Changes in the Pulse Shape of NP0532 As a Function of Color

by

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INTRODUCTION

In the first year after the discovery of optical pulsar NP0532 (Cocke, Disney, and Taylor, 1969) several photometric studies were undertaken in an effort to discover evidence of pulsar variability in intensity or pulse shape. These were made in white light and as a function of color (Wampler, Scargle, and Miller, 1969) (Warner, Nather and McFarlane, 1969) but, to a ±5% level, no variation was found. Recent work has shown the overall pulse shape in white light to be remarkably constant (Papaliolios, Carleton, and Horowitz, 1970); however, no one has re-investigated the possibility of variations as a function of color, though X-ray (Bradt, 1972) and gamma ray (Kurfess, 1971) measures show that intrinsic and progressive changes in the pulse shape occur across the X-ray and gamma ray region (1.5-400 keV).

Under certain assumptions if one calculates the expected variations in the size of the secondary pulse from the existing high-energy data and from the white light observations, a detectable increase across the optical passband may be indicated, if the mechanism responsible for the high-energy enhancement is still at work at optical frequencies. Such an enhancement of the secondary pulse peak and leading edge, at the expense of the trailing edge, would be smaller by at least a factor of two than the errors occurring in the previously published studies. The present investigation, to higher photometric accuracy, finds changes in the secondary pulse shape in qualitative agreement with the progressive alteration in pulse shape throughout the X-ray and gamma ray regions. The magnitude of the effect we report is approximately 3% from the V filter passband to the U passband, and we believe that this result may permit a greater understanding of the mechanism responsible for the increased prominence of the secondary pulse in the X-ray and gamma ray domains, since some remnant of this mechanism is still present in the optical passband where it may be studied in great detail.
OBSERVATIONS

In this paper we present results obtained from a portion of the data gathered during the ongoing series of photopolarimetric observations of NP0532. The observations were made on five nights in November, 1970, and January, 1971, at the Cassegrain focus of the Steward Observatory 229-cm reflector. Although the main purpose of the observations was to acquire data on the linear polarization properties of NP0532 as a function of color, a sufficient number of photon counts was received in all three wavelength regions herein reported to significantly increase our knowledge of the behavior of the pulse shape itself as a function of wavelength. This is particularly demanded by the progressive changes of the pulse intensities and shapes as we observe at wavelengths shorter than 10 Ångstroms. Consequently, the decision was made to investigate if such changes can be observed across the optical passband, and to derive pulse shapes and color differences from our data.

The two-channel polarimeter and allied instrumentation has been discussed elsewhere. (Cocke, Disney, and Gehrels, 1969), (Cocke et al., 1970). The present observations were made with detectors having S-13 response characteristics through a diaphragm of 6 arc-seconds using the U, B, and V filters of the UBV photometric system. All observations were taken with a depolarizer in front of the Wollaston prism of the polarimeter. We integrated in the U, B, and V passbands over a total number of pulsar cycles which were, respectively: 475,000; 164,000; and 137,000. The relative detective quantum efficiencies of the system for different wavelengths were not equal, however, due to the characteristics of the filters and to the spectral sensitivity of the photocells. In addition the pulsar itself has been found to be fainter in the U filter passband than in the
B or V regions. (Kristian, et al., 1970) The total number of photons actually counted in the peak of the main pulse were: U, 77,000; B, 75,000; and V, 51,000.

The use of the CAT (computer of average transients) as a 400-channel signal analyzer has been described before along with the computer program used to determine the instantaneous observed pulsar period. (Cocke, Disney, and Taylor, 1969), (Cocke, Disney, and Gehrels, 1969), (Cocke, et al., 1970) Each of the two output channels of the polarimeter was fed into the CAT and the light curves were displayed and read out onto magnetic tape after each integration. Individual integration times varied from four minutes (7200 cycles) in the B and V observations to thirteen minutes (23,400 cycles) in the ultraviolet where the signal was weakest. Due to the dual inputs used for polarimetry, we sampled each pulse at 186 equally spaced points, giving us a nominal timing resolution of 180 microseconds. The output signal from the photocells was added together and the data reduced using the CDC 6400 computer at the University of Arizona Computing Center. During a single integration the light received from the 2.68 msec interval centered 6.65 msec before the main pulse peak was assumed to arise from the nebular background and the North-following star; consequently, the average number of counts in this interval was subtracted from all the other channels to arrive at the individual light curve for each integration.
DATA REDUCTION

In the course of our investigations several small but potentially confusing sources of error were investigated in an attempt to give as accurate a representation of the data as possible. The matter of pulse area normalization will be discussed later in detail. After our observations were made, a shortcoming of our instrumental design was noted which had the potential for confusing our data by a small, but not negligible, amount. Our electronic buffer memory could only record, due to its design, a maximum of two photons per pulsar cycle per CAT channel, and the possibility existed of losing perhaps a few photon counts near the peaks of the main and secondary pulses. If we expect the number of photon arrivals to be distributed according to a Poisson probability distribution, we can correct our observed number of counts in each channel to the value expected, provided the individual integration time for each run is known.

