IV. OPTICAL RADIATION

OPTICAL OBSERVATIONS OF PULSARS

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ABSTRACT

Optical identification of radio pulsars has only been achieved for the Crab and Vela Pulsars. The luminosity limits for others could be considerably improved: better astrometry and time-resolved photometry could reach $m_V = 27$. The limits for pulsars with unknown periods, for example in extragalactic nebulae, are usually about $m_V = 20$. The luminosity falls rapidly with increasing period: if it follows a power law the index is minus ten at least.

The optical spectrum of the Crab Pulsar falls toward the infra-red and is flat in the ultra-violet. No self-absorption effect is seen in the infra-red. New observations of the minimum intensity and of the polarisation show a highly linearly polarised component continuing through the whole pulse cycle.

In this review I describe the present situation on optical identifications of radio pulsars, and on searches for other pulsars in various likely places. I then review the characteristics of the optical radiation from the two identified pulsars: pulse shape, spectrum, polarisation, and variability.

Among the earliest papers on pulsars are several describing attempts to identify a visible star with CP 1919, the first pulsar to be discovered. At that time there was no clear idea of what star type might be involved; as a result an innocent and irrelevant faint F star was given an unusually thorough examination, and found conclusively not to be the pulsar. This has, unfortunately, set the pattern for later, more precise attempts. The successful identification of the Crab Pulsar encouraged further work on the short-period pulsars, reaching to very faint optical limits; but the many attempts to identify the longer period pulsars have all led to null results. Before we abandon hope in this field, let us see what limits have actually been achieved.

W. Sieber and R. Wielebinski (eds.), Pulsars, 221–234.

Apart from the Vela Pulsar and the Hulse-Taylor binary, the observations have by no means reached the possible limits of sensitivity. Naturally the first attempts at identification are made on Schmidt survey plates. Here we see immediately that the limit is set by the available contrast, which is determined by the photographic techniques and the image quality. But we see also the necessity for careful and accurate astrometry: for example Cocke et al (1969) in one of the early attempts on the Vela Pulsar, found that the best candidate star in their field of 15" was a star with blue magnitude 19. We now know that astrometric accuracies better than 1 arc second are both necessary and possible.

Better contrast against the sky background can be obtained if more photons are collected by a linear detector: a CCD on a large telescope is a considerable improvement, provided that the star images are good. For example, Crane et al (1979) looking for the optical counterpart of the Hulse-Taylor binary, used a CCD on the Kitt Peak 4m telescope, and were able to propose a candidate star at $m_R = 20.9$.

Time resolved photometry can reach much fainter objects, because a very long integration time can be used. If a small diaphragm can be used, giving a field of only 1" or 2", the contrast with the sky background is correspondingly improved. Here we may contrast the attempts of Nevo et al (1974) using the 1-metre Wise telescope on PSR 0950 and PSR 1929, where fields of 39" and 28" respectively yielded limits of $m_V = 19.8$ and 19.7 respectively, with the attempts of Kristian (1970) using the 5-metre Palomar telescope with time resolution on 15 pulsar fields. Using fields around 10" Kristian reached limits of up to $m_V = 25$, including $m_V = 23$ for the Vela Pulsar. These limits could obviously be considerably improved, if it was considered worthwhile.

The ultimate limit is very faint indeed. A 4-metre telescope with a good photomultiplier records about 100 photons s^{-1} per square arc second of dark sky. Integration for 10^4 seconds gives $n^{-\frac{1}{2}} = 10^{-3}$; if a 1 arc second diaphragm can in fact be used, this gives a noise level of $m_V = 29$. We might therefore hope to detect a pulsar at $m_V = 27$ in a practical observation, if we thought it worthwhile to use prime telescope time for such work. Up to this time such faint limits have only been reached for four short-period pulsars (Manchester et al 1978).

THE VELA PULSAR AND THE HULSE-TAYLOR BINARY

It is instructive to follow the attempts to find optical counterparts to the two pulsars with periods next to the shortest. Willstrop (1969) reached a limit of $m_V > 21.5$ on the Vela Pulsar, using time resolved photometry. A better position enabled Lasker (1976) to point out his star M, blue magnitude 23.7, on a photograph of the field: he could not be sure of the identification, however, since the astrometry had reached a sufficient accuracy to show a discrepancy between the position of star M and the latest star position. Eventually Wallace et al (1977), armed with the radio interferometer position of W.M. Goss et al (1977) detected synchronous optical pulsations near star M. The identity of star M and the pulsar was demonstrated by Peterson et al (1978) using Boksenberg's Image Photon Counting System in its two dimensional mode, sampled in eight lines synchronised with the pulsar period.

