Polarization is about the same as in the radio regime, positions of the MP and IP, the fraction of visible linear profiles they show large P.A. variations. At the peak (Smith et al. 1996) polarization profiles show similar linear the Crab pulsar has been available.

The visible wavelength (Smith et al. 1988) and ultraviolet (Smith et al. 1996) polarization profiles show similar linear polarized fractions as the radio, but unlike the radio profiles they show large P.A. variations. At the peak positions of the MP and IP, the fraction of visible linear polarization is about the same as in the radio regime, ≈14%–17%. In the region after the IP in phase, the percentage polarization rises to ≈47% ± 10%, and the P.A. rises above the IP angle and remains nearly constant across the total intensity minimum. Narayan & Vivekanand (1982) found that the visible wavelength polarization P.A. sweeps of the MP and IP suggest that emission comes from two opposite poles of a pulsar whose magnetic axis is nearly orthogonal to the rotational axis. However, arguments from gamma-ray emission theory have surfaced recently (Manchester 1995; Romani & Yadigaroglu 1995) that question this type of geometry by claiming that emission arises from a wide cone in the outer magnetosphere.

So far, the study of radio polarization has not improved our knowledge of the emission and field geometry. The lack of P.A. variation in low-frequency radio profiles is difficult to explain in terms of the simple rotating vector model (RVM; Radhakrishnan & Cooke 1969). Following the serendipitous discovery of additional components in the Crab pulsar’s profile in Paper I, a program of polarization observations was scheduled to study the high radio-frequency polarization characteristics of these new components, perhaps improving the interpretation of the polarization and emission location for the Crab pulsar’s radio components.

1. INTRODUCTION

Past studies of the polarization properties of the Crab Nebula pulsar have been limited to low-frequency radio and visible wavelengths. The pulsar’s steep radio spectrum and interference from the radio-bright nebula make observations above 1 GHz difficult with single-dish antennas. Thus, interpretations of the pulsar’s emission geometry have only been made from the properties of its polarized profiles at visible wavelengths.

Single-dish average profile measurements of the radio polarization are available at frequencies between 110 and 1664 MHz (Manchester, Huguenin, & Taylor 1972; Manchester 1971a). Prior to the work described in Moffett & Hankins (1996, hereafter Paper I), only three components of the pulsar’s average profile were known: a steep-spectrum precursor, which is approximately 100% linearly polarized (Manchester 1971a), plus a main pulse (MP) and interpulse (IP), which are roughly 15% to 25% linearly polarized. The position angle (P.A.) remains constant between all three components, with very little change of P.A. across them. The only other major radio polarization observations that have been published are measurements of the time-variable rotation measure used to probe the magnetic fields of the Crab Nebula’s filaments (Rankin et al. 1988). No high radio-frequency (ν > 1.7 GHz) polarization information for the Crab pulsar has been available.

The visible wavelength (Smith et al. 1988) and ultraviolet (Smith et al. 1996) polarization profiles show similar linear polarized fractions as the radio, but unlike the radio profiles they show large P.A. variations. At the peak positions of the MP and IP, the fraction of visible linear polarization is about the same as in the radio regime, ≈14%–17%. In the region after the IP in phase, the percentage polarization rises to ≈47% ± 10%, and the P.A. rises above the IP angle and remains nearly constant across the total intensity minimum. Narayan & Vivekanand (1982) found that the visible wavelength polarization P.A. sweeps of the MP and IP suggest that emission comes from two opposite poles of a pulsar whose magnetic axis is nearly orthogonal to the rotational axis. However, arguments from gamma-ray emission theory have surfaced recently (Manchester 1995; Romani & Yadigaroglu 1995) that question this type of geometry by claiming that emission arises from a wide cone in the outer magnetosphere.

So far, the study of radio polarization has not improved our knowledge of the emission and field geometry. The lack of P.A. variation in low-frequency radio profiles is difficult to explain in terms of the simple rotating vector model (RVM; Radhakrishnan & Cooke 1969). Following the serendipitous discovery of additional components in the Crab pulsar’s profile in Paper I, a program of polarization observations was scheduled to study the high radio-frequency polarization characteristics of these new components, perhaps improving the interpretation of the polarization and emission location for the Crab pulsar’s radio components.

