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THE OPTICAL STRUCTURE OF THE CRAB NEBULA'S "JET"

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ABSTRACT

A deep, high-resolution [O III] image of the Crab Nebula's northern "jet" is presented which reveals considerably finer details than visible on previous photographs. The jet's small-scale structure appears composed of numerous emission-line filaments and knots which collectively exhibit a strong alignment having well-defined east-west boundaries. Comparison with an earlier published image suggests a proper motion northward (P.A. $\approx 0°$) for one of the jet's emission knots of $\mu = 0''.22 \pm 0''.05$ yr^{-1}. We discuss the jet's optical morphology and compare its properties to predictions of several proposed models. The "shadowed flow" model suggested by Morrison and Roberts appears to explain best the jet's known properties.

Subject headings: nebulae: Crab Nebula — nebulae: supernova remnants

I. INTRODUCTION

Along the Crab Nebula's northern edge, van den Bergh (1970) discovered a "jetlike" column of filaments extending $\sim 90''$ beyond an otherwise well-defined boundary. Subsequent deeper imaging of this "jet" (also described as a "stem," "spur," or "chimney") by Chevalier and Gull (1975), Wyckoff *et al.* (1976), and Gull and Fesen (1982), as well as spectroscopy of its base by Davidson and Humphreys (1976) and Davidson (1978, 1979), indicate it consists of emission-line filaments which emit strongly in [O III] $\lambda\lambda$4959,5007.

Besides its extension well outside the visible nebula, the jet possesses an unusual morphology compared to other regions of the supernova remnant. Its appearance of aligned emission filaments and knots creates the impression of a limb-brightened hollow tube. Optical spectra of its central and southern sections do in fact suggest that its filaments form a tubelike structure with walls that are expanding outward at ~ 360 km s^{-1} (Shull *et al.* 1984) relative to its major symmetry axis. Radio studies of the Crab Nebula by Wilson and Weiler (1982), Velusamy (1984), and Wilson, Samarasinha, and Hogg (1985) at 6, 20, and 49 cm have detected radio emission associated with the jet, and show it to be highly polarized suggesting a nonthermal spectrum.

Several theories for the jet's origin have been proposed, including a stellar-wind wake from the Crab's presumed red-giant progenitor (Blandford *et al.* 1982), a magnetically confined beam emitted from the pulsar early in the remnant's history, causing entrainment of nebular material (Benford 1984), a shadowed shock flow due to an interstellar cloud (Morrison and Roberts 1985), and various instability scenarios involving the nebula's relativistic plasma-filament interface (Chevalier and Gull 1975; Bychkov 1975; Kundt 1983; Shull *et al.* 1984).

In this paper, we present a very deep and high resolution [O III] image of the jet which provides a considerably better look at its optical structure than previously available. A proper-motion estimate for one of the jet's emission knots is also described. The jet's complex yet seemingly well-organized filamentary structure is discussed in comparison to model predictions.

II. OBSERVATIONS

A series of deep [O III] images of the Crab Nebula's jet were recorded on 1983 November 6 using the video camera attached to the 2.1 m telescope at Kitt Peak National Observatory. The video camera consists of a RCA 4849 ISIT electrostatically focused image tube fiber-optically coupled to a silicon target Vidicon. Ten individual 13.6 minute exposures were taken of the jet, using an [O III] interference filter having a peak transmission of 63% at 5009 Å and a bandpass of 22 Å FWHM (± 650 km s^{-1}). This is the same filter employed by Gull and Fesen (1982) to obtain their [O III] image of the jet. A single exposure was also taken using a wider [O III] interference filter ($\lambda_0 = 5025$ Å; FWHM = 70 Å) in order to detect high radial velocity emission of the jet possibly missed using the narrower passband filter. The field of view for each image is $\sim 140''$, with 256 pixels on a side and a pixel-limited resolution of $0''.55$. Image processing involved subtraction of dark exposures from each image and flat field plus geometric distortion corrections. The 10 [O III] images were then coregistered and added using the interactive picture processing system (IPPS) at Kitt Peak. Fortunately, seeing was especially good during the exposures ($\leq 1''$), resulting in high image quality with typical measured resolution for field stars of $0''.9$–$1''.1$ for individual exposures. However, during a few integrations, slight movement of the telescope's secondary mirror produced slightly elongated east-west star images, resulting in lower angular resolution in the combined image. Also, the placement of interference filters in the nearly parallel focus beam of the camera produced some internal reflections off the filter for bright stars in the field of view. Such reflections appear as small diffuse patches of emission just west and northeast of the jet and are indicated in