The binary pulsar is different, because it is so faint that the light from the pulsar itself is unlikely to be detected. A search for the companion, however, needs the very best astrometry. Crane et al (1979), found their candidate star at $m_R = 20.9$ within 0.32" of the radio position. We will hear from D.H.P. Jones that there is still some astrometry to be done before this can be regarded as a good identification. Meanwhile there are upper limits to optical radiation from the pulsar itself, derived from time-resolved photometry, of $m_V > 23$ (Kristian et al 1976) and $m_V > 26.2$ (Nather et al 1977). The latter result was obtained with a 2.7-metre telescope, field 4.2", integration time 7 hours. Jones will also report a recent result from the 3.9-metre Anglo-Australian Telescope, giving a magnitude limit 26.5.

THE RELATION BETWEEN OPTICAL LUMINOSITY AND PERIOD

The total energy loss rate from spin-down is proportional to $\dot{P}\,P^{-3}$. If we assume that all pulsars have the same magnetic dipole field perpendicular to the spin axis, then the total energy loss rate varies as P^{-4}. This certainly does not account for the difference between optical radiation from the Crab Pulsar and any others. We need a larger index n in the ratio P^{-n} which is often sought for in accounting for the large observed ratios of luminosity.

The same conclusion was reached by Kristian (1978) by observing the secular decrease of the total intensity of the Crab Pulsar. He estimates an annual rate of decrease of ½%, and notes that this is incompatible with $n = 5$ but compatible with $n = 10$.

If we assume that the optical radiation is synchrotron radiation, we may work either on the total luminosity L or the average spectral density I_ν. For monoenergetic particles with energy E the critical frequency $\nu_c \propto B\,E^2$, $L \propto B^2 E^2$ and $I_\nu \propto B$ (for frequencies below ν_c). For a power law spectrum of particle energy $N(E) = K\,E^{-\gamma}\,dE$ the spectral density

$$I_\nu \propto B^{\frac{\gamma+1}{2}}\,K\,\nu^{-\frac{\gamma-1}{2}}\,.$$

Pacini (1971) pointed out that large values of n are obtained naturally if the relevant field B is that near the velocity of light cylinder, at radius $r_{cr} = \frac{cP}{2\pi}$, where $B \propto P^{-3}$. The total luminosity

$$L \propto B^2\;E^2\;n\,V$$

https://doi.org/10.1017/S0074180900092950 Published online by Cambridge University Press

where n is particle density and V the volume of the emitting region. Putting $V = r_{cr}^2 \Delta$, so that Δ is the unknown thickness, he finds

$$L \propto E \Delta (n r_{cr}^2 E) B^2 .$$

Equating $n r_{cr}^2 E$ to the total energy flux, which varies as $B_o^2 P^{-4}$, he finds

$$L \propto E \Delta B_o^4 P^{-10} .$$

The two unknowns E and Δ should vary in opposite directions with P, and he therefore concludes that the best value of n is 10.

If we use I_ν instead of L we obtain lower values, around n = 7. If we use a power law energy spectrum, matched to the observed optical spectrum of the Crab Pulsar, we obtain n = 8. But in both these latter cases, we have to assume that Δ/E is invariant: more likely it acts to reduce the value of n.

We conclude that we need a much better theory of particle energy and dynamics before we can safely predict a value of n. But we can also say that large values are more likely to be obtained for theories of emission from close to the light cylinder.

The observed value for n, using the Crab and Vela Pulsars is about 10.5, remarkably close to Pacini's simple theoretical value. The upper limit on the binary pulsar implies n > 9.6. If these results represent a simple general law, then there is not much point in searching for optical emission from other pulsars. But the theory is rudimentary, and the observations should be improved.

SUPERNOVA SITES AND STARS

Attempts to find optical pulsars in supernova remnants, where no radio pulsar has yet been found, cannot penetrate as deeply as searches for pulsars of known periods in precisely known positions. Nevo et al (1974) searched for optical pulsars in Cas A and in Tycho SN 1572, using large fields (78" and 113") and 200 second data strings, folded to search for periods between 4 milliseconds and 200 seconds. The magnitude limit was 17.0 in each.

