OPTICAL SPECTRUM OF MAIN-, INTER-, AND OFF-PULSE EMISSION FROM THE CRAB PULSAR
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ABSTRACT
A dedicated stroboscopic device was used to obtain optical spectra of the Crab pulsar main pulse and interpulse as well as the spectrum of the underlying nebula when the pulsar is turned off. Since the nebular emission is very inhomogeneous, our ability to effectively subtract the nebular background signal is crucial. No spectral lines intrinsic to the pulsar are detected. The main pulse and the interpulse behave as power laws, both with the same dereddened index $\alpha = +0.2 \pm 0.1$. This value was obtained by subtracting the nebular spectrum at the exact position of the pulsar. The underlying nebula is redder, $\alpha = -0.4 \pm 0.1$. Its emission lines are split into approaching ($\sim -1200$ km s$^{-1}$) and receding ($\sim +600$ km s$^{-1}$) components. The strength of the emission line components and the flux in the nebular continuum vary on an arcsecond scale. The nebular line and continuum intensities along the north-south slit are given.

Subject headings: pulsars: individual (PSR B0531+21) — stars: neutron — supernova remnants — techniques: spectroscopic

1. INTRODUCTION
The Crab pulsar (PSR J0534+2200 = PSR B0531+21) was the first pulsating radio source identified at optical wavelengths (Cocke, Disney, & Taylor 1969; Lynds, Maran, & Trumbo 1969). Most subsequent studies have concentrated on the pulse shape in various photometric bands (Percival et al. 1993; Eikenberry et al. 1996; Perryman et al. 1999; Lundqvist et al. 1999). They generally suggested small color variations in the light curve. No spectroscopic data existed until Nasuti et al. (1996) obtained the first optical spectrum. They were able to measure the general flux distribution as well as hint at an unidentified intrinsic absorption feature at 5920 Å. Their spectrum is phase averaged so no information on spectral variation with pulse phase can be extracted.

Here we present the first flux-calibrated optical spectrum, separately for the main-pulse, the interpulse, and the off-pulse components. The spectra of both pulses are compared with phase-resolved photometric studies. Except for a very small ($\sim 1\%$) contribution from the pulsar (Golden, Shearer, & Beskin 2000), the off-pulse spectrum, also presented here, corresponds to the nebular emission along the line of sight of the pulsar.

2. OBSERVATIONS
Observations were obtained with the LFOSC spectrograph at the 2.12 m telescope of the Observatorio Astrofísico Guillermo Haro in Cananeq, Mexico. The useful wavelength range was 4370–9000 Å and the spectral resolution was $\sim 15$ Å. The slit of 2" width was kept in the north-south direction.

The light entered the spectrograph through a frequency and phase controlled chopper. The device, described by Čadež & Galičić (1996), was used before on the same telescope to study the optical light curve of the pulsar. A blade allows light to enter the spectrograph for 10% of each pulse period. This collection window is synchronized with the pulsar and kept on the desired pulse-phase interval. We use the most recent of the Jodrell-Bank monthly Crab ephemerides that have been translated from the solar system barycenter and include real-time corrections for the Earth’s orbital motion. Long photometric observations confirmed that the difference between the pulsar and the chopper phase remains within 5 $\times$ 10$^{-4}$ for at least 3 hours (Čadež et al. 2000). However, the initial chopper-pulsar phase is set by maximizing the apparent magnitude of the pulsar so that the absolute phase is only accurate to 0.03 (Galičić 1999).

