# 2.3 OPTICAL OBSERVATIONS OF THE CRAB PULSAR, AND SEARCHES FOR OTHER OPTICAL PULSARS

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**Abstract.** The optical properties of the Crab nebula pulsar are reviewed. The Crab nebula pulsar has a high degree of constancy at optical wavelengths. No time variations over short or long periods have been detected; the light curve is nearly the same in all colors. The intensity and color of the pulsar are $V = 16.5$, $B - V = +0.5$, $U - B = -0.45$ and $V - R = -0.75$. There is no precursor as found at radio wavelengths and the main pulse contains 65 per cent of the total energy. No lines have been detected.

Searches for other pulsars have been unsuccessful.

The Crab pulsar is still (July 1970) the only known optical pulsar, and its properties have been studied in some detail since it was first seen early in 1969 (Cocke, Disney and Taylor, 1969). I would like to briefly review some of the available data, as well as some results of searches for other optical pulsars. Details of the observations can be found in the papers listed at the end of the present one and in the references which they contain.

All of the visible emission from the Crab pulsar is in its pulsed radiation, as determined photographically (Miller and Wampler, 1969; Chiu *et al.*, 1970a) and photoelectrically (Kristian, 1970a) with an accuracy of a few percent. The light curve is very nearly the same in all colors (i.e., the color of the emitted radiation does not change through the pulses), although recent observations by Visvanathan and Kristian suggest that there may be a very small change through the main pulse. The shape of the pulses has remained remarkably constant. The groups doing optical timing measurements exploit this fact by fitting their observed pulses to a standard shape, which enables them to obtain arrival times with a precision several orders of magnitude better than the time scale of the pulse widths themselves. There is no indication of the splitting of the main pulse into two components which is seen at radio frequencies.

The intensity of visible radiation is secularly constant on all time scales investigated, with the following accuracy at present: successive pulses, a factor of two; 10 minutes to several hours, 5%; night-to-night over a year, 10%; year-to-year since 1920, 35%. There is no evidence for the substantial pulse-to-pulse variations or occasional extremely large pulses seen by the radio observers. As was pointed out very early by Gold, however, the very high brightness temperature of the radio emission requires that it be highly coherent, and changes in the degree of coherence could cause intensity fluctuations. If the radiation at optical and higher frequencies were incoherent, the difference might be qualitatively understood. Several X-ray measurements made at different times show a constant intensity, but the accuracy is quite low.

The broad-band intensity and colors of the optical emission, averaged over times

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of the order of minutes, are V = 16.5, B − V = +0.5, U − B = −0.45 and V − R = −0.75, with the main pulse containing 65% of the total energy in each pass band (Kristian *et al.*, 1970). The detailed energy distribution for the main pulse and subpulse are the same. After correction for interstellar absorption, the flux density shows a broad maximum in the visible, with a decrease in both the ultraviolet and the red, the latter continuing into the infrared to at least 2 $\mu$ (Oke, 1970; Neugebauer *et al.*, 1970). The ultraviolet end and the observed X-ray intensity can be plausibly fit to the same curve, but this is not true for the red end and the radio observations. The radio spectrum has a slope steeper than 2 at 12 cm, while the slope in the infrared has the opposite sign. The general effect is of a two-humped energy distribution, with one hump at radio wavelengths and the other in the visible-to-X-ray region (see, for example, Kristian, 1970a). Good image-tube spectra of the pulsar show a smooth blue continuum, with no lines (Lynds, 1969; Van den Bergh, private communication).

The visible emission shows strong linear polarization, which changes through the pulses, but whose behavior is secularly constant (Kristian *et al.*, 1970). The polarization decreases from about 20% in the leading edges of the pulses to near zero, then increases in a roughly symmetric way to about 10% in the trailing edges. This change in polarization is accompanied by a monotonic sweep of the plane of polarization through 150° during 60° of the pulsar's rotation. The polarization through the main pulse and subpulse is similar and is shifted in both cases with respect to the peaks of the pulses, by about 200 $\mu$sec for the main pulse and 1.5 msec for the subpulse. Circular polarization is absent, with an accuracy of a few percent.