Extragalactic supernova sites are more precise in position, but a pulsar would have to have a much larger intrinsic luminosity to be detectable. Papaliolios and Horowitz (1973) looked at the sites of 31 recent extragalactic supernovae, searching for short-period pulsars which might be more luminous than the Crab. Their observational limit was about m_V = 20 for periods as short as 4 or 5 milliseconds.

Using the 2.5-metre Isaac Newton Telescope at Herstmonceux and a diaphragm of 50 arc sec Korakitis (1979) found magnitude upper limits of 20.3, 20.4 for Cas A, Cas B and 3C 58 respectively.

For S And, the supernova of 1885 in the Andromeda nebula, he used an aperture of 10 arc sec and found an upper limit of 22.5.

Horowitz et al (1971) carried out similar searches among a variety of visible objects, including X-ray sources, nova and supernova remnants, white dwarfs, infrared stars and planetary nebulae. No pulsar was found.

OPTICAL SPECTRUM OF THE CRAB PULSAR

The integrated light of the Crab Pulsar is a featureless blue continuum as reported originally by Baade (1942) and Minkowski (1942). Kristian et al (1970) found the following magnitude and colours:

$$V = 16.5 \quad B - V = +0.5 \quad U - B = -0.45 \quad V - R = -0.75$$

Warner, Nather and Macfarlane (1969) found that the light curve was independent of colour, although small differences have been found by Muncaster and Cocke (1972), Cocke and Ferguson (1974) and by Groth (1975). No interstellar absorption lines have been found: Kristian (1972) reported that Miller and Wampler placed an upper limit of 4% on absorption at Hβ and Ca II H and K.

The small differences in spectrum along the pulse profile have two effects: the leading edge of the inter-pulse is brighter at shorter wavelengths and the peak of the interpulse is also brighter, relative to the main pulse, at shorter wavelengths. These differences amount only to a few per cent of the peak intensity over the whole optical range, and accurate values may even be rather uncertain because of the large polarisation which we now know to exist: the sensitivity of conventional photometers to polarisation is often forgotten.

Our information on the spectrum of the Crab Pulsar in the visible derives mainly from Oke (1969), although the actual V magnitude was determined more exactly by Kristian et al (1970). The measured flux should now be modified to account for the secular decrease of 0.5% per year; it should also be increased by about 7% to take account of the off-pulse component which was not included in Oke's measurements.

It is particularly interesting to extend measurements of the spectrum into the infra-red, where one might expect to observe some self-absorption. Fig. 1, derived from the spectrum presented by Penny and Glass at this Conference shows the visible and infra-red spectra together. The visible spectrum is from Oke (1969), with V magnitude from Kristian et al (1970), and allowing for the 0.5% per annum decrease. The off-pulse correction has not been included. The infra-red points are from Penny and Glass: they do not differ significantly from previous determinations by Becklin et al (1973) and by Neugebauer et al (1969). There is a clear indication of a fall towards longer wavelengths, which suggests self-absorption.

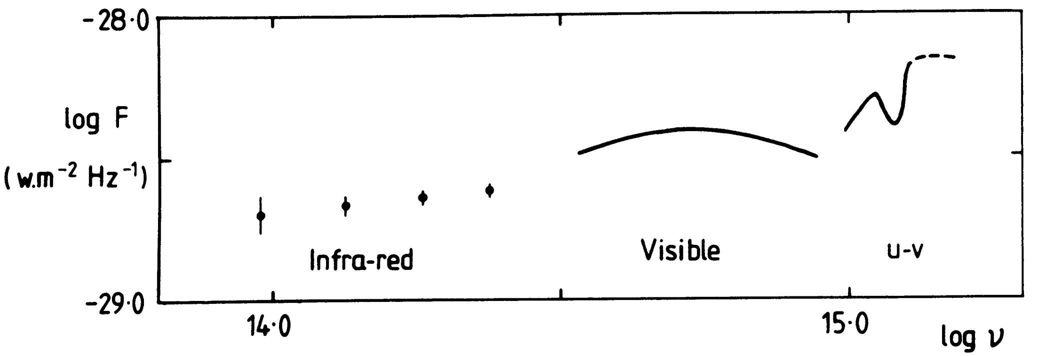

Fig. 1. Visible, infra-red and ultraviolet spectrum of the Crab Pulsar. Visible from Oke (1969), corrected for V magnitude (Kristian et al 1972) and for 0.5% per annum decrease. Infra-red from Penny and Glass (this Symposium). Ultraviolet from Benvenuti et al (1980).