2. OBSERVATIONS

Observations were conducted during several sessions from 1995 October to 1996 October at the Very Large Array (VLA) of NRAO. Between 1996 February 22 and April 18, the data acquisition system was modified to double the number of filter-bank channels that are recorded. Using the phased VLA, the coherent sum of undetected right-hand and left-hand circular polarization (R and L) from all antennas is mixed to 150 MHz and then split into 14 independent frequency channels by a MkIII VLBI filter bank. The filter-bank output is sent to the VLA’s High Time Resolution Processor (HTRP), which consists of a set of 14 multiplying polarimeters. Channels of detected and smoothed LL, RR, RL cos θ, and RL sin θ, where θ is the phase offset between R and L, are continuously sampled by 12 bit analog-to-digital converters in a PC and recorded on disk at a time resolution of 256 μs. The detector time constants are set to optimize sampling of the dispersed time series across the channel bandwidths.

The observations were scheduled so that short scans (typically 30–40 minutes apart) of an unresolved calibrator point source were made between pulsar scans to keep the VLA phased and to record on- and off-source data for flux and polarization calibration of the pulsar data. Within the duration of an observing session, anywhere from five to seven sets of measured Stokes parameter fluxes were recorded from the phase and flux calibrator, 3C138, with enough parallactic angle coverage for instrumental polarization calibration. The flux density and P.A. of 3C138 are regularly monitored by the University of Michigan Radio
Astronomy Observatory. The P.A. of this source remains the same over our frequency coverage, with a value of $\psi = -12^\circ$.

The pulsar data were folded off-line at the pulsar’s topocentric period using a timing model initially provided by D. J. Nice (1995, private communication). Consequent observations of the Crab pulsar using the Princeton/Dartmouth Mark III Pulsar Timing System (Stinebring et al. 1992) provided time-of-arrival (TOA) information reduced using the program TEMPO (Taylor & Weisberg 1989), which yielded new timing solutions for folding at later epochs. Individual channel data were folded into 2 minute average profiles of all four detected polarizations prior to calibration and dedispersion.

The gain amplitudes, relating the received voltage in the data acquisition system to flux density in jansky’s for the $LL$ and $RR$ detector signals, were determined by observation of the phase calibrator source and blank sky. The gain amplitude of the cross polarizations, $RL \cos \theta$ and $RL \sin \theta$, were found directly from solutions for the circular polarization gains $G_L$ and $G_R$ from $LL$ and $RR$, by using $G_{RL} = (G_R G_L)^{1/2}$. For data collected from the lower side-band channels of the MkIII VLBI videoconverters, the sign of the measured Stokes U was inverted, thus removing a known 180° phase shift caused by the image-rejecting mixers within the videoconverters.

Polarization calibration was completed following procedures similar to those used by McKinnon (1992). The polarization characteristics of the phased VLA approximate those of a single-dish antenna with circular polarization feeds. An ideal antenna with orthogonal circular polarization receivers has no cross-coupling. However, imperfections in the reflectors and receiving systems of antennas tend to change the received radiation from purely linear polarized sources into elliptical polarization (Conway & Kronberg 1969).

McKinnon’s method involves measuring the time-dependent Stokes parameters of a polarization calibrator source with respect to the changing parallactic angle and solving for time-dependent and independent instrumental corrections. McKinnon used the polarization from a point source with an amplitude 1%–2% of the MPÈblank sky. For data collected from the lower side-band channels of the MkIII VLBI videoconverters, the sign of the measured Stokes U was inverted, thus removing a known 180° phase shift caused by the image-rejecting mixers within the videoconverters.

Polarization calibration was completed following procedures similar to those used by McKinnon (1992). The polarization characteristics of the phased VLA approximate those of a single-dish antenna with circular polarization feeds. An ideal antenna with orthogonal circular polarization receivers has no cross-coupling. However, imperfections in the reflectors and receiving systems of antennas tend to change the received radiation from purely linear polarized sources into elliptical polarization (Conway & Kronberg 1969).

McKinnon’s method involves measuring the time-dependent Stokes parameters of a polarization calibrator source with respect to the changing parallactic angle and solving for time-dependent and independent instrumental corrections. McKinnon used the polarization from a point in a pulsar’s profile to perform a self-calibration, but he could not determine the absolute P.A. We could have used the Crab pulsar at 1.4 GHz to perform such a self-calibration, but at higher frequencies we were limited by low signal-to-noise ratios. Instead we used a phase calibrator of known polarization characteristics to solve for the instrumental corrections and absolute P.A. at 1.4, 4.9, and 8.4 GHz.

