On the other hand, if the rotation occurs within the source, *depolarization* occurs and cannot be corrected for. This was already being illustrated in the case of the Crab nebula, where the mean polarization at optical wavelengths – where Faraday Rotation is negligible – was as high as 9%.

But even in the case of *external* rotation very large values can do harm by introducing differential rotation within the band of wavelengths being observed. Similar effects can be caused by changes in the rotation measure within the resolution angle of the telescope. But unlike *internal* Faraday rotation, these last two effects can be overcome by achieving higher resolution both in wavelength and angle on the sky, as I shall discuss later.

As a result of the efforts of those early years, it became evident that the real future lay in high-frequency interferometric observations which could reveal the details of individual regions within sources with higher and different polarizations than the average. With modern aperture synthesis instruments this has now come to pass, and in the last part of my talk I shall describe some of these results.

In all of the discussion so far the magnetic fields responsible for the polarization have been very weak, and of the order of micro- or milligauss, associated with currents in the plasma in which they are embedded. I shall turn now to a very different situation, that of the giant planet Jupiter, whose case was an important landmark in the study of radio polarization. In the early fifties it was believed that the planets, like the Moon, would only emit thermal radiation characterized by their physical temperature and surface emissivity. Several planets had been observed at very short radio wavelengths and found to emit about the expected amount of thermal radiation. Jupiter, however, was known to put out bursts of radiation at decametre wavelengths, and it also showed an apparent excess over the expected thermal emission at centimetre wavelengths. This effect was found to be stronger at decimetre wavelengths and led to the speculation that this excess could be cyclotron or synchrotron radiation from a magnetosphere containing trapped relativistic particles ejected by the Sun, similar to the belts around the Earth that had been discovered by van Allen. In work that involved a number of people at the Caltech Observatory it was possible to demonstrate both the high linear polarization of the decimetric non-thermal radiation, and that the emitting region was several times larger than the visible planet. Follow-up

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observations with the same instrument showed a beautiful periodic rocking of the plane of polarization, and led to a determination of the angle between the magnetic and rotational axes of the planet; this also provided a direct measurement of the period of rotation of its *interior*, where the magnetic field was anchored. It may be recalled that optical features on the surface rotate at different speeds depending upon their latitudes.

Further detailed observations at the Parkes Observatory showed that a single 'belt' would not suffice to account for the polarization variation with rotation, and led to a more elaborate model. Finally, aperture synthesis measurements with large telescope arrays in the U.K., Holland and the U.S.A. led to the equivalent of time-lapse *tomography*, and have provided us with an excellent detailed picture of the three-dimensional structure of the magnetosphere of this planet. *In situ* measurements made later by several spacecraft during their fly-by(s) have confirmed and complemented all that was learned from the ground-based measurements.

By astronomical standards Jupiter is a very tiny and 'local' object, but I have discussed it in some detail because its case was important in many ways. It was the second radio source found to be polarized, and it was the most highly polarized known for some years. The polarization decisively established the synchrotron nature of its high-frequency radio emission, but unlike other synchrotron sources it had no internal Faraday rotation. Because of the physical rotation of the object the polarization varies periodically, and it was the first case of such a study revealing the geometry of a magnetic field which had a *separate* origin, and was therefore unaffected by the particles which traced it. But most remarkable in the present context is its similarity in many respects to the next class of objects I shall discuss, namely pulsars, which came along a decade later.

When the incredible objects we now call pulsars were discovered, there were, apart from dozens of minor questions, three major ones demanding urgent answers. What was the nature of the object? What caused the periodicity? And what was the radio emission mechanism? From the observed time-scales and energies involved, the discoverers had already narrowed the choice for the object to one between white dwarfs seen in large numbers, and the theoretically predicted neutron stars which had never been observed. As one can see from the introductory articles in the collection of the first fifty or so papers on pulsars, white dwarfs oscillating in various ways were still the favourite candidate, although Gold had already proposed rotating neutron stars. The discoveries of the Vela and Crab pulsars with their very short periods (by the standards of the day), and the measurement soon after of the lengthening of these periods, as predicted by Gold, put the rotational neutron star hypothesis way ahead of the rest of the field. But the reason for the beaming of the radiation as from a lighthouse was as obscure as ever. The spectrum of the radiation had been shown quite early to be highly non-thermal, but the question of an emission mechanism was generally avoided. The theoretical papers of the time that attempted to address this issue now read like science fiction, all attesting to the strangeness of the objects whose nature we were struggling to fathom.

While the intensity of pulsar radiation had been noted to be highly erratic, there were two features which showed a very systematic dependence on time:

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one was the period and its lengthening already referred to, and the other was the polarization variation within the pulse. The radiation from the Vela pulsar was found in studies at the Parkes Observatory and at Caltech to be highly linearly polarized, with the plane of polarization sweeping systematically through a large angle within the short pulse duration. It was further found that when Faraday rotation in the interstellar medium was corrected for, the instantaneous plane of polarization at any specific point within the pulse envelope was the *same* at all frequencies! When the erratic pulse-to-pulse variations of amplitude were averaged out, the integrated pattern always showed a highly linearly polarized but simple pulse shape of great stability. Taking Vela as the archetype, these observations led directly, to providing *independent* answers to *all three* of the major questions mentioned earlier.