Self-absorption would, however, have an obvious effect on the infra-red pulse profiles: this is not observed. Only a limited time resolution is available at these long wavelengths: for example, Becklin et al obtained 200μs and 1.6ms at wavelengths of 2.2μm and 3.5μm respectively. Within these limitations no flattening of the pulse peak is observed, although the trend towards a lower ratio between main pulse and interpulse continues (ratio 1.7 ± 0.1 at 2.2μm, 1.83 ± 0.02 in V).

Ultraviolet measurements have been made by Benvenuti et al (1980). These results, corrected for interstellar absorption, have been added to Fig. 1. (It should be noted that the published results of Benvenuti et al include the visual spectrum derived from Oke but with different corrections so that they are about 0.16 dex higher than in Fig. 1.) The spectrum is difficult to reconcile precisely with the visual spectrum, and an appreciable, probably spurious undulation can be seen. However, it seems that the spectrum is approximately flat well into the ultraviolet.

It would be useful to have more definitive spectra over the whole range, as the overall curvature is an important parameter in interpreting the emission in terms of synchrotron radiation. A large curvature would indicate a low energy cut-off in the energy distribution of the radiating particles.

PULSE PROFILES OF THE CRAB AND VELA PULSARS

Wampler, Scargle and Miller (1969) were the first to find that the Crab Pulsar does not turn completely off between the main pulse and the inter-pulse. We now know that there is a continuous light curve through the whole period.

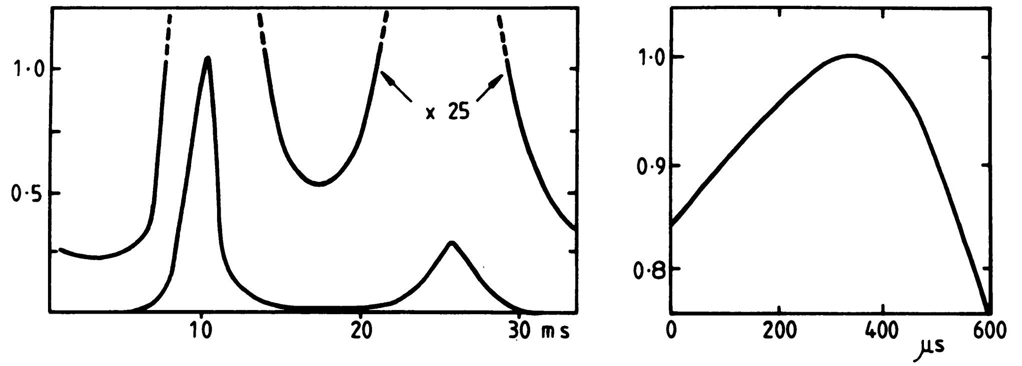

Fig. 2. (a) The pulse profile of the Crab Pulsar, showing the off-pulse component

(b) Resolution of the main pulse

The full pulse profile of the Crab Pulsar has only recently been measured. There are two difficulties: the peak of the main pulse is very sharp, so that it has often been referred to as an unresolved cusp; and the radiation does not turn off completely outside the main-pulse and the inter-pulse. Smith et al (1978) show that the peak has a curvature corresponding to a Gaussian component with half-width 330μs (Fig. 2). Wampler et al (1969) showed that radiation continued between the main pulse and the inter-pulse, and Peterson et al (1978) demonstrated that it continued round the whole cycle; their minimum value for the intensity was 3.6%, which is, as I show later, too high. We now believe it to be 0.9% ± 0.1.

The Vela Pulsar is observed at a B-magnitude of 24.0, about 400 times fainter than the Crab Pulsar. Nevertheless we have a reasonably good pulse profile (Manchester et al 1980) as shown in Fig. 3. It has a double pulse, with peaks about 65° apart. There is a strong suspicion that there is significant pulsed emission outside the double peak; there is a significant dip in the profile at phase 0.4, which suggests that the intensity is at least 10% of the peak over the rest of the pulse cycle.

STABILITY OF THE OPTICAL PULSE PROFILE

As far as is known, the pulse profile obtained by integrating some hundreds of pulses is also the profile of each individual pulse. The only fluctuations from pulse to pulse are due to photon statistics. This was established by Hegyi et al (1969) and by Smith et al (1978). Searches for very short pulses have been made in conjunction with attempts to detect gamma-rays through atmospheric Cerenkov radiation (Jelley and Willstrop 1969): nothing of this kind has been found.