3. RESULTS

Our results at 1.4 GHz (Fig. 1) are similar to published observations at 1.664 GHz (Manchester 1971a, 1971b), but with the addition of three more components (see Paper I, Fig. 2). These three are labeled LFC for “low frequency component,” as it mainly appears at $v < 2$ GHz, and HFC1 and HFC2 for “high-frequency component 1 and 2’’ as they appear only at $v \geq 1.4$ GHz. The MP and IP are both linearly polarized, 25% and 15%, respectively, and their relative P.A.’s are nearly the same. The LFC component is more than 40% linearly polarized, and it has a P.A. offset $\approx 30^\circ$ from the MP, which sweeps down toward the MP. There is also low-level emission after the IP, coincident in phase with components HFC1 and HFC2 found in the total intensity profiles at 4.9 GHz (Paper I). These components are more than 50% polarized, and their P.A.’s appear to be relatively the same, offset from the MP by 60°.

The circular polarization undergoes a sense reversal centered on the MP with an amplitude 1%–2% of the MP peak. We can exclude this as a cross-coupling signature, even though our uncertainties for fitting the instrumental parameters were several times higher for individual frequency channels. The linear polarization is not strong, nor does it sweep rapidly across the pulse at our time resolution. So a coupling of linear to circular power should not produce sense-reversing circular polarization. We can make no comparisons because no previous circular polarization observations of average profiles have been published. The similarity of circular polarization signatures on separate observation dates, and in individual channels, improves our confidence that these signatures are real.

The profiles at 4.9 GHz (Fig. 2) confirm the detection of the HFC components found in Paper I. The pulsar was visible for only three out of seven observing sessions; the profile was formed from about 3.7 hr of data. We attribute the nondetections to heavy scintillation, which affected observations at 4.9 GHz and higher frequencies. The IP, HFC1, and HFC2 are highly polarized, 50%–100%,
while the MP seems to have the same polarized fraction as at 1.4 GHz. HFC1 and HFC2 share a common range of P.A., but it sweeps through them with different slopes. The most important feature to note is the IP. Its relative flux density has increased with respect to the MP, and it has shifted earlier in phase by $\approx 10^\circ$ (see Paper I, Fig. 2).

At 8.4 GHz (Fig. 3), the profiles show some polarization and also confirm the profile morphology found in earlier total intensity observations. The pulsar was visible for only one out of three observing sessions for a total of 2.3 hr, which we again attribute to scintillation. The IP seen in the profile is substantially wider than at lower frequency and the fractional polarization of the IP and HFCs is reduced. As in Paper I, no evidence is found of the MP, whose predicted flux from a spectral index of $\alpha = -3$ (§ 4.3) is below the noise level of the profile recorded at this frequency.

Observations made on 1996 April 18, 19, and 20 were conducted at several frequencies within the 1.4 GHz receiver band, and evidence for Faraday rotation was found between the separate frequencies. A rotation measure, $\text{RM} = -46.9 \text{ rad m}^{-2}$, was found after comparing the P.A.'s of the major components, and its effects have been removed from all profiles reported here. Past measurements show the RM near $-43.0 \text{ rad m}^{-2}$ (Rankin et al. 1988), but it is known to be variable on timescales of months, as the line of sight to the pulsar passes through the Crab Nebula’s filaments. After removing Faraday rotation effects, the P.A.'s of the MP, HFC1, and HFC2 are found to align at 1.4 and 4.9 GHz, and the P.A.'s of the IP, HFC1, and HFC2 align at 4.9 and 8.4 GHz. However, the IP is found to have a P.A. difference between 1.4 and 4.9 GHz of 90$^\circ$ (see Fig. 4). So the IP has a discontinuous change of positional phase, flux, and polarization between 1.4 and 4.9 GHz. It obviously cannot be the same component at both frequencies.

4. ANALYSIS

The unique and confusing discoveries described in the previous section are the first successful, fully polarimetric observations of the Crab pulsar above the 1.4 GHz band. In the following sections, this pulsar’s emission geometry is explored by comparing properties of the its polarization profile with known properties of other pulsars and possible emission geometry models.

4.1. Multiple Components

The components of the Crab pulsar appear in six distinct positions in rotational phase at all observed radio fre-
Fig. 4.—Comparison plot of polarization P.A.’s at 1.424 GHz (filled circles), 4.885 GHz (open circles), and 8.435 GHz (squares). Note the 90° P.A. separation of the IP between the 1.4 GHz and higher frequencies.

Fig. 5.—Phase separation of selected components from the MP with frequency. MP-IP separation at low frequencies lie on a line drawn at \( \delta \phi = 0.406 \). Best-fit lines and solutions are shown for HFC1 and HFC2.