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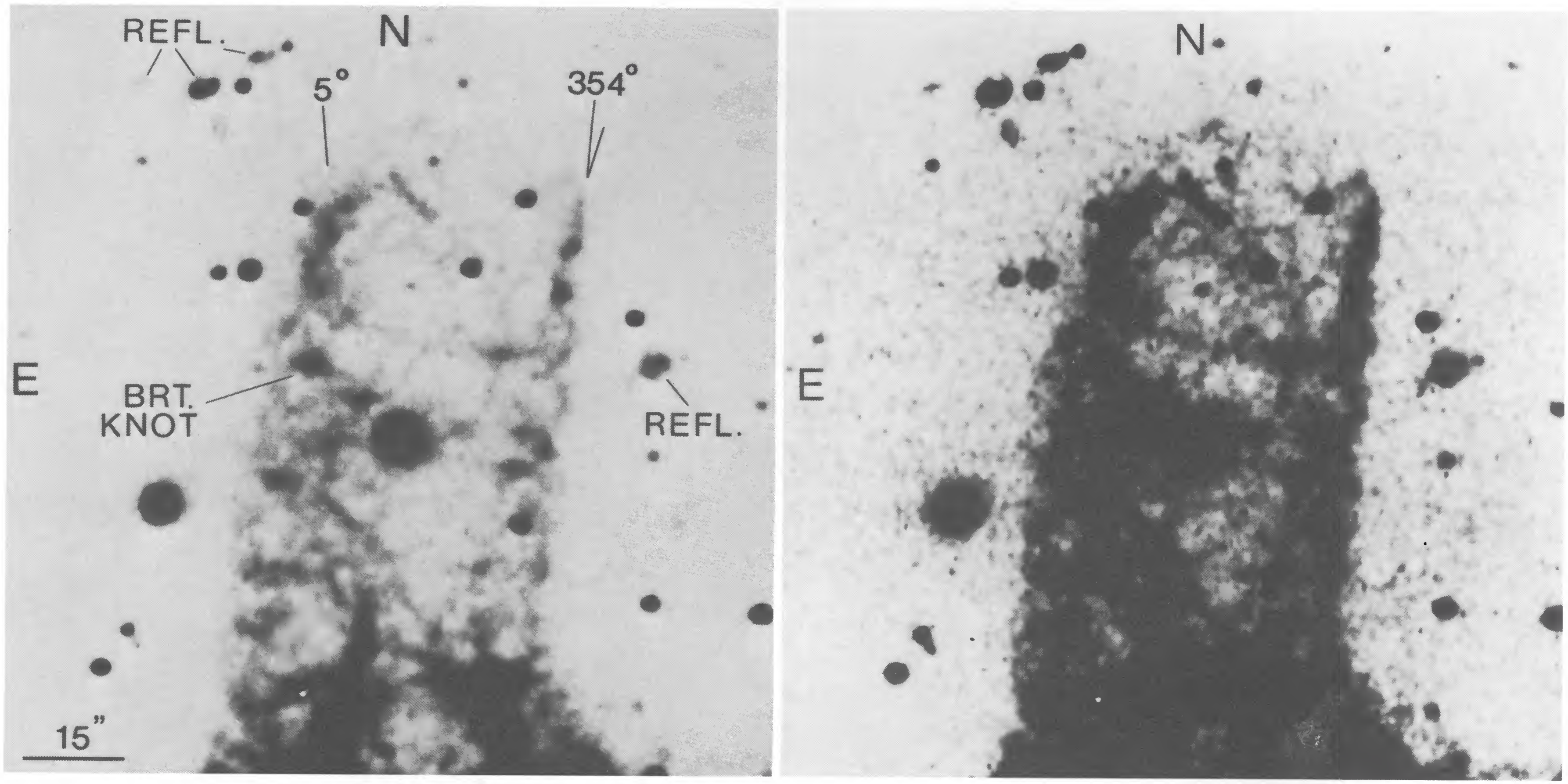