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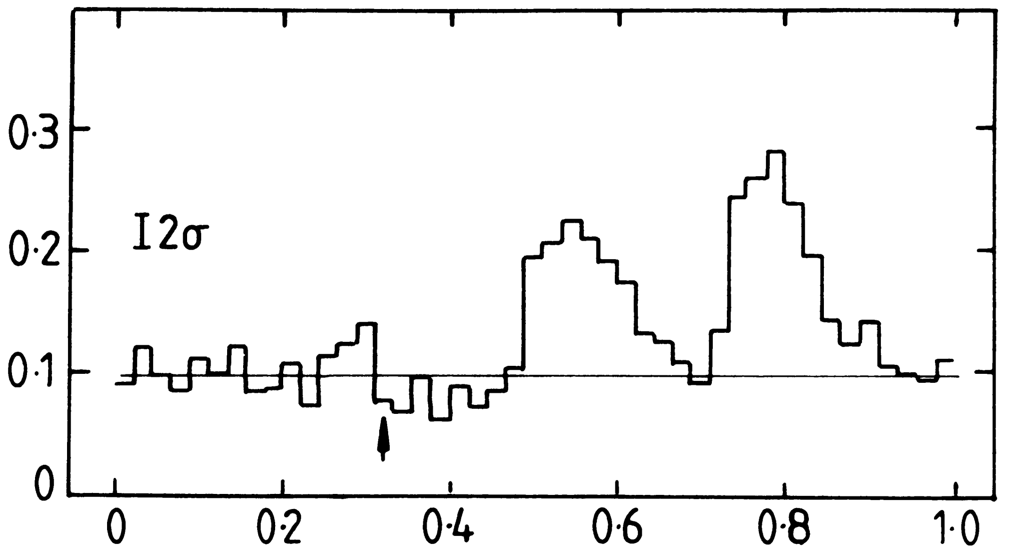

Fig. 3. The pulse profile of the Vela Pulsar (from Manchester et al 1980). The arrow marks the phase of the radio-pulse.

The integrated pulse profile is itself very stable from year to year. Jones et al (1980) find that over 7 years the only detectable changes in shape amount to less than 1% of the peak intensity. These changes appear as a small change in the steep fall-off from the main peak, a change in the relative levels of the baseline before and after the main peak, and a decrease in the inter-pulse intensity relative to the main peak. Any relative movement between the two peaks cannot be greater than 25μs, corresponding to about 0.25° of pulsar rotation phase.

POLARISATION OF THE CRAB PULSAR

Soon after the discovery of the Crab Pulsar it was found that the pulsed light was strongly linearly polarised, with a position angle that swings rapidly during the pulse (Warner, Nather and Macfarlane 1969; Wampler, Scargle and Miller 1969). Subsequent observations were made by Cocke, Ferguson and Muncaster (1973) and by Ferguson, Cocke and Gehrels (1974). Following the successful interpretation of the radio polarisation of the Vela Pulsar in terms of a rotating source (Radhakrishnan et al 1969), some detailed model-fitting was attempted for these optical observations of the Crab Pulsar (Ferguson 1976). There can be no doubt of the value of such data in unravelling the geometry of the pulsar, but I have to report that recent observations have considerably modified the data.

The measurements of the polarisation of the Crab Pulsar optical radiation have up to now been based on the assumption that the polarised radiation from the pulsar falls to zero between the interpulse and the main pulse. In observations at the Anglo-Australian Telescope (1980 January), Jones, Wallace and I avoided this assumption by using as a baseline the background radiation in a very small annulus, only 4" in diameter, centred on the pulsar. We were also able to improve the signal-to-noise ratio by using an aperture only 1''.3 in diameter. This is made possible by paying particular attention to accurate astrometry, and by taking advantage of the excellent guiding of the AAT.

With such a small annulus, there will be some contamination of the background by radiation from the pulsar, even under very good seeing conditions. This spill-over can, however, be easily detected and measured because of its pulsed nature. The polarimeter comprised a two-channel photometer with a Foster prism beam-splitter, and a rotating half-wave plate, synchronised to a submultiple of the pulse frequency. The synchronisation was sufficiently precise that we could resolve down to 2° of pulsar rotation phase.

Preliminary results are shown in Figs. 4 and 5 which give the intensity, percentage polarisation and the position angle as observed at intervals of 186 microseconds (2° of pulsar rotation). Fig. 6 shows the same data after correction for interstellar polarisation (25% at 160°, see Martin and Angel 1974).