IP are generated at higher altitudes where the emission beam is much wider. However, we note that interpreting the frequency-dependent properties of the IP and the HFCs with this geometric model is quite difficult.

Another set of components, the LFC, precursor, and MP, form what may be a cone/core triplet. The LFC–MP separation is \( \approx 45° \), nearly what one expects for the inner conal width, and the precursor behaves much like a core component, with its high polarization and steep spectrum (Rankin 1990). But why the MP is so much brighter than the LFC requires explanation.

It is interesting to note that one pulsar, B1055 – 52, has a similar distribution of components (precursor, MP, and a strong IP located 155° away) at low frequency (McCulloch et al. 1976). And like the Crab, it also has pulsed high-energy emission X-rays (Ogelman & Finley 1993) and pulsed gamma-rays (Fierro et al. 1993), and it has been recently detected as continuum source at visible wavelengths (Mignani, Caraveo, & Bignami 1997).

4.2. Radius to Frequency Mapping?

Using the MP as the fiducial point of the Crab’s profile (Paper I), we found that the separations from MP to IP, and from MP to the HFCs are frequency-dependent (see Fig. 5). From 1.4 to 4.7 GHz, the IP jumps \( \approx 10° \) earlier in phase, while the HFCs appear to make a smooth linear transit in phase between 1.4 and 8.4 GHz. This property is reminiscent of the smooth phase shift of conal components in radius-to-frequency mapping (Cordes 1978; Rankin 1983b; Thorsett 1991). The phase separation of conal components usually can be best fit by a power-law function, \( \Delta \phi \propto \nu^p \), where 1.1 \( \leq \eta \leq 0.0 \). The phase separations from the MP to both HFC1 and HFC2 are best fit with \( \eta = 1 \) (fit parameters found in Fig. 5). The HFCs are both moving toward later rotational phase with increasing frequency, unlike conal components of other pulsars, whose phase separation decreases to a common fiducial point. Curiously, the HFCs

The phase separation between the MP and IP, \( \Delta \phi_{MP-IP} \approx 140° \), is too low to argue for a line of sight crossing of both poles. When compared with the high-energy emission (infrared to gamma-ray), the morphology of the MP and IP implies that they arise from a wide conal beam, high above a single pole (Manchester 1995). With the wide-beam picture in mind, one apparent symmetry in the distribution of the Crab’s components can be seen if we draw a line through the midpoint between the MP and IP and the midpoint between HFC1 and HFC2 (see Fig. 3 of Paper I). The midpoints between the component pairs are separated by \( \approx 170° \) at 4.9 GHz. So the Crab’s components could arise from conal emission regions above both poles, one wider than the other. In fact, the HFCs do show promise as a conal pair. Rankin’s (1993a) empirical relations for inner and outer conal width (assuming the Crab to be an orthogonal rotator, \( x = 90° \)) yield

\[
\rho_{\text{inner}} = (2 \times 4°33) \nu^{-1/2} = 47°3,
\]
\[
\rho_{\text{outer}} = (2 \times 5°75) \nu^{-1/2} = 62°8.
\]

The phase separation of the HFCs, \( \Delta \phi_{HFC1-HFC2} \approx 56° \), is within Rankin’s predicted values for inner and outer conal widths for a pulsar of the Crab’s period. It is possible that the HFCs are generated at low altitudes, and the MP and

quencies. The distribution of components is difficult to explain in a low-altitude, dipolar, or hollow-cone emission models (Rankin 1983a; Lyne & Manchester 1988), mainly because of their number and wide separation. Up to five components have been seen from “normal” pulsars (PSR B1237 + 25 and B1857 – 26). The separation of profile components is usually restricted to a small range of pulse phase (\(< 30°\)), corresponding to a cone of emission above one pole of the star. However, a few interpulsars exist, whose components can be attributed to emission from the observer’s line of sight passing above both poles (orthogonal rotator) or from one pole (aligned rotator).

The phase separation between the MP and IP, \( \Delta \phi_{MP-IP} \approx 140° \), is too low to argue for a line of site crossing of both poles. When compared with the high-energy emission (infrared to gamma-ray), the morphology of the MP and IP implies that they arise from a wide conal beam, high above a single pole (Manchester 1995). With the wide-beam picture in mind, one apparent symmetry in the distribution of the Crab’s components can be seen if we draw a line through the midpoint between the MP and IP and the midpoint between HFC1 and HFC2 (see Fig. 3 of Paper I). The midpoints between the component pairs are separated by \( \approx 170° \) at 4.9 GHz. So the Crab’s components could arise from conal emission regions above both poles, one wider than the other. In fact, the HFCs do show promise as a conal pair. Rankin’s (1993a) empirical relations for inner and outer conal width (assuming the Crab to be an orthogonal rotator, \( x = 90° \)) yield

\[
\rho_{\text{inner}} = (2 \times 4°33) \nu^{-1/2} = 47°3,
\]
\[
\rho_{\text{outer}} = (2 \times 5°75) \nu^{-1/2} = 62°8.
\]

