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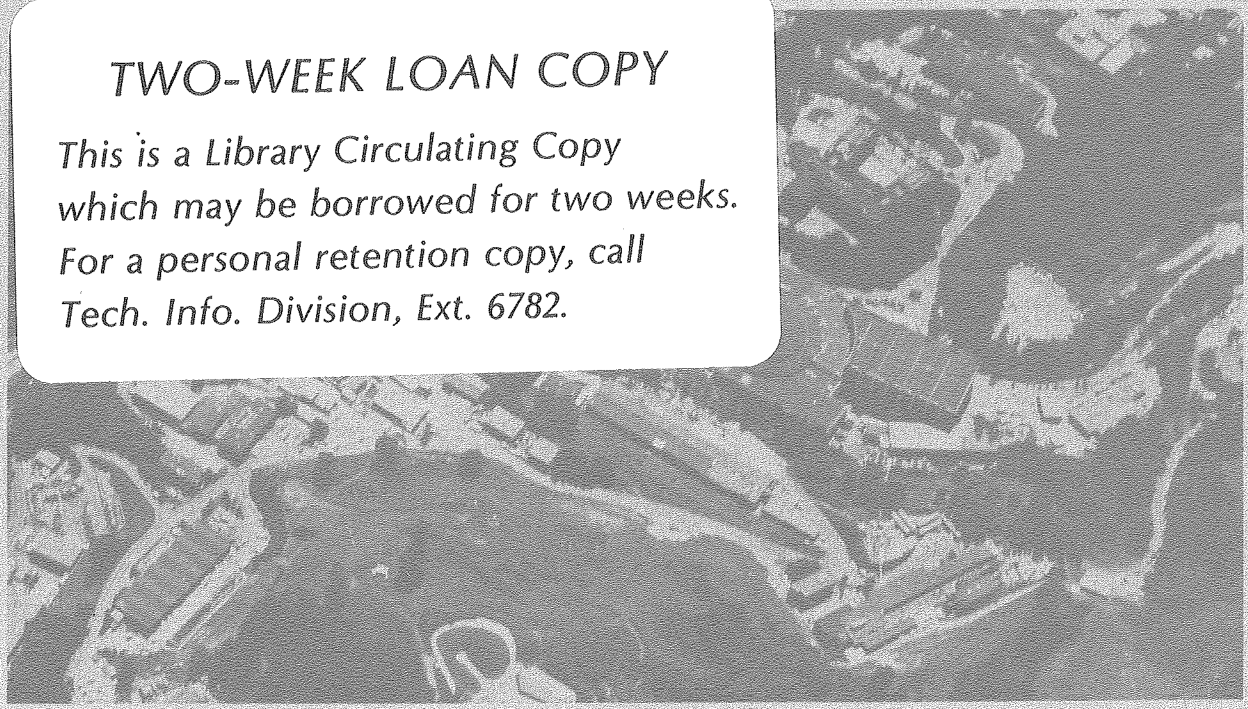

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DISCLAIMER

INFRARED STUDIES OF PULSARS

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ABSTRACT

The light curve of the Crab Nebula Pulsar has been studied in the near infrared (.9μm - 2.4μm) and found to be similar to the optical light curve except for a shoulder after the main peak. A search for infrared pulsations from other promising candidates was negative, with typical upper limits 3 - 5 magnitudes fainter than the Crab.

I. INTRODUCTION

The recent availability of low noise infrared detectors has prompted the following research, as part of a continuing program of pulsar observations. Although the number of detected radio pulsars is well past 200, there are still only four detected optical pulsars (Crab, Vela, HZ Herculis, and 4U1626-67). This disparity may be caused by synchrotron self-absorption (see Section IV), interstellar obscuration by dust, or some other emission mechanism with little optical output. The former two of these mechanisms allow radiation at near-infrared wavelengths to reach earth with much less attenuation than radiation at optical wavelengths. As a guide to the relative effects of interstellar absorption and scattering, we calculate that it would take approximately the same amount of time to detect a Crab-like pulsar in the optical part of the spectrum as it would in the infrared, if it was 3 kpc from the earth. However, because of the preferential absorption and scattering of the optical light by the interstellar grains (2 mag/kpc for visual and .34 mag/kpc for 1.6μ wavelengths), a Crab-like pulsar at 10 kpc would be detected in $\sim 3 \times 10^{14}$ sec in the optical, but would be detected in only $\sim 1 \times 10^{5}$ sec in the infrared.