Observations were obtained on 1998 December 13 and 14 and on 1999 October 18 and 20 under nearly photometric conditions and $\sim 1$" seeing. A total accumulated exposure on the main pulse and the interpulse was 11,700 and 9000 s, while the total off-pulse observing time was 10,200 s. The off-pulse interval was chosen $\sim 0.25$ in phase after the main pulse. Several direct images of the pulsar field were obtained in order to control the atmosphere transparency and phase of the pulsar. The wavelength calibration is generally good to 2 Å and somewhat worse at the blue end. The flux calibration, obtained through several exposures of the star EG 50 and Hiltner 600, is accurate to 5% in both color and absolute fluxes. All spectra were obtained between air masses 1.01 and 1.3. The pulsar spectra were dereddened assuming that $E_B-V = A_V/3.1 = 0.51$ (Percival et al. 1993) and that

$$A_v/E_B-V = -7.51 \log (\lambda/\lambda_0) + 1.15; \lambda_0 = 1 \mu m, \quad (1)$$

which follows the average Galactic extinction curve (Savage & Mathis 1979) to better than 1% for $0.48 < \lambda/\lambda_0 < 1.0$.

Spectra were reduced with standard IRAF routines used according to our particular purpose. First, all the spectra were aligned with respect to the tracing of the pulsar and of another star 11'.4 south of the pulsar. In order to achieve an optimal flux calibration, a relatively wide aperture of 7" was used, which included all pulsar-related flux and allowed for any wavelength variations of the focus of the spectrograph. All individual spectra were flux calibrated, but no nebular
background was subtracted at this stage. That was done subsequently by subtracting the off-pulse flux-calibrated spectrum. This technique makes an assumption-free subtraction of any nebular light, scattered light, or telluric contributions. The chopper effectively enables us to take the pulsar off the sky and subtract the nebular emission at the pulsar's exact position. This is important since the nebular emission is varying on arcsecond scale (cf. § 4).

### 3. Pulsar

The flux-calibrated dereddened spectra of the main pulse and interpulse are presented in the upper panel of Figure 1. The surface flux of the underlying nebula is plotted in the lower panel. Both axes are plotted in logarithmic scale. The colors of the main-pulse and interpulse continuum are identical, but the nebular continuum is redder (see Table 1).

The pulsar's spectrum features no lines apart from telluric bands and weak nebular-line residuals. Note that the [O i] λ5579 line is of telluric origin. The upper limits to equivalent widths of nebular lines are 5 and 10 Å for the main pulse and interpulse, respectively. This translates to the very stringent limits on absolute fluxes of pulsed emission lines that are given in Table 2. We did not find any trace of the λ5920 absorption feature hinted by Nasuti et al. (1996). We conclude that they were right in attributing this feature to imperfect flux calibration of their spectrum.

Note that the nebular continuum is rather strong. The use of the 0.1 phase window with the chopper suppressed it by a factor of 10, however. This emphasizes the advantage of our observing method.

### 4. Nebula

Davidson (1979) published the first study of selected condensations in the Crab Nebula. Nasuti et al. (1996) discuss the nebular spectrum 2° east of the pulsar position. Our slit had a north-south orientation, so a brief discussion of the spectrum along this direction as well as directly on the pulsar position is in order.

The shape of the (dereddened) nebular continuum is constant along the slit (a = −0.4 ± 0.1) except for its strength. Spatial variations of surface flux continuum (dereddened nebular continuum per square arcsecond) are shown in the lower panel of Figure 2. The horizontal axis is the relative displacement in north-south direction with respect to the position of the pulsar, and the vertical axis displays the continuum surface flux at 6000 Å. There is a chance superposition of a star 11.4 south of the pulsar, so no flux is given around its position.

The upper panels of Figure 2 give the dereddened surface fluxes of emission lines as a function of position relative to the pulsar. The lines are generally well separated into approaching and receding components (Fig. 3). The exception is a blend of the red component of [O iii] λ4959 and the blue component of its λ5007 counterpart that are plotted together. The H i λ6563, [N ii] λλ6548 + 6584 region was resolved assuming a standard 3:1 ratio of the [N ii] line intensities.