The phase separation of the HFCs, \( \Delta \phi_{HFC1-HFC2} \approx 56° \), is within Rankin’s predicted values for inner and outer conal widths for a pulsar of the Crab’s period. It is possible that the HFCs are generated at low altitudes, and the MP and...
would merge at a common point at the MP phase if their phases are extrapolated to a frequency above 60 GHz.

4.3. Spectral Index

The amplitude calibration method for these observations was based on gains transferred from a standard extragalactic continuum calibration source, whereas the flux densities in the profiles presented in Paper I were estimated using known radiometer characteristics. We used the integrated flux density under the major components and computed spectral indices for the MP and IP:

\[ \alpha_{mp} = -3.0 \] for the MP, and \[ \alpha_{ip} = -4.1 \] for the IP at \( f \leq 1.4 \) GHz. Independent of the uncertainty of the flux density measurements, the relative spectral index differences between components were determined simply through ratios of their integrated flux densities using the following relation:

\[
\frac{S_{C1}(v_1)/S_{C1}(v_2)}{S_{C2}(v_1)/S_{C2}(v_2)} = \frac{v_1}{v_2} (\alpha_{C1} - \alpha_{C2}),
\]

where the fluxes, \( S \), and spectral indices, \( \alpha \), correspond to the components C1 and C2. The spectral index difference of components using these ratios yields a spectral index, \( \alpha_{pc} \approx -5.0 \) for the precursor. The spectral indices we have found for the three major components of the Crab pulsar profile agree with previous measurements by Manchester (1971a).

In Figure 6, we plot the flux density spectrum of the MP and IP and of the two HFC components. Below 1.4 GHz, the IP follows a power-law spectral index of approximately \(-4\), but above 1.4 GHz, the plot shows that the IP has a flat spectral index, as do the HFC components, although no power-law can be determined from the plot. Such a turn-up or flattening of pulsar spectra has been observed by Kramer et al. (1996) in two other pulsars. They have suggested that a transition from coherent to incoherent emission would cause changes in the expected flux density. Sampling pulsar radiation at very high frequencies gives limits to the bandwidth of the coherent emission mechanism. A simple extrapolation of the Crab pulsar spectrum from radio to infrared wavelengths (Fig. 4-2 in Manchester & Taylor 1977) implies that the flux must rise and the emission mechanism must change. So the change in spectral index lends support to our hypothesis that the low-frequency IP and high-frequency IP are two different components.

We should note that when compared with other pulsars, the spectral indices of the Crab pulsar’s MP and IP are much steeper than the components of other pulsars (\(-1.5 < \alpha < -3\)). The Crab’s mean spectral index, \( \alpha_{crab} = -3.1 \), is also greater than the average spectral index, \( \alpha = -1.5 \), of most detected pulsars (Lorimer et al. 1995).

4.4. Polarization Properties

The polarization P.A. of the Crab changes across the full period, although not significantly within components. There are no sudden well-defined P.A. sweeps (S-shaped sweeps) within components, as seen at optical wavelengths. However, we should note the radio components are much narrower, and some polarization information is smeared by dispersion and scattering. The lack of P.A. variation between close components implies that the observer’s line of sight trajectory does not fall close to the magnetic poles, where the P.A. of field lines varies quickly.

The fraction of linear to total intensity of the MP and HFCs is nearly constant from 1.4 to 4.9 GHz. But the IP becomes substantially more polarized (from 20% to 100%) between the two frequencies, as well as undergoing a 90° P.A. shift. The spectral change in phase and P.A. could be due to a mechanism (birefringence) affecting the propagation of the two orthogonal modes (ordinary, or O-mode, and extraordinary, or X-mode) of linear polarized radiation within the pulsar’s magnetosphere (Barnard & Arons 1986). The ordinary mode waves are forced to travel along magnetic field lines, while the extraordinary mode waves are unaffected. A sudden change in plasma conditions could cause one of the modes to be beamed out of the line of sight. However, this process is sensitive to frequency, and any transitions we see should be continuous. The change of the phase and P.A. of the IP between 1.4 and 4.9 GHz is rather abrupt, but this does not rule out birefringence effects, since we have not yet seen the IP at an intermediate frequency (Moffett & Hankins 1996).