Horowitz, et al. (1971) searched for pulsations from three radio pulsars in the 5 - 20μm range; Neugebauer, et al. studied the Crab pulsar in the near-infrared in 1969, and the Palomar group remeasured it in 1973 and found the pulsed 2.2μ magnitude 17.8 mag. (Becklin, et al.).

In this experiment, the light curve and infrared magnitude of the Crab pulsar were measured, and a search for infrared pulsations from a number of interesting radio pulsars, supernovae remnants, and X-ray stars was conducted.

II. TECHNIQUES

The infrared detector is similar to that used at other observatories (e.g., see Hall, et. al., 1975), but optimized for faster time response, and lower noise at high frequencies. It is a liquid nitrogen cooled InSb photodiode preceded by a cooled filter[1] passing .9 μm to 2.4 μm light. The preamplifier, a current-to-voltage converter, has a cooled field-effect transister (FET) front end, a cooled feedback resistor[2], and an ambient temperature monolithic operational amplifier. The FET selected for low voltage noise[3] is used in the "common-source" mode (voltage gain = 25).

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[1] Manufactured by Quantum Detector Technology, Burlington, MA

[2] Manufactured by Eltec Instruments, Inc., Daytona Beach, FL

[3] 2N6550, Manufactured by Crystalonics, Inc., Cambridge, MA

The noise at high frequencies (∿250 Hz) is due to the FET, so particular care was taken in its implementation.

The amplified electrical signal from the detector modulates a voltage-controlled-oscillator, which acts as the analog-to-digital converter. The output of the oscillator is then recorded in a manner similar to that used by Horowitz, *et. al*. (1971); i.e., recording the signal pulses on one channel of a stereo tape recorder simultaneously with clock signals (typically 5 KHz) on the other channel. These tapes are later digitized in the laboratory, and Fourier analyzed in sections of 512 x 1024 point transforms. Frequency domain results of successive transforms on the same object are stacked to increase the signal/noise ratio and maintain a high Nyquist frequency (250 Hz). For the Crab pulsar, the signal pulses are fed into a 1024-channel signal-averager, that sweeps synchronously with the pulsar period.

All observations were conducted at the 61" reflector at Agassiz Station, Harvard, Massachusetts.

III. RESULTS

a) Crab Nebula Pulsar Light Curve

A light curve observed (.9 μm - 2.4 μm wavelength) from the Crab pulsar is shown in Fig. 1a. Evident is the faster fall than rise in the main peak, and the converse in the interpulse observed in the optical light curve. We note, however, that there is a shoulder following the falling edge of the main infrared peak, that is not present in the optical light curve (Fig. 1b). Fig. 1c shows both the infrared light curve, and the optical light curve smoothed to match the infrared detector time constant and normalized to equalize the areas under the main peak. The shoulder is well above the noise, and is observed on every run. This shoulder contains about 20% ± 3% of the light of the main peak. Although the apparent size of the shoulder might have been reduced by normalizing the peaks differently, the disagreements between the other parts of the optical and infrared main peak and interpulse would have been even more striking. We present the shoulder interpretation as the most natural.

Careful testing of the equipment with a Crab-like electrical pulse driving an infrared light-emitting-diode, at Crab-pulsar signal levels, duty cycle, and repetition rate, always yielded a faithful reproduction of the test infrared light pulse, thus ruling out the shoulder as a systematic error.

b) Luminosity of the Crab Pulsar

The near-infrared energy per pulse of the Crab-pulsar was determined to be $(8\pm1.5) \times 10^{-31}$ joules/M^2/Hz (average flux≈ .24± .05 mJ_4).

This value is an average over the three infrared bands (I, J, and K), with the shoulder not included. It is corrected for interstellar absorption, and is within one-standard-deviation of the Palomar group's.

c) Upper Limits on Other Objects

A number of other interesting objects were examined including supernovae remnants, radio pulsars, and X-ray stars. Upper limits are presented in Table 1, and comments on individual objects are made in the discussion that follows.

Corrections to Table 1, because of variable noise, or partial harmonic summing for the objects of unknown period are listed in Table 2. Sections of a Fourier transform (plotted raster-like) of the Crab pulsar (near 30 Hz) are shown in Fig. 2a, and its summed harmonics in Fig. 2b. Because of line frequency induced microphonics in the front-end, the limits on unknown frequencies do not apply to 60, 120, and 240 Hz, ± .1 Hz.