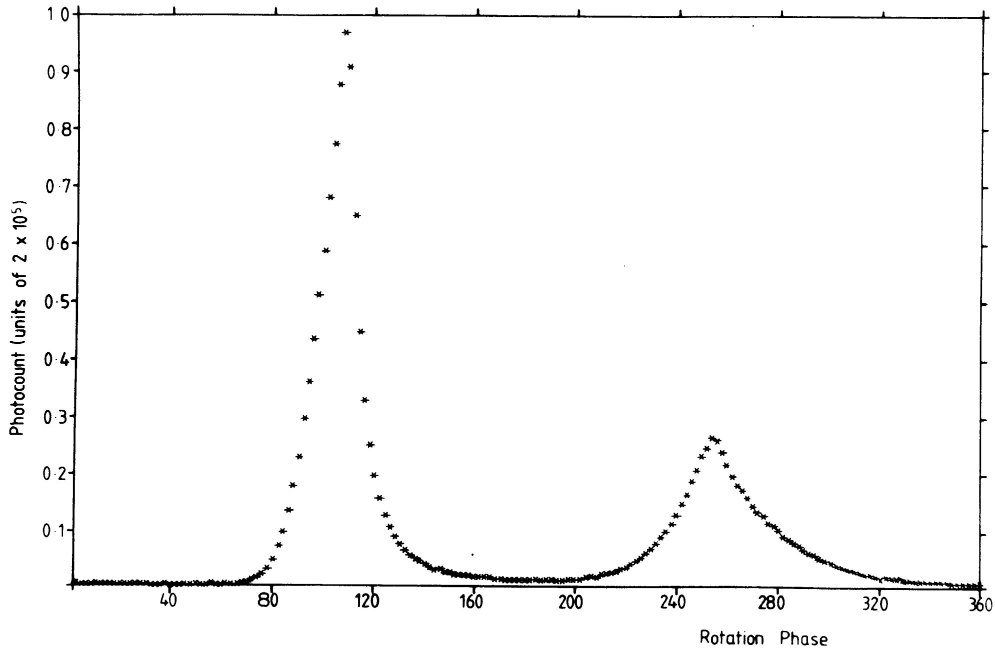

Fig. 4. The intensity profile of the Crab Pulsar

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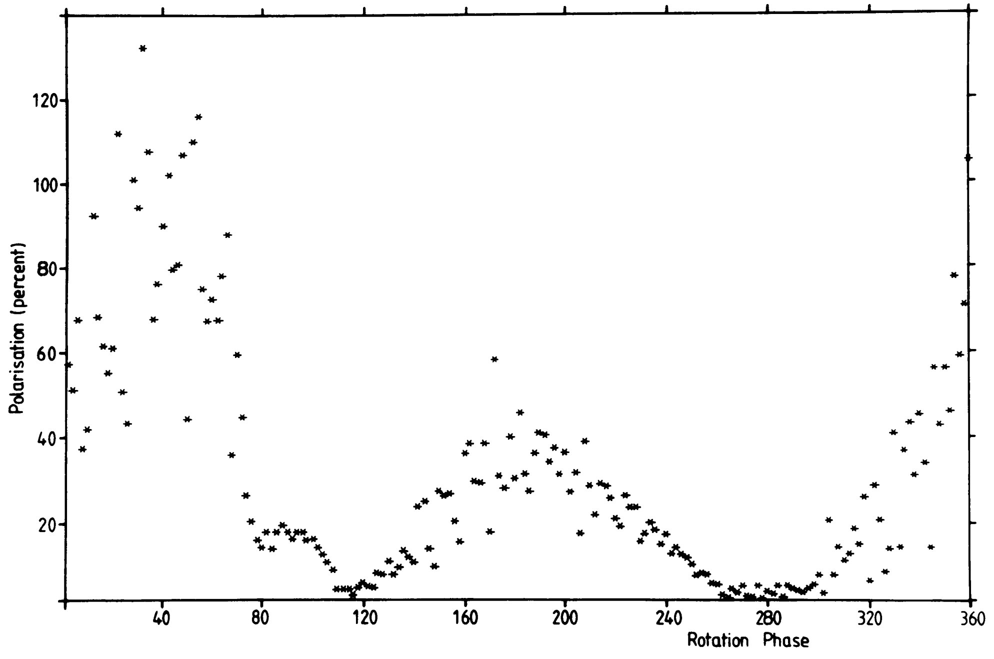