Let us consider

\[ P_\lambda(n) = \frac{e^{-\lambda} \lambda^n}{n!} \]

to be the expected distribution of photons arriving at our detector. Then we expect to count in each channel in each pulsar cycle

\[ \langle n \rangle = \sum_{n=0}^{\infty} \frac{n e^{-\lambda} \lambda^n}{n!} = \lambda \text{ photons.} \]

If we observe, however, a number \( \langle n_t \rangle \) such that

\[ \langle n_t \rangle = \sum_{n=0}^{\infty} n' P_\lambda(n), \quad \text{where } n'(n) = n \text{ for } n \leq 2, \quad n'(n) = 2 \text{ for } n > 2 \]

Then,

\[ \langle n_t \rangle = \sum_{n=0}^{n=2} \frac{n e^{-\lambda} \lambda^n}{n!} + \sum_{n=3}^{\infty} \frac{2 e^{-\lambda} \lambda^n}{n!} = \lambda_t \]

We can thus solve for an expression for \( \langle n \rangle \), our desired quantity. Since

\[ \langle n_t \rangle = 0 + \lambda e^{-\lambda} + \lambda^2 e^{-\lambda} + 2 \left( \sum_{n=0}^{\infty} \frac{e^{-\lambda} \lambda^n}{n!} - \sum_{n=0}^{n=2} \frac{e^{-\lambda} \lambda^n}{n!} \right) \]

\[ = -\lambda e^{-\lambda} + 2(1 - e^{-\lambda}). \]

An iterative process can be set up which quickly returns a value \( \lambda \gg \langle n_t \rangle \).
according to the number of observed counts \( \langle n_t \rangle \). Since we recorded the length of the individual integrations, this correction was made to each of these integrations. In the peak of the main pulse the corrections never exceeded \( \% \).

An additional correction was examined in order to determine whether telescope drift during the separate integrations could systematically affect the data. Since the electronic memory corrections previously noted are sensitive to the individual integration times, if the telescope were drifting slightly so as to sweep the pulsar in and out of the diaphragm, then the time necessary to record a certain number of pulsar photons would be only \( (1 - f) \) of the recorded integration time, where \( f \) is the fraction of time the pulsar was not in the diaphragm. By a separate reduction of the data with a value of \( f = \frac{1}{6} \), certainly an overestimate, only a negligible effect was observed on the results. No systematic effect has thus been introduced by imperfect telescope tracking which may have occasionally occurred.

To obtain comparable pulses for comparison of their shapes, the light curves were normalized by multiplying the individual channel intensities by a factor such that the integrated intensities outside the region of the main pulse be constant. Objections may be raised to the procedure of rejecting the main pulse observations for the purpose of normalizing the light curve, but this can be answered by the following arguments. First, since the main pulse cannot be resolved with our timing resolution (in fact, not with 32 microsecond resolution (Papaliolios, et al., 1970)), then the position of the main pulse (determined to only \( \pm \frac{1}{3} \) data channel) may be in error by \( \pm 90 \) microseconds. During this interval of time the main pulse can increase or decrease by several percent of its peak intensity. We thus limit our overall photometric accuracy by inclusion of
this data. Secondly, since we expect the largest number of photon counts per individual pulse cycle to be emitted near the main pulse peak, then the finite buffer memory capacity corrections to the observed number of counts are least certain in this region. We are thus hesitant to assign greatest confidence to the accuracy of our data in this portion of the light curve which would be implied by using it in the normalization process. The height of the secondary pulse peak is only one-third that of the primary; hence, such Poisson corrections will be at most one-ninth as significant as those for the main pulse peak. The resultant effects present from a combination of the above complications may be impossible to determine, so we reject the main pulse from the normalization process. We have carried through an error analysis for cases when the entire area under the pulsar light curve was normalized, or when one or the other of the individual pulses was excluded from the total normalized area. When the main pulse area was deleted, the resultant errors were least, presumably because of the above arguments.