The supernovae were searched using a 1 arc-minute aperture pointing at the best-defined (by the radio emission) center of the remnant. If a pulsar were born at the center of the remnant during the supernova explosion, and if it had typical pulsar proper motions, it would have moved less than half the aperture diameter from the center of the remnant since its birth.

IV. DISCUSSION

a) Infrared Crab Light Curve

The shoulder that follows the falling ecge of the main peak is the most interesting feature of the light curve. The earlier work on the Crab pulsar in the infrared (Becklin, *et. al.*, 1973) did not show a shoulder, although their noise was almost large enough to hide it. Note, however, that this experiment differs from Palomar's in the spectral coverage. Palomar looked at radiation from 2 to 2.4 μm--whereas this experiment looks at radiation from .9 to 2.4 μm wavelength.

b) Luminosity of the Crab

Our measurement of the energy per pulse from the Crab Nebula pulsar confirms, as observed by Palomar (Oke, 1969; Becklin, 1973), the departure from the higher-energy strict power law behavior. One of the most satisfactory explanations of this turnover is the phenomenon of synchrotron self-absorption, first applied to the Crab pulsar by Shklovsky (1970). For synchrotron radiation from a relativistic plasma of electrons of differential energy spectrum $\frac{dN}{dE} \alpha E^{-\gamma}$, the peak of the emission will occur (Pacholczyk, 1975) at frequency ν_1, where

$$(\nu_1)^{(\gamma+4)/2} = C_{14}(\gamma)(H \sin \Theta)^{\frac{1}{2}} \frac{F\gamma\nu^{(\gamma-1)/2}}{\Omega}$$

$F\gamma$ is the flux at some frequency γ at a higher frequency than the peak, H is the magnetic field and Θ the angle between it and the particles velocity, and $C_{14}(\gamma) = 7.22 \times 10^{30}$ for $\gamma = 3.4$. With typical neutron star and Crab flux parameters, the peak of the emission from the Crab is derived from this equation ($\sim 10^{14}$Hz), consistent with the measured peak. This evidence for synchrotron self-absorption causing the turnover in the higher energy portion of the spectrum allows some hope for detection fo infrared pulsations from radio pulsars.

c) Upper Limits for Pulsed Infrared Light from Radio Pulsars

One expects the higher energy emission from radio pulsars to peak in the infrared for several reasons. Ter Haar (1972), e.g., predicted, on the basis of fairly general thermodynamic assumptions, that the emission from slower pulsars will peak in the infrared. He claims that the higher energy emission from PSR 0950 would peak at 1.5 μm, PSR 0329 at 2 μm, etc.

Another reason for possible infrared peaking is synchrotron self-absorption. In this model, since the emergent radiation is less for slower pulsars, and for light-cylinder type theories, the magnetic field smaller and the solid-angle of emission larger, then the peak of the emission for slower pulsars will be in the infrared. The exact wavelength peak, using Pacholczyk's (Eqn.6.38) formula depends on where the emission originates (i.e., near the neutron star surface or further out) but in any case, it is in the infrared.

Pacini (1971) also argues that the emission peak, due to conventional synchrotron peaking, should occur in the infrared for slower pulsars.

For these reasons, it was considered worthwhile to investigate the radio pulsars for infrared pulses. No such pulses were seen, and the observed limits are shown in Table 1. This means that even in the near infrared, strict synchrotron self-absorption or synchrotron formulae are not of much use in predicting the intensity of radiation, based on results from the Crab (see Kristian, 1970). The Crab is still very much a unique pulsar.

d) Upper Limits on Supernovae Remnants

These results on the supernovae remnants rule out interstellar obscuration as the only reason for lack of detection of pulsars. The lack of a detected pulsar in 3C58, a Crab-like remnant, suggests that we are not in the pulsar beam pattern.

V. CONCLUSIONS

The Crab pulsar infrared light curve has been observed in the .9 μm to 2.4 μm window. A shoulder that does not exist in the optical data follows the main peak, and the infrared magnitude measurement of the pulsar by Becklin, *et. al*. (1973) is confirmed.

No other infrared pulsars were seen.