FIG. 2.—(*a*) Low-contrast negative print of video camera image of Crab Nebula's jet. Internal camera reflections due to bright field stars are indicated. (*b*) High-contrast copy of same image with intensity transform set just above sky background to show maximum extent of detected [O III] λ5007 emission.

Figure 2*a*. No reflections are believed to be superposed on the jet itself.

III. RESULTS

a) Optical Structure

The image of the Crab Nebula's jet shown in Figures 1 (Plate 14) and 2 provides a clearer view of its optical structure than previous photographs (Gull and Fesen 1982; Koutchmy *et al.* 1985; Véron-Cetty, Véron, and Woltjer 1985). With a resolution near 1″, features as small as 0.01 pc in size are visible in the jet, assuming the Crab's distance to be 2 kpc (Trimble 1973). The jet's fine-scale structure appears clumpy, composed of numerous emission-line filaments and knots that collectively exhibit a nonradial alignment with well-defined east-west boundaries. Individual emission knots appear to have typical sizes of 3″–5″, implying linear dimensions of $\sim$0.03–0.05 pc. If the jet is really a hollow, tubelike structure, as the measured radial velocities suggest, then it is a relatively thin walled tube with a thickness approximately equal to the knots' dimensions.

Measured from its southern boundary with the remnant's brighter filaments, the jet's [O III] emission extends $\sim$75″ (=0.75 pc) in a nearly due north direction (P.A. = 354°). Exhibiting an average angular width of 50″, the jet narrows a bit near its northern tip to a width of 44″. Most of this observed narrowing appears to be due to its northeastern emission. The jet's western edge appears remarkably straight and sharply defined, more so than its eastern edge.

As shown in Figures 1 and 2, the jet's [O III] emission appears to terminate abruptly and evenly at its northern end. However, an image obtained with a wider [O III] filter indicated the possible presence of very faint, additional nebulosity northwest of the jet's northern tip. If confirmed, this might imply radial velocities for this northernmost region in excess of 500 km s^{-1}—i.e., outside the narrower [O III] filter's bandpass. Such velocities would be considerably higher than the $\pm$360 km s^{-1} reported by Shull *et al.* (1984) for the line-of-sight expansion of the jet and the $+100 \pm 150$ km s^{-1} found by Gull and Fesen (1982) for the jet's bright northeastern filaments.

Despite its collimated morphology, the jet's major symmetry axis is not aligned either with the remnant's determined center of expansion or the pulsar's current position (Trimble 1968; Wyckoff and Murray 1977). When projected back into the nebula, the jet's major axis misses the center of expansion by $\sim$25″ to the east. However, the jet's very straight western edge projects nearly exactly back (i.e., within 5″) toward the nebula's expansion center, as already noted by Morrison and Roberts (1985).