We have already seen in the case of Jupiter that there were two simple and natural consequences of the polarization depending on a dynamically dominant magnetic field associated with a rotating body. One is that the plane of polarization was a function of longitude as the object rotated, and the other was the stability of the period, since the field is anchored in the object (planet or star) and not related to surface or atmospheric phenomena like sunspots, aurorae, etc. Misalignment between the rotational and magnetic axes is essential to observe the periodicity, and the shape of the position angle versus longitude curve would reflect the geometry of these axes relative to the direction of the observer. From the excellent agreement of the observed shape of this curve for Vela, with that expected for a dipolar field, it seemed more than suggestive, almost compulsory, to identify pulsars with *rotating* – as opposed to vibrating – objects. To appreciate the strength of this argument against the vibrational models which were still rife, it should be noted that the polarization sweep does not reverse after the peak of the pulse, but continues in the *same* sense. Taking this as proof of rotation, white dwarfs could be ruled out, as the observed period of Vela of 89 ms was far too high a rotation rate for them. Pulsars *had* to be neutron stars.

The observed rate of position angle sweep was also very high compared to the rate of change of longitude, and in this picture gave a direct indication of the proximity of the radiating region to a magnetic pole. The symmetry of the polarization pattern also showed that the pulse straddled the longitude that contained the projected magnetic axis. Further, of all the field lines which emanate from each magnetic pole, only those which subtend less than a certain angle with the magnetic axis are *open* field lines, and would have relativistic particles streaming along them as predicted by Goldreich and Julian. This automatically provided a cone centred on each magnetic pole, and there was thus a simple explanation both for the location of a rotating beam of limited angular extent and for the stability of its period.

Given the high magnetic fields expected for neutron stars ($\sim 10^{12}$ G), the energetic particles discussed by Goldreich and Julian would radiate away any energy and momentum they had *transverse* to the magnetic field in a negligible time, and be forced to move strictly along the field lines in their lowest Landau levels. But as the field lines curve away from the magnetic axis, the acceleration associated with motion along them should produce radiation in the observed radio range. Given the high Lorentz factors

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estimated for the particles, the expected polarization would be almost totally linear. It was in fact so, as observed in Vela, and was much higher than the maximum of 70% expected in any synchrotron source. In this model the electric vector would be parallel to the projected field lines and this incidentally enables one to fix the projected direction on the sky of the axis of rotation of the neutron star!

In putting forward this simple picture a number of important but awkward details were swept under the carpet, like the coherence mechanism to explain the very high specific intensity of pulsar radiation, the intrinsic variability of this intensity over short time-scales and, most seriously in the present context, sudden and often drastic departures in the polarization behaviour from that expected of the simple model. These aspects all continue to be tackled in increasingly more elaborate models spanning the twenty-year period to the present time. My point here is only to illustrate how much could be gleaned about pulsars from just a study of their polarization.

In the last part of my talk I would like to touch briefly on work in recent times, which shows what can be revealed by high-resolution observations at high frequencies with high sensitivity and dynamic range. As examples, I have chosen the same three strong sources where early attempts at longer wavelengths and with no resolution led to limits of a few tenths of a per cent for the average polarization. Let me start with Cas A, which is the strongest source in the sky at low frequencies and is the remnant of a supernova outburst possibly witnessed by Flamsteed in 1680. The NRL group again were the ones to make the first breakthrough in 1968 and their beam size at 1·5 cm wavelength was just small enough to resolve the source. It was polarized but the polarization was circumferential, indicating a radial field geometry. This explained immediately why average values tended to be near zero, but raised other interesting questions. At the time of these observations our understanding of the evolution of supernova remnants was more primitive and one tended to think of any field inside the remnant as the galactic magnetic field in the region of the explosion modified in some way by the expanding material. A nicely radial field geometry raised the question, at least in my mind, as to whether it was an accident of the direction from which the remnant was being viewed; for example, if we happened to be looking along the direction of the interstellar field before the explosion. On the other hand, if a mean radial field is what one would see from any angle, this would clearly suggest that the field had to be manufactured in the course of the expansion and stretched out radially in the process.

The new observations that I shall discuss were all made with the Very Large Array* in New Mexico, the largest and most powerful synthesis radio telescope in the world today. Recent pictures obtained by Rick Perley and colleagues with this instrument had a quarter of a million picture points within *each* of the beam areas of the original NRL measurements and have been put together to make a map of the total intensity from this supernova remnant representing the most detailed radio image yet constructed. Among numerous other details it reveals conical extensions of its circular outline.

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These have been interpreted as more slowly expanding material from deeper within the star breaking through the shell, which has been decelerated sufficiently sweeping up surrounding interstellar material. A similar picture of the linearly polarized 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 recognize 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 as shown by Braun *et al.* (1987).

I turn next to Cygnus A, the second strongest source in the sky at low frequencies and whose distance determination by Baade and Minkowsky 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 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 polarized 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. Perley and his colleagues have made many 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.