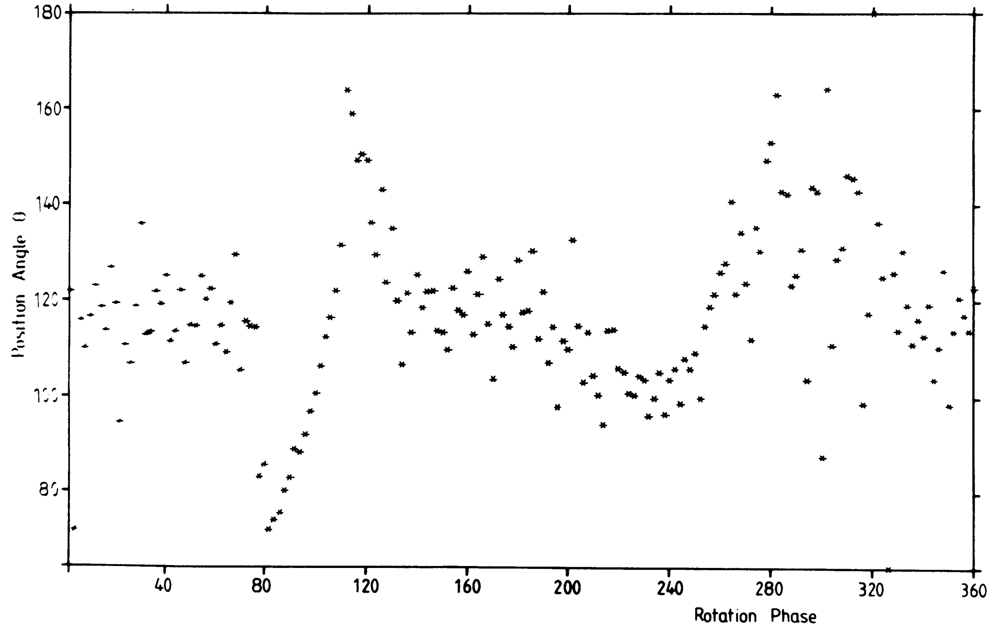

Fig. 5. The percentage polarisation and position angle as observed through the whole cycle of the Crab Pulsar

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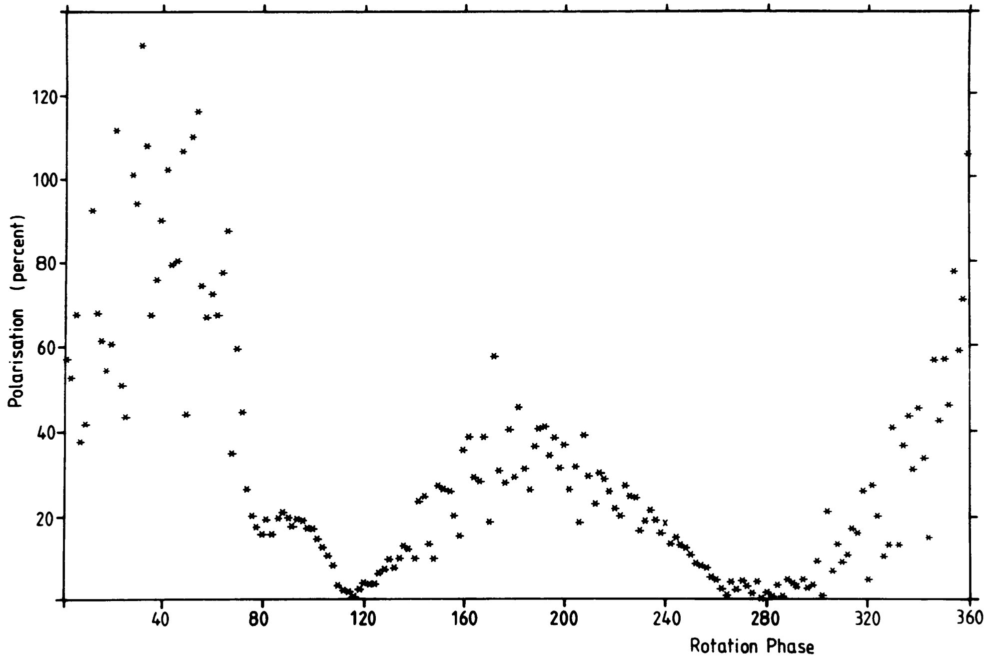