In general, the polarized fraction of other pulsars decreases with frequency, and the P.A. gradient is independent of frequency (Xilouris et al. 1996). It is generally believed that pulsar depolarization toward higher frequencies is due to the instantaneous superposition of emitted orthogonal or quasi-orthogonal polarization modes (Stinebring et al. 1984a). Our results seem to indicate that one polarization mode dominates the emission from the IP and HFCs for \( f > 1.4 \) GHz.

Following the standard RVM, the polarization P.A. traces the projected magnetic field of the pulsar if emission occurs along the open field lines. The P.A. of the RVM is given by Manchester & Taylor (1977) as

\[
\psi(\phi) = \psi_0 + \tan^{-1} \left[ \frac{\sin \alpha \sin (\phi - \phi_0)}{\sin \zeta \cos \alpha - \cos \zeta \sin \alpha \cos (\phi - \phi_0)} \right],
\]

where \( \psi_0 \) is a P.A. offset, \( \phi_0 \) is the pulse phase at which P.A. variation is most rapid, \( \alpha \) is the inclination angle from the rotation axis to the magnetic axis, and \( \zeta \) is the angle...
between the rotation axis and the observer’s line of sight. The observer’s impact angle with the magnetic axis is just the difference $\beta = \zeta - \alpha$. It can also be determined from the maximum slope of P.A. with phase by using

$$\left(\frac{d\psi}{d\phi}\right)_{\text{max}} = \frac{\sin \alpha}{\sin \beta}.$$  

This simple geometric construct is only useful if emission is located close to the polar cap, since the line-of-sight angle $\zeta$ in the model passes through the center of the star (which is not the case in reality).

We have made rudimentary fits of equation (1) to our polarization profiles in an attempt to match polarization signatures to the low-altitude dipole model. In Figure 7, we plot the P.A.’s of the Crab’s major components at 1.4, 4.9, and 8.4 GHz with the best fit to the RVM overplotted. The RVM does not fit well for the case where the P.A. of the IP at all frequencies is left at its 1.4 GHz value, so we have shifted the IP P.A. at 1.4 GHz by $90^\circ$ to match the that at higher frequency. From the fit, the angle found between the rotation and magnetic axes is $\alpha = 56.0^\circ$, with one pole projected near the IP and the other near the LFC. With $\alpha$ fixed in equation (2), the slope of the P.A. of phase yields an impact angle, $\beta \approx 51^\circ$, for the IP. The LFC has a smaller impact angle, $\beta \approx -30^\circ$, and the maximum slope of the fitted curve occurs just ahead of the LFC. At this location, $\beta \approx -18^\circ$. The impact angles for the components near the IP are much larger than those found from other pulsars (Rankin 1993b; Lyne & Manchester 1988). The fitted impact angles are much larger than the polar cap width expected for the Crab pulsar, given by Goldreich & Julian (1969) as $\rho_{PC} = (2\pi r/cP)^{-1/2} = 4.56$, where $\rho_{PC}$ is the width of the polar cap, $r$ is the height above the surface, $c$ is the speed of light, and $P$ is the pulsar’s rotational period. So our solution to the RVM fit appears to find emission both close to (LFC) and well away from (IP, HFC1, and HFC2) expected low-altitude dipole fields above the polar cap.

Our radio wavelength RVM fit does not agree with values found from fitting the visible wavelength P.A. sweeps (Narayan & Vivekanand 1982): $\alpha = 86^\circ$, $\beta_{MP} = 9.6^\circ$, and $\beta_{IP} = -18^\circ$. The large inclination angle and the small observer impact angles of this fit imply that both poles sweep by the observer. However, the visible wavelength fits were obtained by only fitting for the maximum sweep through each component individually, not by fitting the P.A. over the whole pulsar period.

A simple comparison of the visible polarization profiles (Smith et al. 1988) and the high-frequency radio profiles show a few similarities. First, the P.A. of the MP and IP at 1.4 GHz matches the visible P.A. at the phase of the radio components. And although P.A.’s of components at higher radio frequency do not match the visible, the P.A.’s and polarized fraction of both the visible and radio profiles increase in the region occupied by HFC1 and HFC2.

