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INFRARED STUDY OF THE CRAB PULSAR: THE "SHOULDER" PULSE AND THE 3.45 MICRON PULSE PROFILE

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ABSTRACT

Infrared measurements of the Crab pulsar with the NASA IRTF 3.0 m telescope show that the spectrum of the main pulse turns downward for wavelengths longer than 3 μm. The "shoulder" pulse discovered by Pennypacker is measured in the 0.9–2.4 μm region, but disappears at 3.5 μm. This pulse rises from 0 to 20% of the height of the main pulse within 1 to 2 ms after the main pulse peak and decays with a 4 to 5 ms time constant. Excess infrared flux also appears after the interpulse. The main peak itself may be narrower at 3.45 μm than in the optical to 2.2 μm band.
Subject headings: infrared: sources — pulsars

I. INTRODUCTION

We have measured the Crab Nebula pulsar (NP 0532) in the near-infrared. The pulsar had previously been measured at these wavelengths by Becklin *et al.* (1973), and the pulse had been shown to be similar to the optical measurements. More sensitive measurements by Pennypacker (1981) confirmed the previous work's flux measurements, but the main peak of the averaged infrared light curve was shown to have excess flux following the peak which is not found in the optical light curve. The "shoulder" pulse has been studied in more detail in this work, and we have also measured the 3.5 μm light curve for the first time, where the shoulder pulse is absent. In addition, we measure the spectrum of the main pulse which reveals a turndown at wavelengths longer than 3.5 μm.

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II. OBSERVATIONS

NP 0532 was observed from the University of Hawaii/NASA IRTF 3.0 m telescope at Mauna Kea from 1981 December 18 to 1981 December 20. In addition to the usual *J*, *H*, *K*, *L*, and *M* bands, observations were made with a special broad-band filter ("*UC*") (see Table 1) which transmitted between 0.9 and 2.4 μm. A liquid helium-cooled InSb detector and preamplifier (RC2) was provided by the IRTF. This detector was optimized for high time resolution photometry yielding a 3 dB decrease in gain at 200 Hz. The detector time response was measured using an infrared LED with a signal generator. In contrast, the

TABLE 1
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Run	Date (1981)	Starting Time (UT)	Filter	Sampling Rate (Hz)	Data Length (words)	Detector
Infrared: NASA IRTF 3.0 m						
1	Dec 18	1203	*UC*	4000	2,640,000	RC2
2	Dec 18	1258	*K*	4000	2,400,000	RC2
3	Dec 18	1320	*J*	4000	2,400,000	RC2
4	Dec 19	0902	*UC*	4000	1,052,000	RC2
5	Dec 19	0917	*J*	4000	2,400,000	RC2
6	Dec 19	0934	*L*	2000	6,800,000	RC2
7	Dec 19	1038	*K*	4000	2,400,000	RC2
8	Dec 19	1138	*UC*	1000	528,000	RC1
9	Dec 20	0812	*J*	2000	1,052,000	RC2
10	Dec 20	0833	*H*	2000	1,052,000	RC2
11	Dec 20	0903	*M*	1250	8,372,000	RC2
Optical: University of Arizona/NASA 1.5 m						
A	1982 Jan 17	0434	...	1000	1,060,000	EMI 9658A

InSb detector in normal use (RC1) was measured to have a 3 dB point at 5 Hz.

The internal amplifier gains of the detectors were set to 10, while an external preamplifier gain was set between 10 and 50. The signals were then digitized at 0 to 1023 counts for −2.500 to +2.495 volts and the resulting bit patterns were translated into 16-bit words in the PDP 11/45 data acquisition computer. The computer was controlled by an IRTF program which continuously recorded data on magnetic tape at rate of from 1000 to 4000 words s^{-1}. Most of the observations were made through a circular aperture of 7″ diameter; a few were made through a 5″ aperture.

Optical observations of NP 0532 were made with the University of Arizona/NASA 1.5 m telescope at Mount Lemmon on 1982 January 17, using a 16″ circular aperture. The counts from an unfiltered EMI 9658A photomultiplier tube were recorded onto magnetic tape at 1 ms intervals for later analysis in which the optical and infrared data were compared.