There are two important reasons why the main pulse cannot be included in the intensity difference plots we obtain from the normalized light curves. Since the position of the main pulse peak in the composite light curves is known only to ±90 microseconds, then the position of the leading and trailing edges of the pulses may occur at a random position within one of our 180 microsecond CAT channels. When we now subtract the intensity curves we obtain a systematic error in the difference plots, even though each composite curve may have exactly the same shape. FIGURE 1 illustrates this effect on a sample intensity difference curve. If the period generation apparatus does not exactly match the pulsar cycle time, instrumental broadening of the pulses will occur. This can result in marked differences in the measured half-widths (full width
at half-maximum) of the composite pulses. A broadened composite pulse will have a depressed peak relative to a less broadened one, and the resulting intensity difference curves will have artificial systematic errors present. FIGURE 2 shows two pulses of equal area in which this effect will give spurious effects in the difference plots.

In contrast to the uncertainty in measurement of the primary pulse, the secondary pulse is well resolved and the composite pulses coincide exactly and yield identical half-widths. Because of this the light curves of different colors can be normalized to correspond and we can definitively analyze the secondary pulse and interpulse regions for changes with color. These regions are of great interest since they seem to be progressively changing with frequency throughout the X-ray and gamma ray passbands, as we will discuss in a later section.

By subtracting the normalized curves obtained in the different wavelength regions we obtain the difference curves which are plotted in FIGURE 3. The difference plots have been smoothed by averaging over adjacent channels in the manner of Wampler et al. (1969), obtaining for each point an intensity

\[ I_j = \frac{1}{4} \left( I_j + \sum_{j-2}^{j+2} \left( I_k / k-j \right) \right) \quad \text{for } k \neq j. \]

We have excluded the differences near the main pulse peak for the reasons mentioned earlier, and channels numbered 28-55 (peak in channel 45) are thus not shown. Times excluded are from -2.86 msec to +5.31 msec relative to the main pulse peak.
RESULTS

The uncertainties in our difference curves are about ± 250 counts, corresponding to a relative error of about ±0.8% near the secondary pulse peak. We find in the interpulse regions between the pulses that there are no trends in the U-B, U-V, and B-V curves. We expect the interpulse region over which we sampled the background light not due to the pulsar to yield no net color, since there are no net counts received, and this is what is found. For the secondary pulse, however, a trend is noted for the leading edge and peak to be consistently blue in each color and for the trailing edge to be red, notably in the U-V measures, which cover the greatest frequency span. In this region we find a consistent difference which at the pulse peak is 2.8% ± 0.8% in the U-V data. Thus the height of the secondary pulse measured in the U filter band is 2.8% higher than that measured in the V passband, though a smaller effect can be noted in both the U-V and B-V intensity difference curves as well. The failure of the earlier observations to determine a color dependence of pulse shape is thus explained as due to poor photon statistics. If the earlier data is examined, it is apparent from FIGURE 3 of Wampler, et al. (1969) that the statistical error is of the order of at least ±5%. That of Warner et al., from their FIGURE 5, is about ±7%.
DISCUSSION

The question arises whether we might expect to detect a priori any variations in the shape of the secondary pulse with color, especially since the white light pulse parameters are remarkably constant. (Papaliolios, et al., 1970)

We may correlate data from the X-ray and gamma ray results (Rappaport, Bradt, and Mayer, 1971) (Smathers, Chubb, and Sadeh, 1971) which show progressive changes along with the white light observations and plot the ratio of interpulse region (between main pulse and secondary pulse) height above background to that of the main and secondary pulse heights themselves. Another correlation may be attempted between the ratio of the main and secondary pulse heights. Such a graph appears in FIGURE 4 a-c, wherein we have represented the values and their errors as can be determined from an inspection of the relevant articles. A plot of the observations strongly suggests that a correlation exists between the secondary pulse shape and frequency. If we assume that any differences in the interpulse height across the optical region would be quite difficult to detect, we can at least draw some conclusions about the behavior of the secondary pulse characteristics.

If we now assume a linear relation exists between the secondary pulse to main pulse ratio and \( \log \nu \), we see that expected variations across the optical passband would be small. An exponential relation between these quantities would produce even smaller changes across the optical window, probably \( \pm 2\% - 4\% \) if linear, \( \pm 1\% \) or less if exponential.