Maps of the polarization show that the direction of the magnetic field varies considerably within the source and that in several places it changes direction to align with the filamentary structure seen in the total intensity distribution. In such maps the field direction indicates the flows involved, as for example along the boundaries of the lobes. These lobes are giant versions, of those that occur in miniature in Cas A. The field there also becomes tangential at the *apices* of the conical extensions where matter was pushing through the shell and flowing back along the sides.

As the mapping of the field direction requires the determination of the intrinsic polarization 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. Dreher *et al.* (1987) have finally succeeded in sorting out this problem and have produced maps displaying enormous rotation measures which vary from -4000 to $+3000$ rad/m^2 over the face of the source. Their 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 per arc second and that this number is typical of the *maximum* RM encountered due to passage of radiation even through the plane of our Galaxy.

The overall pattern in rotation measure suggests that the magnetic field is ordered on scales of 20–30 kpc. But most remarkably there is no evidence for internal depolarization in spite of these high RM values. In fact, there are regions where the linear polarization actually reaches 70%, the theoretical maximum for synchrotron radiation. The operative Faraday screen must therefore be outside the radiating region, either just surrounding the lobes or in the intracluster gas from which X-radiation is observed. If it is in this gas,

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the minimum fields required are of the order of several microgauss, comparable to what is found in interstellar regions within our galaxy! If, on the other hand, the Faraday screen is in a dense sheath around the lobes, Dreher *et al.* have calculated that the field required is very much higher, approximately 100 microgauss, and not too different from what is estimated for the field in the lobes themselves.

There is one aspect of the distribution of rotation measures in the two lobes – namely that it was twice as great in one lobe as in the other – whose significance was only appreciated later. Laing (1988) and Garrington *et al.* (1988) have shown very recently that in a sizeable sample of double-lobed sources with a single jet, the depolarization at longer wavelengths is systematically and considerably greater in the lobe not associated with the jet. If due to an externally depolarizing Faraday screen, then it affects the jet-less lobe more than the other. This has been interpreted by Laing as due to a halo of hot gas around the associated galaxy or quasar, and supporting the Doppler beaming hypothesis according to which only that jet is seen which is pointing towards us. What is interesting and important here is that observations of the polarization are supplying a third dimension to the previously two-dimensional distributions of total intensity.

I turn next and last to M87, the extraordinary galaxy in the Virgo cluster in which Baade had found an optical jet I referred to earlier, and whose radio counterpart is beautifully seen in VLA observations by Frazer Owen and colleagues. At the time of the Cygnus A observations it was believed that this source had a relatively low rotation measure. This was puzzling as M87, like Cygnus A, is also immersed in a dense halo of X-ray-emitting gas. Very recent observations by Frazer Owen at the VLA have, I think, solved this puzzle as indicated by unpublished information he made available to me. Observations around 6-cm wavelength have revealed Faraday rotation measures typically 1000–2000 rad/m^2, and reaching 8000 rad/m^2 in small regions. And as in the case of Cygnus A, the higher rotation measures are in the lobe away from the jet. But most of the source is significantly polarized, showing again that the Faraday screen is in front of the radio-emitting region rather than mixed with it.

An estimate of the field required to explain the observations is of the order of 40 μG, a value approaching an energy density not too far below the thermal gas energy density. It should be mentioned that in the case of Coma and several other such rich clusters, all estimates for the field strength gave very low values, generally much less than a microgauss, suggesting that Cygnus A may be unique in some way. These new observations of Virgo A, however, support the idea that very high rotation measures may be typical of all radio sources in clusters with dense X-ray emitting gas but relatively fewer galaxies in them. As Cygnus A and Virgo A are the first extragalactic sources that have been studied in such detail, there are sure to be others with similar characteristics, and it is clear that these observations have revealed something very important whose full significance is yet to be appreciated. In particular it is not obvious how much of the magnetic field found in these observations is primordial, and whether it played any role in the evolution of the structure of the Universe as we see it now.

The spectacular observations I have just described demonstrate the state-

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of-the-art in obtaining radio pictures of remote objects in the universe with the biggest and most complicated camera in the world. They represent a magnificent technical feat showing what can be achieved by stretching both hardware and software to the limit of present ingenuity and in that sense they need no further justification. But in the context of today's discussion, one may ask for the *message*, i.e. what has one learnt about the workings of the objects we are looking at in increasing detail. My personal assessment is that with this kind of detail the observations have overtaken the theories. The plasma magneto-hydrodynamicists face a formidable challenge if they are hoping to explain every detail that is seen in these images. But there is no question that such pictures of the magnetic field are indispensable in improving and refining current models. And as we have seen, it is the study of the polarization which can and is providing us with them.

As I indicated in the beginning, I have necessarily had to omit discussion of a number of topics connected with polarization, all of which form part of the whole story. But in every case that I have discussed, and many which I have not, it is the polarization that is laying bare the magnetic field which Eugene Parker, its highest priest, has called 'the radical element responsible for the continuing thread of cosmic unrest'. Not bad, you will agree, for what started as the strange behaviour of two images in a window pane, of the setting Sun viewed through a crystal of calcite.

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