III. ANALYSIS

The data from observations of NP 0532 were Fourier-transformed in order to establish the apparent frequency of the pulsar. In general, the apparent pulse frequency from the IRTF observations differed from the frequency predicted by an ephemeris generated from the data of Lohsen (1981). This inconsistency was traced to a drift in the clock of the data acquisition system by a few parts in 10^7 on the time scale of a few hours. This drift was monitored during the observations and found to be too small to affect the data adversely.

An integrated pulse profile was produced from the optical data by folding the time series at 30.0585424(4) Hz and then convolving the resulting light curve with the measured RC2 infrared detector response. The convolution may be expressed as:

$$G'(t) = (1/\tau_0) \int_0^\infty G(t - \tau) e^{-\tau/\tau_0} d\tau \ , \qquad (1)$$

where $\tau_0 = (2\pi \times 200 \text{ Hz})^{-1} \approx 0.8$ ms is the detector's exponential time constant, G is the raw optical pulse profile, and G' is the pulse profile to be compared with the raw infrared pulse profiles.

The pulse profiles for the infrared data were examined and the light curves obtained while using the J(1.25 μm), H(1.65 μm), K(2.20 μm), and "UC"(0.9–2.4 μm) filters all appeared to be equivalent to within statistical error. Accordingly, all of the runs (except those in L, M, or "UC" with the slower RC1 detector) were summed together directly with equal detector voltages receiving equal weights. To sum the different runs, each was fitted to the pulse profile of run 1, so that the offsets in phase of the profiles could be standardized. The results of this analysis are plotted in Figure 1*a*, together with the optical G' light curve.

In order to correct the infrared light curves for the 0.8 ms detector response, the pulse profile of each individual run was Fourier-analyzed, and the statistical

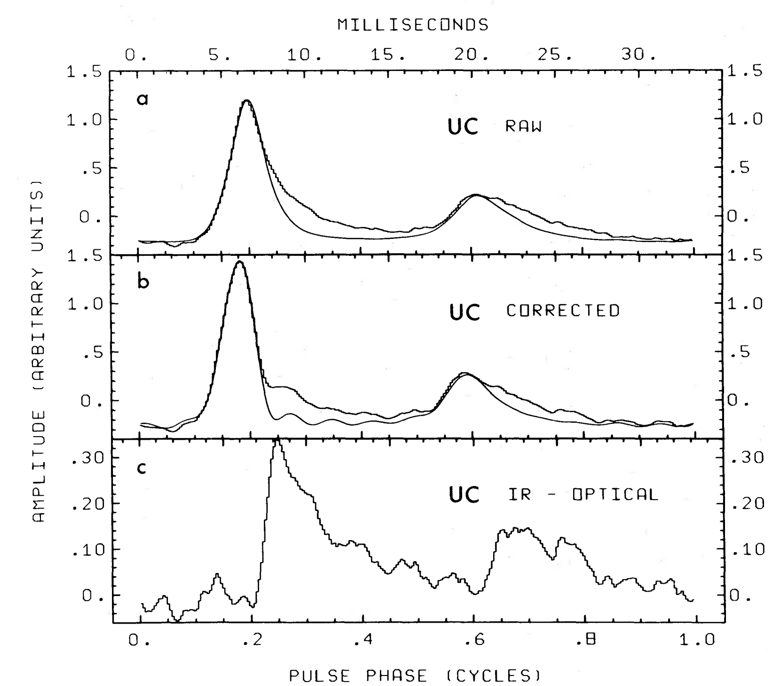

FIG. 1.—The 0.9–2.4 μm infrared pulse profile of the Crab pulsar (*histogram*) is plotted against the optical pulse profile (*curve*). Fig. 1*a* shows the raw infrared data and the optical pulse profile which has been convolved with the 5 ms/2π infrared detector response. Fig. 1*b* shows the two profiles after correction for this detector response through the 13th harmonic (390 Hz). The ripples present in both curves are due to the incomplete harmonic reconstruction of the corrected pulse profiles. Fig. 1*c* shows the difference between the infrared and the optical pulses—the "postcursor" or "shoulder" pulse of Pennypacker (1981).