Optical searches for other pulsars continue, both for visible counterparts of known radio pulsars and for radio quiet pulsars associated with a variety of galactic and extragalactic objects. The most extensive searches of the latter kind have been made at Harvard, and are reported by Horowitz at this symposium.

A radio pulsar of particular interest has been 0833–45, the Vela pulsar, because it is the fastest pulsar after the Crab, and the only other pulsar known to be associated with a supernova remnant, although searches have been made for pulsars near known supernova remnants and for supernova remnants near known pulsars. Negative results for 0833 have been reported by a number of groups, the faintest limit at present being $V \gtrsim 24$ (Chiu *et al.*, 1970b; Kristian, 1970b). After corrections for distance and interstellar absorption, this implies an absolute visible luminosity for the Vela pulsar at least 4000 times fainter than that of the Crab.

Limits for visible counterparts of 15 radio pulsars searched for at Palomar (Kristian, 1970c) range from 3 to 9 magnitudes fainter than the Crab. Rough limits for the absolute luminosities of these objects, based upon their dispersion measures, range from $10^{-1}$ to $10^{-6}$ that of the Crab. The results appear to rule out the possibility that the visible pulsed emission of all pulsars scales as (frequency)$^4$ and is normalizable to the Crab. If all pulsars were normalizable to the Crab, the data indicate that the visible pulsed emission would have to scale by factors as large as (frequency)$^{8.4}$ for the best established case (Vela).

There is still no satisfactory theory for the pulsar emission mechanism. Even as

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basic a question as the location of the emitting region, whether at the surface of the star, the velocity of light cylinder, or some intermediate region, remains unanswered. A complete theory must account for a great deal of observational data, especially from the Crab pulsar, which has now been observed in some detail at accessible wavelengths from the radio to the X-ray regions. A few general remarks, however, can be made at present. There no longer seems to be a serious doubt that the pulsars are rotating objects, probably neutron stars. The optical measurements of the Crab imply that its pulses are due to a polarized emission pattern, locally fixed in the object, which is azimuthally scanned as it rotates. The data also provide fairly direct evidence for the existence in the pulsar of a long-lived non-axisymmetric magnetic field. Any emission mechanism may be expected to involve highly relativistic particles, and the secular constancy of the optical pulses requires that the flux of such particles be constant. It is attractive, on the grounds of economy of hypothesis, to suppose that the particle flux itself may be generated by the rotating magnetic field.

The polarization measurements can be interpreted in terms of a general geometrical model which requires that the pulsar's rotation axis must lie within 30° of the plane of the sky, and be either parallel or perpendicular to the magnetic field of the nebula in the immediate vicinity of the pulsar (Kristian, *et al.*, 1970). This suggests that the magnetic field of the nebula may have been generated by the pulsar, and provides evidence for a direct connection between the central star and the nebular field.

The coincidence in pulse arrival times of radio, optical and X-ray pulses from the Crab, and the similarity of their gross structure, indicate that they must be due to the same basic phenomenon, but the detailed differences in pulse shape, energy distribution, secular intensity and polarization are striking and complex, and will require considerable effort and ingenuity to unravel.

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## Discussion

*W. J. Cocke:* I would like to report briefly on some optical polarisation observations of NP 0532 done by myself, M. J. Disney, T. Gehrels, and G. Muncaster. Last year we published results which we believed showed that the polarisation was variable, on a time scale of an hour or so. We have since discovered that the variability was most likely due to a time-dependent malfunction in our photomultiplier electronics.

We repeated our observations in October, 1969, at the Steward Observatory 90-inch telescope, and have obtained polarisation curves that agree very nicely with those of Kristian and Visvanathan. However, we have measured a somewhat different value for the interstellar polarisation, and therefore our final corrected curves do look somewhat different.