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Table I

Objects Searched and Upper Limits

Supernovae Remnants*	Magnitudes Fainter than the Crab Nebula Pulsar
3C58	4.3
Kepler's	3.2
Tycho's	3.7
Cas A	3.5
Radio Pulsars	
PSR	
0239	3.9
0611	3.6
0950	5.2
1749-28	3.4
1913+16	4.7
2002	4.9
X-ray Stars	
Hz-Herculis	4.1
Cyg X-3*	3.7

*Limits for 30 Hz given for SNR and Cyg X-3; for other frequencies, subtract column 3 of Table II.

Table II

Corrections to Table I

Frequency Dependence of Noise

Frequency (Hz)	Noise/(Noise @ 30 Hz)	Subtract this Magnitude from Stated Limit
.2	2.8	1.1
1	2.1	0.8
2	2	0.75
5	1.4	0.37
10	1.2	0.2
30	1	0
50	1	0
100	1.1	0.1
150	1.2	1.4*
200	1.3	1.5*
250	1.4	1.6*

*No harmonic summing at these frequencies.

FIGURE CAPTIONS

Figure 1a: The infrared light curve of the Crab Nebula pulsar. The time axis is binned in units of 30μsecs.

Figure 1b: The optical light curve of the Crab pulsar, from Horowitz, et al., 1971. The horizontal scale is the same as in Figure 1a.

Figure 1c: Comparison of the infrared and optical light curve of the Crab pulsar. In the subtraction of the optical curve from the infrared curve, shown at the bottom, the negative spike coincident with the peak of the main pulse is an artifact of the alignment of the two curves. The main positive broad shoulder following the main peak is always present irrespective of minor changes in alignment and normalization.

Figure 2a: Portion of the power spectrum of the Crab pulsar near 30 Hz. The peak in the fourth line is the fundamental mode of the pulsar. The frequency bins are ∿.002 Hz wide, and are plotted raster like.

Figure 2b: Sum of the power in the fundamental and the power in the succeeding five harmonics of the fundamental frequency of the Crab pulsar, showing power vs. frequency. The rows are .4 Hz wide, are plotted raster like, and the plot begins at 29.2 Hz.