significance of each harmonic was computed using the noise levels derived from the Fourier transforms of the time series. All harmonics, up to and including the 13th at approximately 390 Hz, which were more statistically significant than 2 standard deviations (power/local power greater than 3.0), were scaled according to the formula

$$a_n' = \{(a_n^2 - r)[1 + (nf_0/200 \text{ Hz})^2]\}^{1/2} \quad (2)$$

and the phases of the harmonics were increased according to

$$\phi_n' = \phi_n + \tan^{-1}(nf_0/200 \text{ Hz}) , \quad (3)$$

where f_0 is the frequency of the fundamental (approximately 30.06 Hz) and r is the local power level at nf_0. The original harmonics were subtracted from the pulse profiles, and the corrected harmonics were re-added. The G' light curve was similarly corrected; harmonics 1 through 13 were large enough that the noise level could be neglected (the power level in the 13th harmonic was 218 times the local level). A composite corrected infrared light curve was generated exactly as done for Figure 1*a* and is plotted against the best fit of the "corrected" optical light curve in Figure 1*b*. The ripples present in both curves of Figure 1*b* are due to the incomplete harmonic reconstructure of the corrected pulse profiles. The curves in Figure 1*b* are plotted at their corrected position, approximately 0.5 ms earlier than the uncorrected pulse profiles.

Figure 1*c* shows the difference of the two curves in Figure 1*b*. The curve rises from zero to its peak of 20% of the main peak height in 1 ms. The decay of this infrared excess is much slower, with an exponential time constant of 4 to 5 ms. A similar excess is also evident for the interpulse; the excess is possibly slower to decay than the excess associated with the main pulse. Both of these postcursor pulses peak approximately 2 ms following the usual pulse and interpulse peaks. The good agreement of the fits between the optical and infrared pulse profiles for most of the main peak argues against any flaw in the analysis described above. In addition, in tests with an infrared LED, the system faithfully reproduced a pulse similar to the Crab pulsar optical pulse. The harmonic reconstruction technique was also tested by restoring the pulse profile taken on RC1 (run 8), which was significantly degraded by this detector's slow response. We can think of no reason for this difference other than that it represents a real physical difference between the optical and infrared pulse profiles. This flux is barely discernible as a break in the slope of the main pulse in the less statistically significant data of Becklin *et al.* (1973; see their Fig. 1), but was originally noted by Pennypacker (1981).

More evidence in favor of the reality of the postcursor pulse and against any possible unusual behavior in the detector comes from the pulse profile obtained with the L filter (3.45 μm) shown in Figure 2. Although this curve is noisier than the *JHK-UC* composite curve, the fortuitous statistical result of "negative" flux following the main peak makes the existence of a postcursor pulse in L much less probable. In addition, the main peak of this pulse profile appears to be significantly narrower than the optical main pulse—the optical pulse is too wide, and consequently the fit falls short of the top of the infrared peak. In contrast, the fits to the J, H, and K profiles all satisfactorily

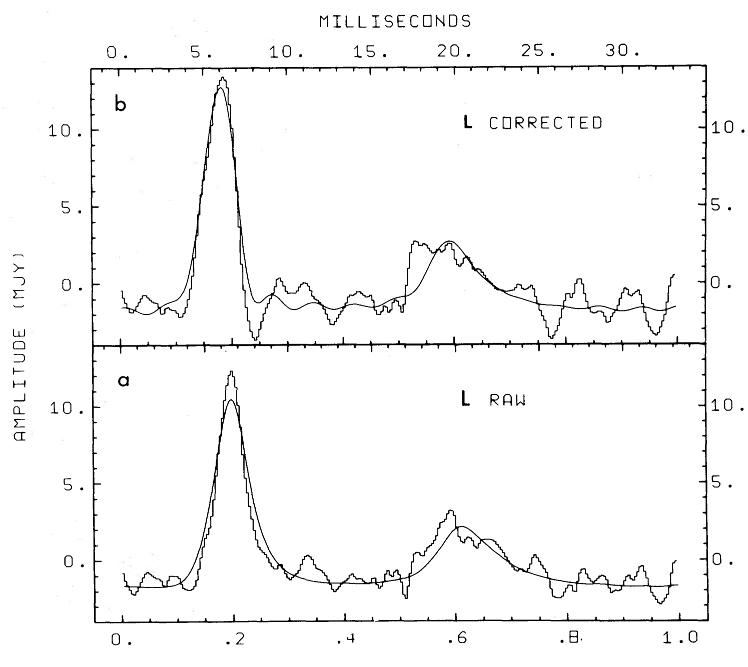

FIG. 2.—The pulse profile of the Crab pulsar in the L band (3.45 μm) is plotted with the best fit on the optical profile

TABLE 2

CALIBRATIONS

Band	Zeta Tauri (volts)	Magnitudes	Jy	0 Mag. (Jy)
J	0.33	3.20	79.8	1520
H	0.235	2.99	62.4	980
K	0.195	2.94	41.3	620
L	0.050	2.76	22.0	280
M	0.005	2.62[a]	13.6[a]	153
UC	0.860	...	...	...