5. EMISSION GEOMETRY

It is difficult to interpret the emission geometry from the profile morphology and polarization measurements we have acquired. There are six sites in rotational phase where pulsed emission occurs and some evidence of radius to frequency mapping. The HFC components appear to be separated by a width comparable with the conal width expected of a pulsar of this period (Rankin 1993a, 1993b), as do the LFC and MP pair. The precursor may even be a core-type component between the LFC and MP. However, the sweep of P.A. through these components is shallow, suggesting that radiation comes from far outside a low-altitude emission cone.

So far, our interpretation has followed a simple emission geometry proposed by Smith (1986), which places the location of emission at both low and high altitudes. The MP and IP are generated in the inner magnetosphere, near the light cylinder, where the dipolar fields are swept back, and the rotational phase of components and their P.A.’s is not the same as above the polar cap. Although no clear evidence of field sweep back has been found for pulsars, if the emission does originate at high altitudes, the swept-back dipole fields of the pulsar would allow the MP and IP to be formed from either the two sides of the same dipole cone above one pole or from just the leading edges of dipolar fields above both poles of an orthogonal rotator (Smith et al. 1988). The precursor and LFC are then generated close to the surface of the star above one pole. However, this simplistic model does little to interpret the HFC components, how the IP’s properties change, or the nature of the polarization P.A.

Another model, proposed by Romani & Yadigaroglu (1995), ties gamma-ray emission of several pulsars to particle production in an outer magnetospheric gap. Through Monte Carlo simulations of particles in the gap, they have generated gamma-ray profiles similar to the Crab and Vela pulsars and have successfully generated a polarization P.A. profile similar to that of the optical polarization of the Crab by projecting the magnetic fields (or polarization of high-energy photons) in the outer gap. Using this model, it is even possible to find a less powerful outer gap surface that could drive particle acceleration at rotational phases where HFC1 and HFC2 reside (Romani 1996). The processes by which radio radiation is generated in the outer magneto-
sphere are still unknown, although they must be similar to normal pulsar radio production to yield comparable radio power and spectra. Romani & Yadigaroglu (1995) also claim that one should see low-altitude emission alongside the outer magnetospheric emission if the orientation of the pulsar allows it. This is true for the Crab pulsar’s precursor as well as the Vela pulsar’s single radio component, which is offset in phase from its X-ray emission.

One last piece of information that may aid in efforts to interpret the polarization, is evidence for the Crab pulsar’s orientation on the sky. Using optical images from Hubble Space Telescope, Hester et al. (1995) link certain features found at visible wavelengths with structures found in ROSAT X-ray images. The wisps, arcs, and jetlike features, which probably came from interactions of the nebula with a pulsar wind, show a cylindrical symmetry, implying that the spin axis of the pulsar is at an angle of 110° east of north, projected ≈30° out of the plane of the sky to the southeast. If the geometry proposed by Hester et al. is tied to the true spin axis of the pulsar, then the angle of the spin axis to the observer is α = 90° − 30° = 60°, very close to our fitted value for the observer impact angle to the spin axis determined through RVM fits (α = 55°; § 4.4).

6. CONCLUSION

We have presented new polarimetric observations of the Crab pulsar at frequencies between 1.4 and 8.4 GHz that are difficult to interpret under the classical polar cap model.

There are more than the typical number of components seen in other pulsars, and they arise from all over the pulsar’s rotational phase. The new pulse components (LFC, HFC1, and HFC2) found in Paper I all have high linear polarization. We reconfirmed the phase shift and spectral change of the IP between 1.4 and 4.9 GHz, and found that the component also undergoes a 90° relative P.A. shift with respect to the other components! A good fit is made of the low-altitude, rotating-vector model to the polarization P.A. at high frequencies, but the line-of-sight impact angles to the magnetic axis are very large, implying that emission is arising from angles beyond the width of the low-altitude polar cap region. It appears that the MP and IP do not arise from low-altitude dipole emission. However, the LFC and HFC components show some properties inherent to conal emission (just as the precursor exhibits core-type emission). The Crab profile appears to be associated with a mixture of low- and high-altitude emission, with the IP being the greatest mystery.

The authors wish to thank Phil Dooley and the LO/IF group at NRAO-Socorro for their maintenance of the HTRP system. D. M. acknowledges support from a NRAO predoctoral fellowship, and from NSF grants AST 93-15285 and AST 96-18408. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This research has made use of data from the University of Michigan Radio Astronomy Observatory, which is supported by the SF and by funds from the University of Michigan. We also acknowledge the use of NASA’s Astrophysics Data System Abstract Service (ADS), and the SIMBAD database, operated at CDS, Strasbourg, France.