The detailed behavior in the high-energy observations of the Crab Nebula Pulsar pulse shape is as follows: The leading edge and peak of the secondary pulse in the X-ray and gamma regions becomes relatively larger with decreasing wavelength so that, while apparently rising in white light some seven or eight
milliseconds after the main pulse peak (Papaliolios, et al., 1970), it begins
at about six milliseconds after the main pulse peak in the 1.5-10 keV (Rappaport,
et al., 1971) and 30-100 keV (Smathers, et al., 1971) observations, and in the
100-400 keV measures (Kurfess, 1971) it is found five milliseconds after the main
peak. Accompanying the steady increase of the leading edge is a decrease in
the intensity of the trailing edge. These experiments report the trailing edge
drops off more and more steeply into the background some six milliseconds
after the secondary peak with the apparently complete absence above 1.5 keV
of the slowly declining trailing edge characteristic of the secondary pulse
in the optical region. (In the optical wavelengths the trailing edge is traced
out some nineteen msec after the secondary peak.) In the higher energy observ-
ations, then, the trailing edges of both pulses appear quite similar.

The present data indicate that the secondary pulse intensity increases by
approximately 2.8% ± 0.8% from the V filter passband to the U filter passband.
Between these two wavelength regions there is a 50% increase in frequency;
whereas, between the optical (5000Å) and 10^8 regions is a frequency factor of
500. If the secondary pulse changes shape in a linear relation with with fre-
quency, then of necessity the changes across the optical window will be small
and difficult to detect. Consequently, confirmation of our observations and
the possible detection of changes in the interpulse region of the light curve
must await future observations. In the present work we have sacrificed time
resolution for an increased number of photon counts per channel to achieve
maximum photometric accuracy within instrumental limitations, but it does not
seem desirable to make future observations at high pulse resolution when the
aim is to detect what are certainly not rapidly time-varying effects. An
improved procedure would be to preserve timing precision and consequently
minimize instrumental pulse broadening. Another suggestion would be to observe in only two filter passbands, permitting a decrease in the total observing time needed, but this has the hazard of possibly allowing a spurious effect to occur for which there would be no internal experimental checks, as when three or more passbands are sampled. With the present experimental arrangement different filters could be placed in front of the two photocells so as to eliminate the relative effects of timing and period generation inaccuracies. By this means simultaneous two-color photometry would be possible, though the total observation time would be unchanged over that required to observe in one color at a time. To improve the pulse resolution as well, however, would then require a linear increase in the required observing time to attain a specified precision. To double our precision using the present experimental (or the simultaneous two-color) arrangement would require at least a week of observing time with a telescope comparable to the Steward 229-cm reflector, but to confirm our findings should take only two or three complete nights of observations. It is hoped that in the 1972-73 observing season, we may be able to study this interesting object, NP0532, further.
APPENDIX

It is of interest to speculate that the main pulse remains at constant height throughout the frequency regime of $10^{15} - 10^{20}$ Hz. If this were true, we should expect to find a greater variation in the secondary pulse height across the optical window if the relation between secondary pulse height and $\log \nu$ is linear than if the relation is exponential. To determine the form of this relation should then assist in the determination of the secondary pulse emission conditions. To this end, accurate observations made at a point intermediate in frequency between the observations to date is desirable, for example, in the ultraviolet at about 1000Å. A sizable difference in the slope in the secondary pulse height vs. $\log \nu$ relation is to be expected in that vicinity ($\log \nu = 15.5$). It is hoped that in the future pulse-resolution photometry can be performed in the far ultraviolet.

Ferguson has determined (private communication) that the polarization data obtained on NP0532 (Cocke, et al., 1970) is consistent with the primary and secondary pulses having different emitting regions. A mechanism to produce the flat high energy spectrum in the secondary pulse should also be consistent with the photometric results presented here. At present the high energy data are extremely interesting, but are not of high precision. Conversely, in the optical window, where we can make accurate observations, the variations in the pulsar pulse shapes are small. It is imperative that optical observations be extended as far as possible into the near-UV and infrared with sufficient precision to determine the behavior of the secondary pulse contour with wavelength in the accessible regions of the electromagnetic spectrum.
REFERENCES


FIG. 1 - Schematic effect of subtracting two identical pulses not coincident in time
FIG. 2 - Schematic effect of subtracting two pulses of nearly equal areas but appreciably different half-widths
FIG. 3 - Intensity differences as a function of pulsar phase

\[ a - U - B \\ b - U - V \\ c - B - V \]

Secondary peak

0.0 9.0 18.0 27.0 (−6.0)

TIME (msec)
FIG. 4 - Ratios of interpulse(I), secondary pulse(S), and main pulse(M) heights above background.

A) Secondary: Main

B) Interpulse: Secondary

C) Interpulse: Main
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## Smoothed Intensity Differences Between Filters U and B

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SOOMED

INTENSITY DIFFERENCES BETWEEN FILTERS B AND V