[a] Values extrapolated from the shorter wavelengths.

match the widths of the main pulse until 1 ms past the peak, when the optical profile drops below the infrared profiles. There is also a suggestion that the pulse-interpulse separation may be less than in the optical pulse profile, although this difference may be due to statistical effects. Further study of the *L* pulse profile of NP 0532 is clearly warranted.

Because of the difference between the optical and infrared pulse profiles, the infrared fluxes were estimated by using the height of the main pulse, rather than by integrating the pulse area as done by Neugebauer *et al.* (1969) and Becklin *et al.* (1973). The RC2 detector was calibrated by measurements of the infrared standard star Zeta Tauri, whose *J*, *H*, *K*, and *L* fluxes were taken to be 79.8 Jy, 62.4 Jy, 41.3 Jy, and 22 Jy respectively. An *M* flux of 13.6 Jy was estimated by extrapolating a power-law fit from the *K*-*L* region. See Table 2. The power-law index was in turn determined by an extrapolation of the indices determined by sections of the infrared data. This index fell between 1.5 and 2.0, so that if the flux from Zeta Tauri is Rayleigh-Jeans beyond 3.4 μm, this technique will overestimate the *M* flux.

The infrared data were corrected for interstellar absorption by assuming the net absorption to be $0.817/\lambda$ (μm) mag. This is constant with Miller's (1973) measurement of 1.6 mag of absorption in the visual and the review of Aannestad and Purcell (1973) which generally places the infrared absorption slightly below the extrapolation from the visible bands. The absorptions applied are listed in Table 3. It is assumed that the airmass extinction corrections for the runs on NP 0532 and the calibrations on Zeta Tauri will cancel.

One other small systematic correction was applied to the data, the correction for the addition of noise. In effect, because of statistical fluctuations, the actual peak of the pulse profile as determined by rigorous fitting will be higher than the real peak because of the addition of noise (and the center of the fit will be shifted toward the location of the positive fluctuation). Accordingly, the *J*, *H*, and *K* fluxes were each decreased by approximately 5% depending on the net amount of noise in the composite pulse profiles. Because of the poor match of the *L* pulse profile to the optical light curve, no correction was made for this band.

The optical data of Oke (1968) were corrected for the interstellar absorption measured by Miller (1973). For this purpose, the optical pulse profile used for the data analysis was measured to estimate the height of the main pulse, given the integrated flux of the entire profile. If the integrated magnitude is 16.55 as seems likely (Kristian *et al.* 1970; Oke 1969), then the peak of the main pulse is 14.17 mag. This calibration was used to plot the data of Oke together with the infrared data of this work in Figure 3. The upper limit for the *M* pulse profile was established by folding the data at an estimated value for the apparent frequency of NP 0532.

The flux of 30–35 mJy for the *JHK* bands is consistent with Becklin *et al.*'s *K* filter measurement of $4.5(\pm 0.4) \times 10^{-31}$ J m^{-2} Hz^{-1} = 45($\pm$4) Jy s for the time-averaged energy in the main pulse. Using 1.75 ms as the FWHM of the main pulse and assuming an approximately triangular waveform, this time-averaged *K* flux corrects to 26($\pm$2) mJy which agrees reasonably with this work. However, the measurement of the *L* flux of Becklin *et al.* relative to their *K* flux is about 2 σ higher than our value. This inconsistency may be due to unfortunate statistics in the previously measured *K* and *L* fluxes or it may have been caused by the addition of noise to Becklin's data, by the process described above for the systematic correction to our infrared data. It is unlikely that this difference is caused by light loss outside of the 7″ circular aperture used in the *L* observation, since our entire data set was taken through 7″ or 5″ circular apertures. Moreover, the *J* flux