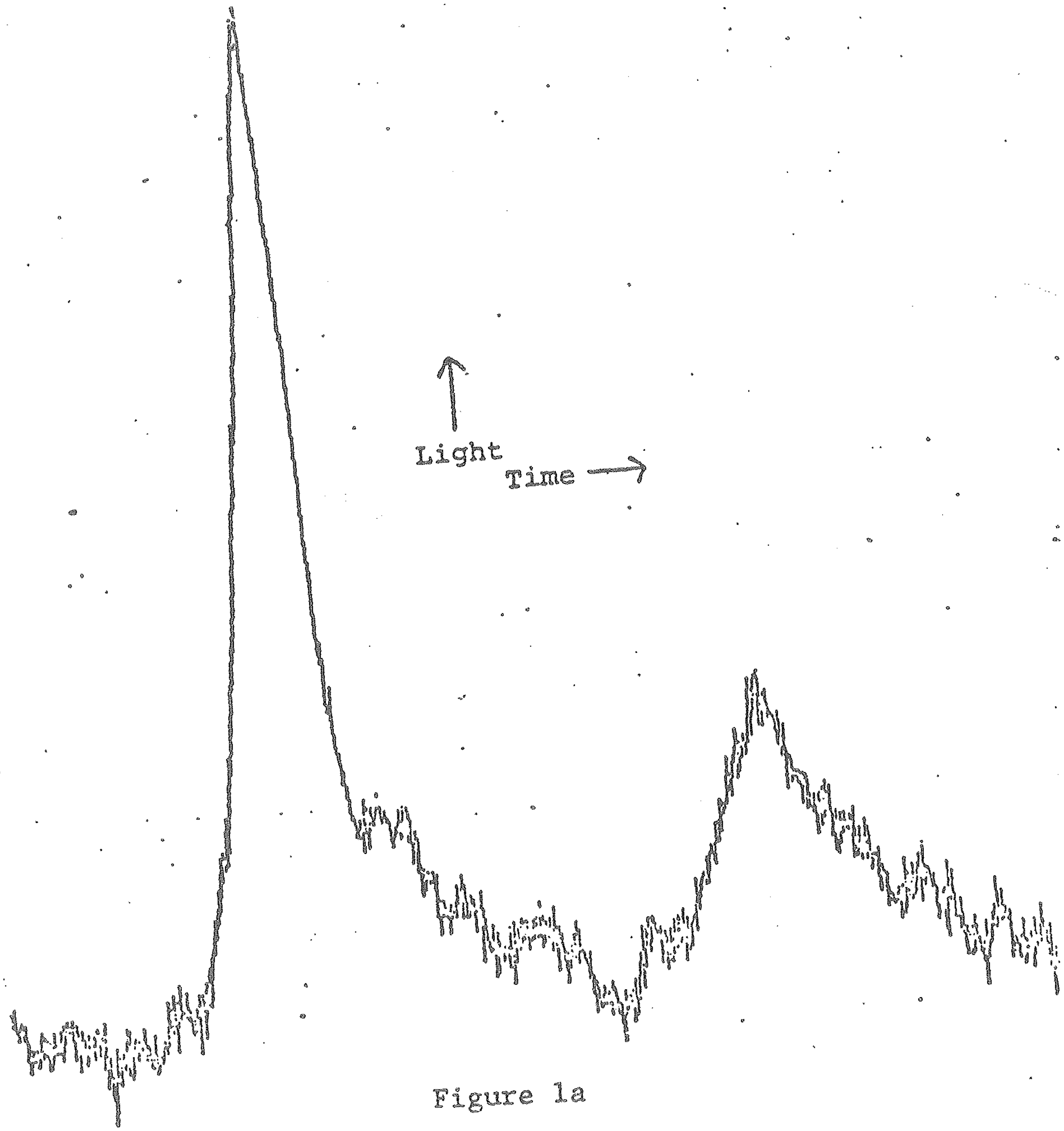

Figure 1a

Infrared Light Curve

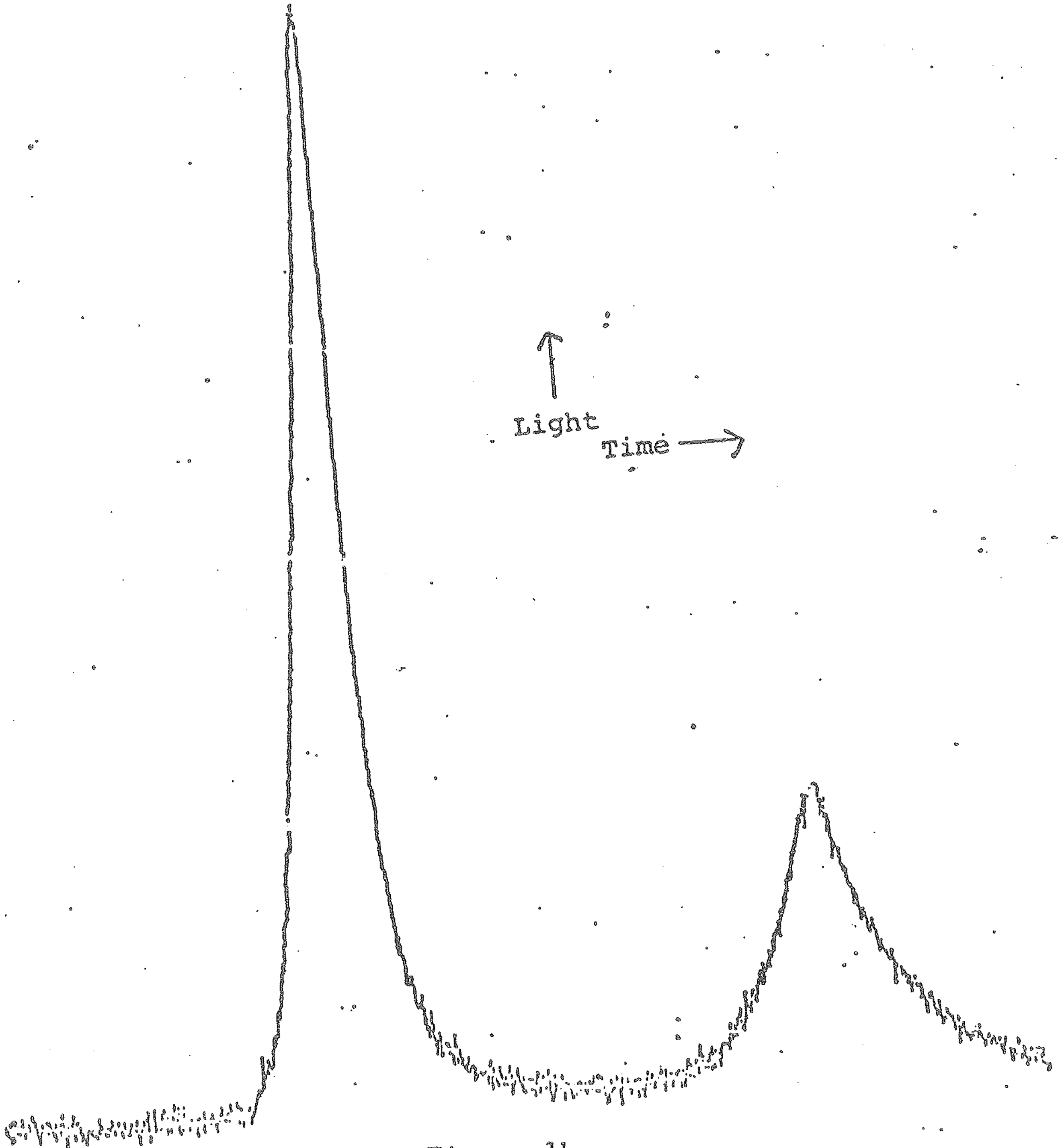