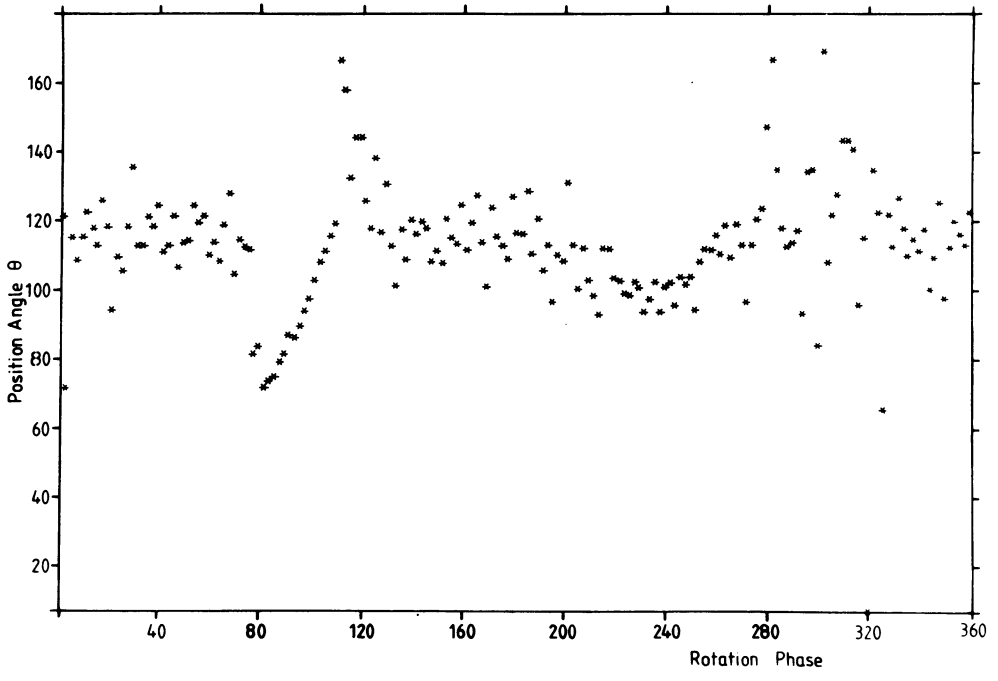

Fig. 6. The percentage polarisation and position angle corrected for interstellar polarisation of 2% at position angle 160°

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The most notable features of these curves are:

(i) The minimum intensity is 0.9 ± 0.1% of the peak, occurring 6 ms before the peak.

(ii) The minima between the peaks are very highly linearly polarised.

(iii) The total swing of position angle is restricted to 70°.

(iv) Outside the main pulse and inter-pulse the swing of position angle is restricted to a total range of 30° or less.

We suggest that these results favour geometrical interpretations in which the source is distributed circumferentially, with only a small part visible at any phase due to an intrinsic narrow beaming. If this is correct, this interpretation favours an origin close to the velocity of light cylinder rather than at the polar caps.

A full account of this work will be submitted for publication in MNRAS.

CIRCULAR POLARISATION

By analogy with the radio observations, and with the theory of synchrotron radiation in mind, we might expect to see a component of circular polarisation at some part of the pulse cycle. So far the results are negative. Angel, Hegyi and Landstreet (1971) found zero circular polarisation to about 1% of the peak intensity, averaging over an interval of 1.9 milliseconds in various parts of the cycle. Perhaps the most likely part to look at again is the low-level inter-pulse radiation, which is more highly linearly polarised and must therefore come from a more organised source in which the two hands of circular may not be completely cancelled.

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DISCUSSION

MANCHESTER: For the Crab pulsar the amount of linear intensity in the "off-pulse" region is about the same as in the "bridge" region. Also both regions have the same position angle. These two facts suggest that there may be a baseline subtraction problem. Can you put limits on possible systematic errors in determination of baselines for the Stokes parameters?

F.G. SMITH: The observations repeat very well from run to run and night to night, including variations in the background from the moon. The only way to get a different value is to have a sharply irregular nebular background within the 4 arc second annulus.

FERGUSON: It seems clear to me that the unpulsed emission of the Crab pulsar is competing in position angle with the main-pulse emission at the beginning of the main pulse. Perhaps it is a different kind of emission which should be subtracted from the pulsed emission before model fitting.

F.G. SMITH: That is obviously a matter of opinion. I prefer to keep to a single simple theory, especially as the variations of position angle are remarkably small through the whole angle.

VENTURA: You seem to exclude the possibility of having seen the neutron-star surface in the optical frequencies. Could it be that the highly polarized component comes from the stellar surface?

F.G. SMITH: I prefer to think in terms of a longitudinal spread of emission, round a complete circumference. The radius is the next question, but it seems to me easier to place the emission far out. I see no reason to place it on the surface.