TABLE 3

MEASUREMENTS

PARAMETER	*V* Peak	*V* Mean	*J* Peak	*J* Mean	*H* Peak	*H* Mean	*K* Peak	*K* Mean	*L* Peak	*L* Mean	*M* Peak	*M* Mean
Raw mag	14.17	16.55	12.17	14.13	11.63	13.64	11.08	13.03	10.69	13.26	> 10.85	> 12.51
Interstellar absorption ..	1.6	1.6	0.65	0.65	0.50	0.50	0.37	0.37	0.24	0.24	0.17	0.17
Corrected	12.57	14.95	11.52	13.48	11.13	13.14	10.71	12.66	10.45	13.02	> 10.7	> 12.4
$F\nu$ (mJy)	33.9	3.8	37.5	6.16	34.6	5.43	32.24	5.35	18.5	1.73	< 8.0	< 1.7
$F\nu$ (corr. for noise)	...	...	35.5	...	32.2	...	30.0	...	18.5	...	...	...
Postcursor	< 2.7	...	8.5	...	9.1	...	7.5	...	< 1.0	...	...	...

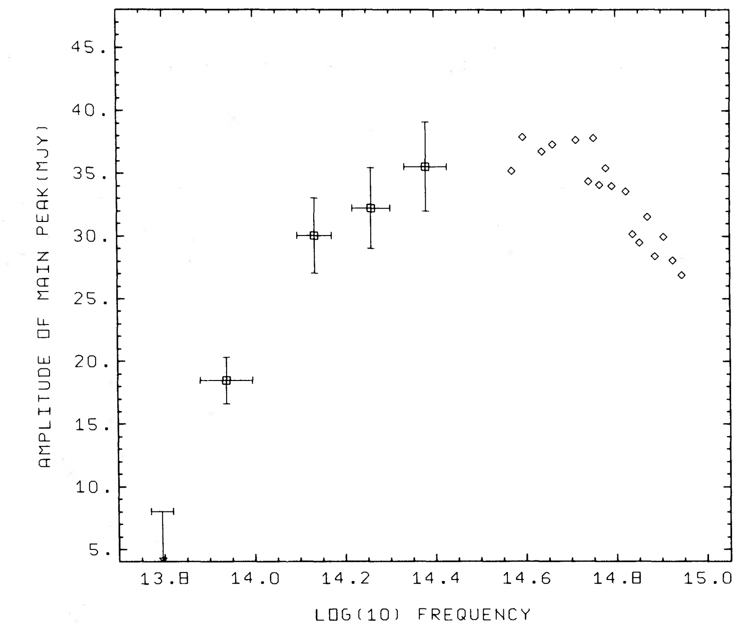

FIG. 3.—The infrared main pulse height of the Crab pulsar (*squares with error bars*) of this work are plotted with the optical measurements made by Oke (1969) (*diamonds*). No simple model fits this data well (see § IV).

derived from a run in a 5″ aperture (run 9) was at least 85% of the fluxes measured through the 7″ aperture (runs 3 and 5). Furthermore, the turnover in the *L* and *M* bands cannot be due to the systematics of the detailed analysis procedure described above, which has possibly *overestimated* these fluxes.

In view of the uncertainties involved in the estimation of the infrared main pulse heights, the errors were set at 15% of the measured values. Estimates for the heights of the postcursors to the main pulse are also listed in Table 3.

IV. DISCUSSION

No one single spectral model could adequately fit the data shown in Figure 3. Blackbody fits with T approximately 9000 K fitted Oke's optical data but fell far below the infrared points. Similar fits to the *M*, *L*, and *K* points of the infrared data surpass the *H* and *J* fluxes before turning over to fall through the optical data. Optically thin synchrotron models (Rybicki and Lightman 1979) can come close to matching the turnover toward the ultraviolet but cannot match the fall of the infrared points at the longer wavelengths.

It is possible that the turnover of the spectrum at infrared wavelengths is due to synchrotron self-absorption. The infrared spectrum rises with a spectral index of about $\frac{2}{3}$ in the infrared. Self-absorption produced in a nonuniform plasma and the nonuniform dipolar magnetic field of the pulsar can yield a spectral index of this value. However, self-absorption might tend to broaden the main pulse (Smith 1980), and this is not observed.

The origin of the postcursor pulse(s) is even more of an enigma. The long time scale decay is suggestive of radiative cooling, while the rapid rise suggests a geometrical change of the radiative direction—both effects might be produced by the neutron star. Finally, the apparent change of shape of the *L* pulse profile merits further investigation.

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