Figure 1b

Optical Light Curve

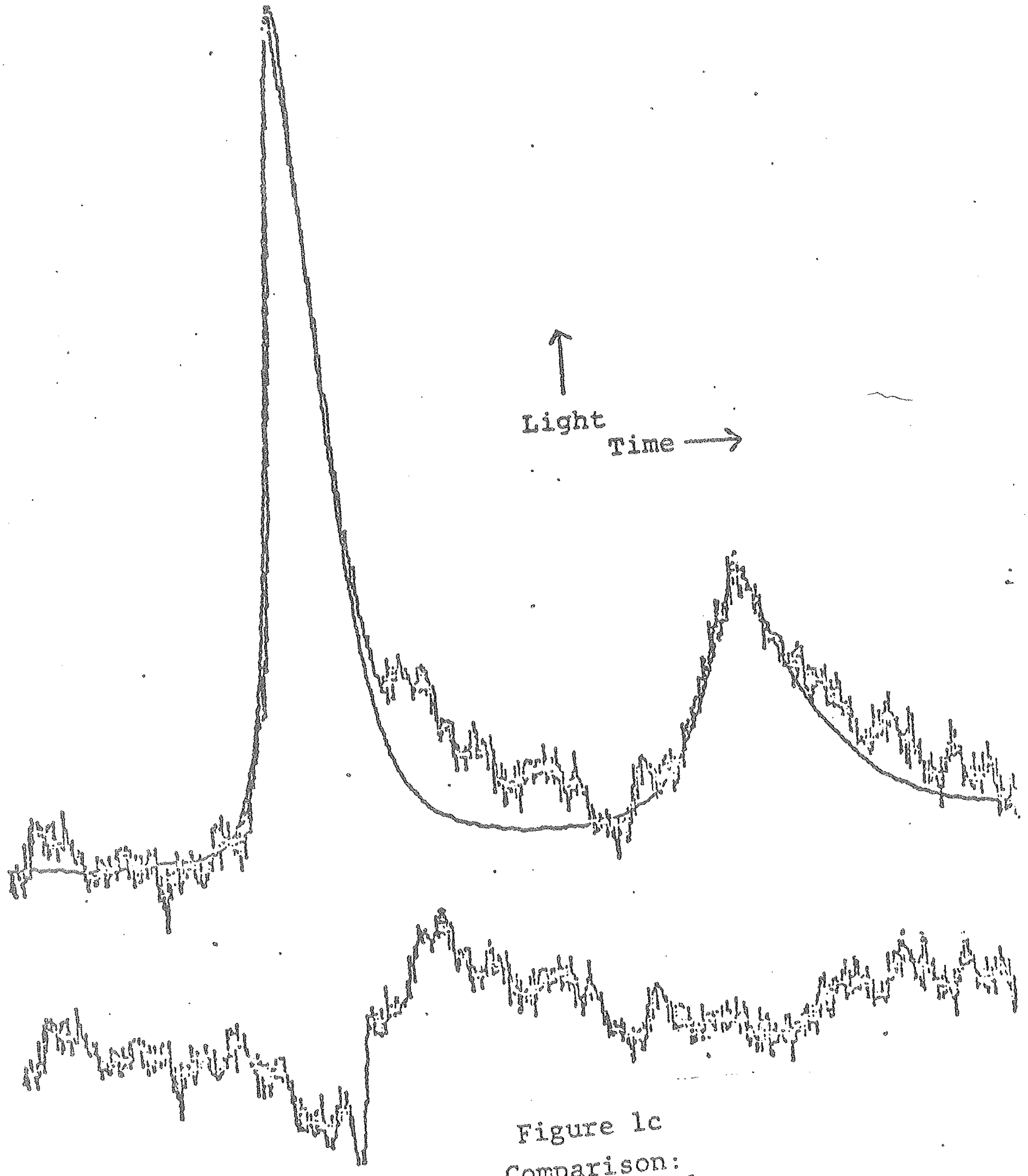

Figure 1c
Comparison:
IR vs. Optical