REFERENCES

Barnard, J. J., & Arons, J. 1986, ApJ, 302, 138
Conway, R. G., & Kronberg, P. P. 1969, MNRAS, 142, 11
Cordes, J. M. 1978, ApJ, 222, 1006
Fierro, J. M., et al. 1993, ApJ, 413, L27
Goldreich, P., & Julian, W. H. 1969, ApJ, 157, 869
Hester, J. J., et al. 1995, Ap, 448, 240
Kramer, M., Xilouris, K. M., Jessner, A., Wielebinski, R., & Timofeev, M. 1996, A&A, 306, 867
Lorimer, D. R., Yates, J. A., Lyne, A. G., & Gould, D. M. 1995, MNRAS, 273, 411
Lyne, A. G., & Manchester, R. N. 1988, MNRAS, 234, 477
Manchester, R. N. 1995, J. Astrophys. Astron., 16, 107
——. 1997a, ApJ, 163, L61
——. 1971b, ApJS, 23, 283
Manchester, R. N., Huguenin, G. R., & Taylor, J. H. 1972, ApJ, 174, L19
Manchester, R. N., & Taylor, J. H. 1977, Pulsars (San Francisco: Freeman)
McCulloch, P. M., Hamilton, P. A., Ables, J. G., & Komesaroff, M. M. 1976, MNRAS, 175, 71P
McKinnon, M. M. 1992, A& A, 260, 533
Mignani, R., Caraveo, P. A., & Bignami, G. F. 1997, ApJ, 474, L51
Moffett, D. A., & Hankins, T. H. 1996, ApJ, 468, 783 (Paper I)
Narayan, R., & Vivekanand, M. 1982, A&A, 113, L3
Ogilman, H., & Finley, J. P. 1993, ApJ, 413, L31
Pendleton, D. A., & Maclsaigue, P. 1971b, ApJS, 23, 283
Smith, F. G., Jones, D. H. P., Dick, J. S. B., & Pike, C. D. 1988, MNRAS, 219, 729
Smith, F. G., Dolan, J. F., Boyd, P. T., Biggs, J. D., Lyne, A. G., & Percival, J. 1996, MNRAS, 282, 1354
Smith, F. G., Jones, D. H. P., Dick, J. S. B., & Pike, C. D. 1988, MNRAS, 233, 305
Stinebring, D. R., Cordes, J. M., Rankin, J. M., Weissberg, J. M., & Boria-koff, V. 1984, ApJS, 55, 247
Stinebring, D. R., Kaspi, V. M., Nice, D. J., Ryba, M. F., Taylor, J. H., Thorsett, S. E., & Hankins, T. H. 1992, Rev. Sci. Instrum., 63, 3551
Taylor, J. H., & Weissberg, J. M. 1989, ApJ, 345, 434
Thorsett, S. E. 1991, ApJ, 377, 263
Xilouris, K. M., Kramer, M., Jessner, A., Wielebinski, R., & Timofeev, M. 1996, A&A, 309, 481
Radhakrishnan, V., & Cooke, D. J. 1969, Astrophys. Lett., 3, 225
Rankin, J. M. 1983a, ApJ, 274, 333
——. 1983b, ApJ, 274, 359
——. 1990, ApJ, 352, 247
——. 1993a, ApJ, 405, 285
——. 1993b, ApJ, 405, 285
Rankin, J. M., Campbell, D. B., Isaacman, R. B., & Payne, R. R. 1988, A&A, 202, 166
Romani, R. W. 1996, ApJ, 470, 469
Romani, R. W., & Yadigaroglu, I.-A. 1995, ApJ, 438, 314
Smith, F. G. 1986, MNRAS, 219, 729
Smith, F. G., Dolan, J. F., Boyd, P. T., Biggs, J. D., Lyne, A. G., & Percival, J. 1996, MNRAS, 282, 1354
Smith, F. G., Jones, D. H. P., Dick, J. S. B., & Pike, C. D. 1988, MNRAS, 233, 305
Stinebring, D. R., Cordes, J. M., Rankin, J. M., Weissberg, J. M., & Boria-koff, V. 1984, ApJS, 55, 247
Stinebring, D. R., Kaspi, V. M., Nice, D. J., Ryba, M. F., Taylor, J. H., Thorsett, S. E., & Hankins, T. H. 1992, Rev. Sci. Instrum., 63, 3551
Taylor, J. H., & Weissberg, J. M. 1989, ApJ, 345, 434
Thorsett, S. E. 1991, ApJ, 377, 263
Xilouris, K. M., Kramer, M., Jessner, A., Wielebinski, R., & Timofeev, M. 1996, A&A, 309, 481