All lines show well-separated red and blue components that are similar to those reported by Nasuti et al. (1996). Component velocities, given in Table 3, remain constant (to

### Table 1

| Flux | K  | a  |
|------|----|----|
| Main pulse | $5.9 \times 10^{-15}$ | $+0.2 \pm 0.1$ |
| Interpulse | $1.9 \times 10^{-15}$ | $+0.2 \pm 0.1$ |
| Underlying nebula | $3.4 \times 10^{-15}$ | $-0.4 \pm 0.1$ |

**Note.**—In the 0.1 phase window centered on the main pulse and interpulse. The last row is the unpulsed flux of the underlying nebular continuum in the 1 arcsecond box centered on the pulsar. $F_p = K \times (\lambda/\lambda_0)^{-a-2}$, $\lambda_0 = 6000$ Å, 5000 $< \lambda < 7500$ Å. Fluxes are in ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$. All data were dereddened using eq. (1).

### Table 2

| Lines | Main Pulse | Interpulse | Nebula |
|-------|------------|------------|--------|
| [O iii] λλ4959 + 5007 | $<1.0 \times 10^{-13}$ | $<8.2 \times 10^{-14}$ | $8.4 \times 10^{-12}$ |
| [O i] λ6300 | $<1.3 \times 10^{-14}$ | $<1.2 \times 10^{-14}$ | $8.6 \times 10^{-13}$ |
| [O i] λ6363 | $<9.5 \times 10^{-15}$ | $<8.8 \times 10^{-15}$ | $2.6 \times 10^{-13}$ |
| H i + [N ii] λλ6548 - 6584 | $<2.5 \times 10^{-14}$ | $<3.0 \times 10^{-14}$ | $4.5 \times 10^{-12}$ |
| [S ii] λλ6716 - 6731 | $<2.2 \times 10^{-14}$ | $<2.7 \times 10^{-14}$ | $2.4 \times 10^{-12}$ |

**Note.**—Upper limits to dereddened fluxes (in ergs s$^{-1}$ cm$^{-2}$) of nebular emission lines for the 0.1 phase window centered on the main pulse and the interpulse. The last column gives fluxes of nebular lines in a 2° (east-west) × 6′9 (north-south) box centered on the pulsar.
Fig. 2.—Panels a–f: Spatial variation of fluxes of the nebular emission lines. Flux is in $10^{-13}$ ergs s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. The slit had a north-south orientation; distance along the slit is given with respect to the position of the pulsar. Thick lines refer to a receding component, and thin lines refer to an approaching component of each line. Components of [O III] lines are overlapping, so we plot the receding component of $\lambda5007$ (bold line), the approaching component of $\lambda4959$ (normal), and the sum of $\lambda5007$ (blueshifted) and $\lambda4959$ (redshifted) (dashed line). Flux errors are $\sim 0.15 \times 10^{-13}$ ergs s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ (2 $\sigma$), rendering them smaller except for the [O I] lines. Panel g: Flux in the continuum at 6000 Å in units of $10^{-15}$ ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$ arcsec$^{-2}$ per panel. Region $\sim 11'$ south of the pulsar is omitted because of contribution of a chance superposition star.

within 200 km s$^{-1}$) up to $\sim 30'$ from the pulsar. All lines show similar velocity shifts, $\sim 1800$ km s$^{-1}$, except for the very strong receding component of [O III] $\lambda4959$ and 5007 lines, which are receding at double velocity.

The intensity of the blue and red components is highly spatially variable and uncorrelated (Fig. 2). A simple interpretation is that of an expanding shell, which has been proposed already by Davidson (1979). The receding components of forbidden nebular lines show a wide pronounced peak $\sim 3'$ north of the pulsar. The slope of the condensation, however, extends well behind the pulsar itself. The approaching components are generally weaker and show a condensation $\sim 4'$ south of the pulsar. The kinematics and strength of Hα are similar to those of forbidden lines, but a pronounced receding component to the north of the pulsar is missing.