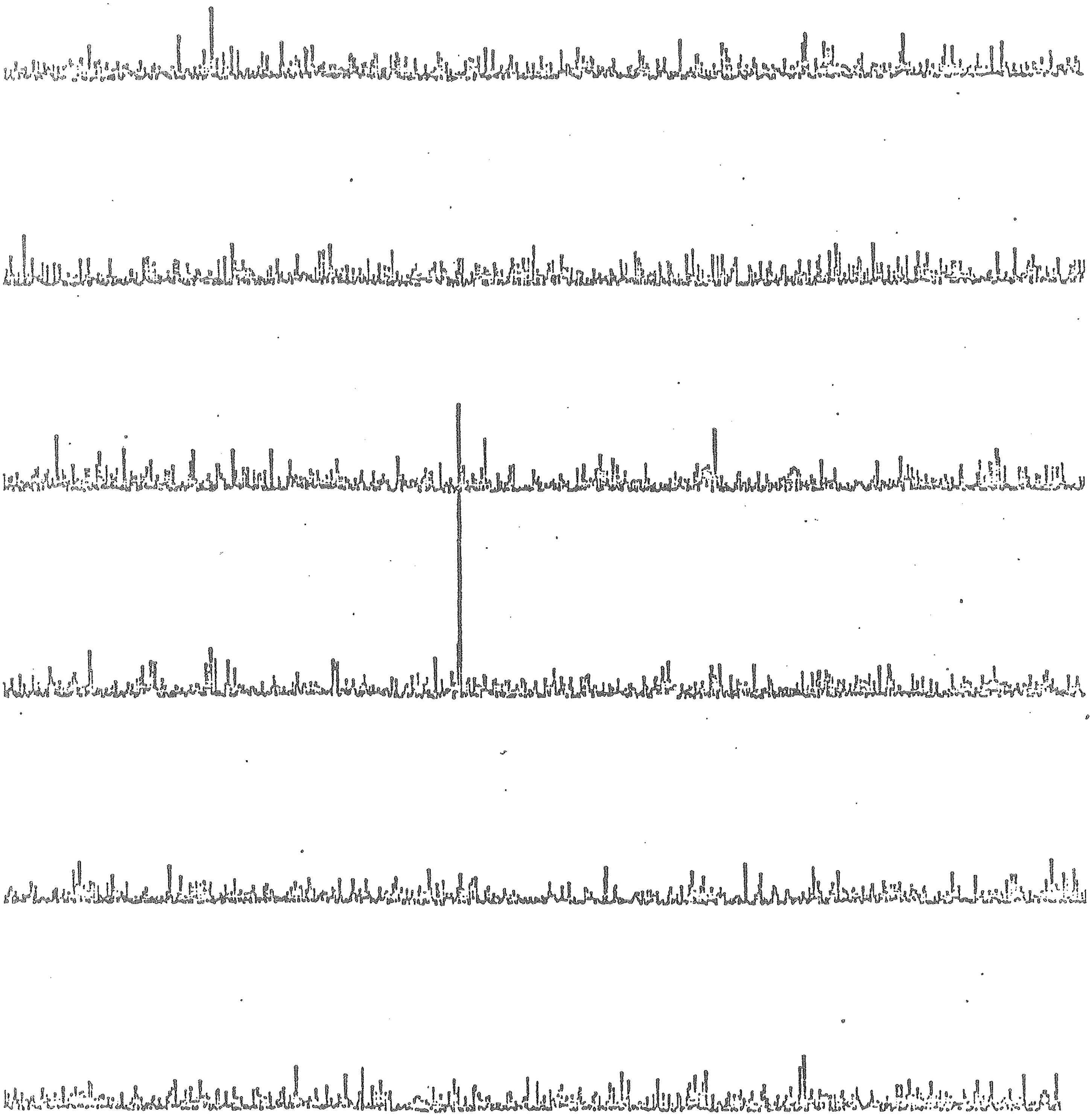

Figure 2a

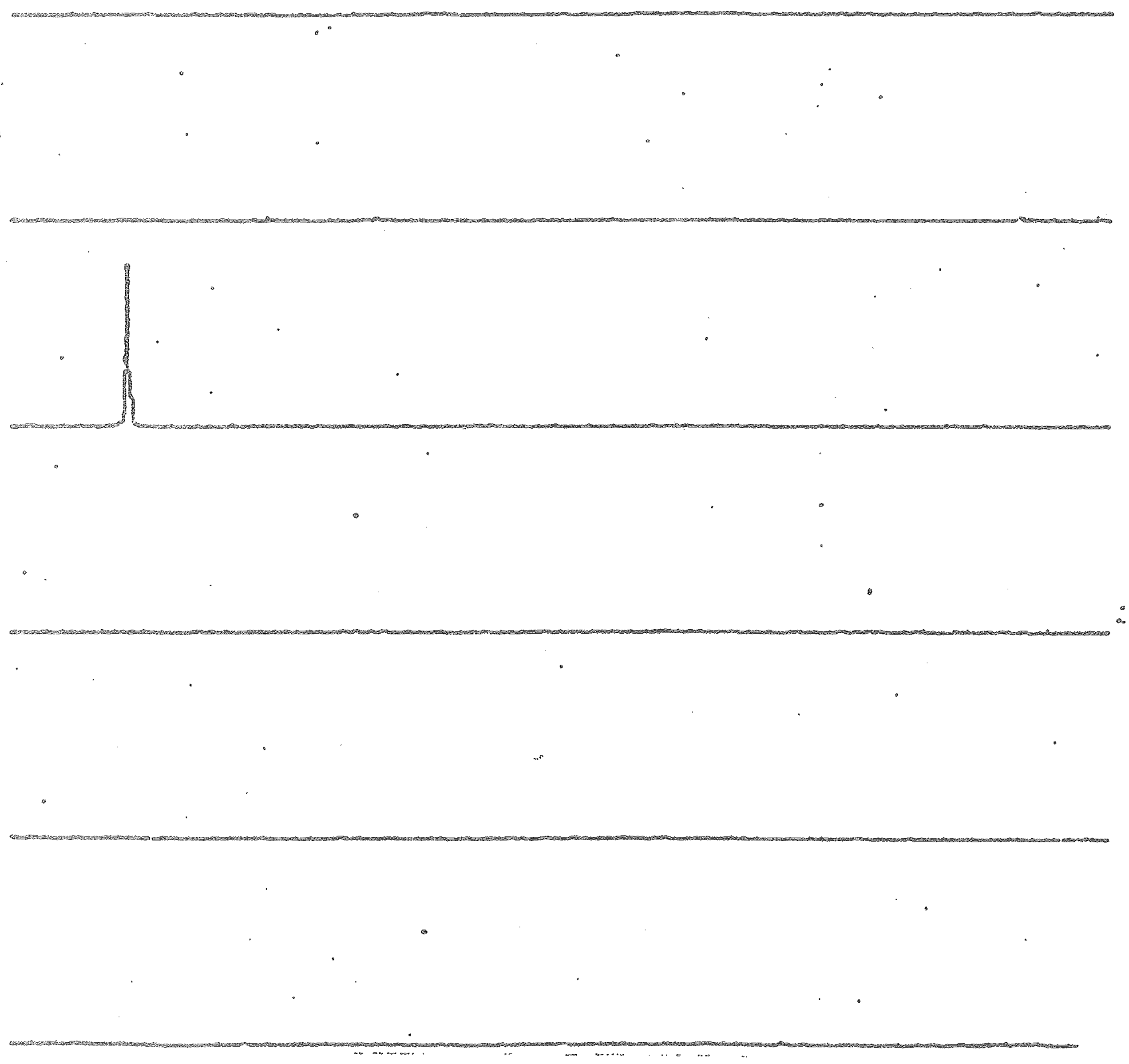

Figure 2b

Summed Harmonics from Power Spectrum of Crab

(plotted raster-like, .4Hz/line, starting at 29.2 Hz)

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