5. DISCUSSION AND CONCLUSIONS

The main result of this work is the flux calibrated time resolved spectrum of the Crab pulsar. It shows no intrinsic spectral lines with the continuum following a power law with $\alpha = +0.2 \pm 0.1$. The spectra of the main pulse and the interpulse are identical; the flux of the main pulse multiplied by 0.32 equals that of the interpulse (Fig. 4), where the formal upper limit to the difference in the power law index for the main pulse and the interpulse is 0.01 (2 $\sigma$). The above value of $\alpha$ refers to dereddened main-pulse and interpulse spectra with nebular spectra subtracted at the exact area of the pulsar’s point-spread function. This crucial subtraction was made possible by the dedicated chopper device that effectively enabled us to take the pulsar off the sky.

### TABLE 3

| Lines    | Approaching | Receding |
|----------|-------------|----------|
| [O III] $\lambda4959, 5007$ | $-1200 \pm 100$ | $+1150 \pm 100$ |
| [O I] $\lambda6300, 6363$    | $-1050 \pm 200$ | $+600 \pm 200$ |
| H i $\lambda5563$            | $-1200 \pm 100$ | $+650 \pm 100$ |
| [N II] $\lambda6548, 6584$  | $-1200 \pm 100$ | $+650 \pm 150$ |
| [S II] $\lambda6716, 6731$  | $-1300 \pm 200$ | $+650 \pm 200$ |

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The underlying nebula is redder ($\alpha = -0.4 \pm 0.1$) and of varying intensity. We expect that this fact may explain why the power-law index for the pulsar spectrum reported in the literature is slightly redder than the one deduced here. Nasuti et al. (1996) find that $\alpha = -0.1 \pm 0.01$ in optical spectrum. Gull et al. (1998) give $\alpha = -0.1 \pm 0.2$ (if $E_{B-V} = 0.51$ is assumed) in the UV spectrum. Without the possibility of directly subtracting the off-pulse spectrum, one must make a model for the surrounding nebula. We simulated such modeling and took as an example the nebular spectrum that is 4° north and south of the pulsar as the background. This led to the derived value of $\alpha = +0.1$ in very good seeing (FWHM ~ 0.7) or even 0.0 in more mediocre conditions. We also note that errors below 0.1 in $\alpha$ appear unrealistic, since they imply a color calibration accurate to better than 7%—a goal difficult to achieve on a patchy nebular background and given the uncertainties in the extinction law.

We detected no color variation in the pulsed light. Photometric investigation of Eikenberry et al. (1996) reports slight color variation on pulse slopes. Note, however, that our observations were obtained close to the centers of the main pulse and interpulse. So the two studies are somewhat difficult to compare; we present flux-calibrated spectra with slightly uncertain absolute phase, while Eikenberry et al. have an excellent phase definition but lack absolute color calibration. Romani et al. (1999) report on a relative decrease of the main-pulse flux in the IR ($1.4 \mu m < \lambda < 1.8 \mu m$) with respect to the optical spectrum ($0.38 \mu m < \lambda < 0.83 \mu m$). We cannot confirm a similar trend in our optical spectra, even if the breaking of the power law beyond 800 nm could possibly be interpreted in this way. Since the nebular spectrum has a similar break, we would like another independent confirmation. A phase-resolved spectrum of the Crab Nebula was presented by Perryman et al. (1999). In agreement with our results they detected no color dependence of the pulse shape in the optical. Note, however, that a limited resolution ($\sim 100$ nm) and performance of the otherwise promising superconducting tunnel junction detectors together with modest seeing prevented them from flux-calibrating their spectrum and subtracting the nebular contributions. By perfecting the stroboscopic technique we were able to obtain the spectrum of the pulsed emission of the Crab pulsar on a medium size telescope. We are now using the same technique to identify optical counterparts of known radio pulsars.

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Note added in proof.—Recent observations of the Crab pulsar in the UV and visual light (J. Sollerman et al., ApJ, 537, 861 [2000]) point to a similar value of the power law index.