The emission measures of the jet's detected features on our [O III] image can be roughly estimated using Davidson's (1978, 1979) measured line fluxes. Adopting an average [O III] λ5007/Hα ratio of 5 for the jet's filaments (Davidson 1978, 1979), an $A_v = 1.5$ mag (Wu 1981), we related Davidson's observed [O III] λ5007 photon fluxes in the jet to Hβ fluxes using Fesen and Kirshner's (1982) measurements for Davidson's filament "D1". We estimate emission measures of 300–500 cm^{-6} pc for Davidson's positions A1, A2, and A7 located near the jet's southern edge, and $\sim$100–200 cm^{-6} pc for position A3 located along the western edge. Judging from the [O III] image, this latter value is probably close to the jet's overall average and is consistent with Davidson and Humphrey's (1976) earlier estimate.

Emission measures of 100–200 cm^{-6} pc, when combined with probable line-of-sight depths similar to the linear sizes of the observed individual emission knots (i.e., 0.01–0.03 pc), suggest electron densities of $\sim$100 cm^{-3}. While this is considerably lower than previously reported for the remnant's bright filaments (Davidson 1979; Fesen and Kirshner 1982), similar values might exist for other faint periphery regions by virtue of similar [O III] intensities. The somewhat brighter filaments along the jet's base could have higher densities of order 200–500 cm^{-3}. The observed ratio of the electron density sensitive [S II] λλ6717,6731 lines for several filaments in this region (Davidson 1978, 1979), although poorly determined, are consistent with electron densities much less than the nebula's observed average value of 1300 cm^{-3}.

As shown in Figure 2*b*, the detected [O III] emission in the jet follows closely the structure and location of that of its brighter filaments. Little or no emission appears near the jet's central symmetry axis, particularly toward the north. This can also be seen clearly in the photometric data of Véron-Cetty, Véron, and Woltjer (1985). Virtually no [O III] emission down to an estimated emission measure of $\sim$25 cm^{-6} pc was detected in our image outside the jet's well-defined boundaries. Although very faint, this value is still, however, several times larger than the estimated 7 cm^{-6} pc for the suspected Crab Nebula's Hα halo (Murdin and Clark 1981).

Continuum synchrotron emission associated with the jet was briefly searched for using a $V + R$ filter combination ($\lambda_0 \approx 5900$ Å; FWHM = 250 Å). Faint continuum emission was detected only near the base of the jet. Previous continuum images of the Crab Nebula's outer structure (e.g., Woltjer 1957; Scargle 1970) suggest very faint continuum emission might be present near the jet's location. This needs to be investigated. Sufficiently deep continuum imaging is feasible and would be important in clarifying the relative structure and extent of any high-energy plasma associated with the jet's thermal gas.

b) Proper Motion

A determination of the jet's proper motion is vital if we are to understand its nature and origin. However, accurate measurements are severely hampered by the poor resolution and weak detection of the jet on previous images, coupled with relatively short epoch coverage. Gull and Fesen (1982) estimated a rough upper limit of $\sim$5000 km s^{-1} for the jet's outward expansion velocity, based upon a comparison of the jet's northernmost extension on their 1981 image with van den Bergh's 1970 discovery Schmidt plate. However, the accuracy of this comparison is poor in view of the extremely weak detection and lack of visible structure of the jet on the 1970 image.

The jet's brightest emission knot lies near the eastern edge of the jet (see Fig. 2*a*). Examination of film copies and original plates of several earlier and relatively deep, broad passband images of the Crab Nebula (including Baade's Mount Wilson 100″ superb 1942 January 19 plate and Mayall's Lick 3 m image of 1959 November 30) unfortunately revealed no accidental early detection of this feature. However, this emission knot is visible (but just barely) on Chevalier and Gull's (1975) 20 minute [O III] plate taken on 1974 January 16 using the KPNO No. 1 0.9 m telescope. A preliminary comparison of this knot's position on the 1974 plate to our higher resolution 1983 November image at first suggested a proper motion northward (P.A. ≈ 0°) of $\mu = 0\farcs4 \pm 0\farcs2$ yr^{-1}. This implied an outward expansion velocity of $\sim$4000 km s^{-1}. Measurement

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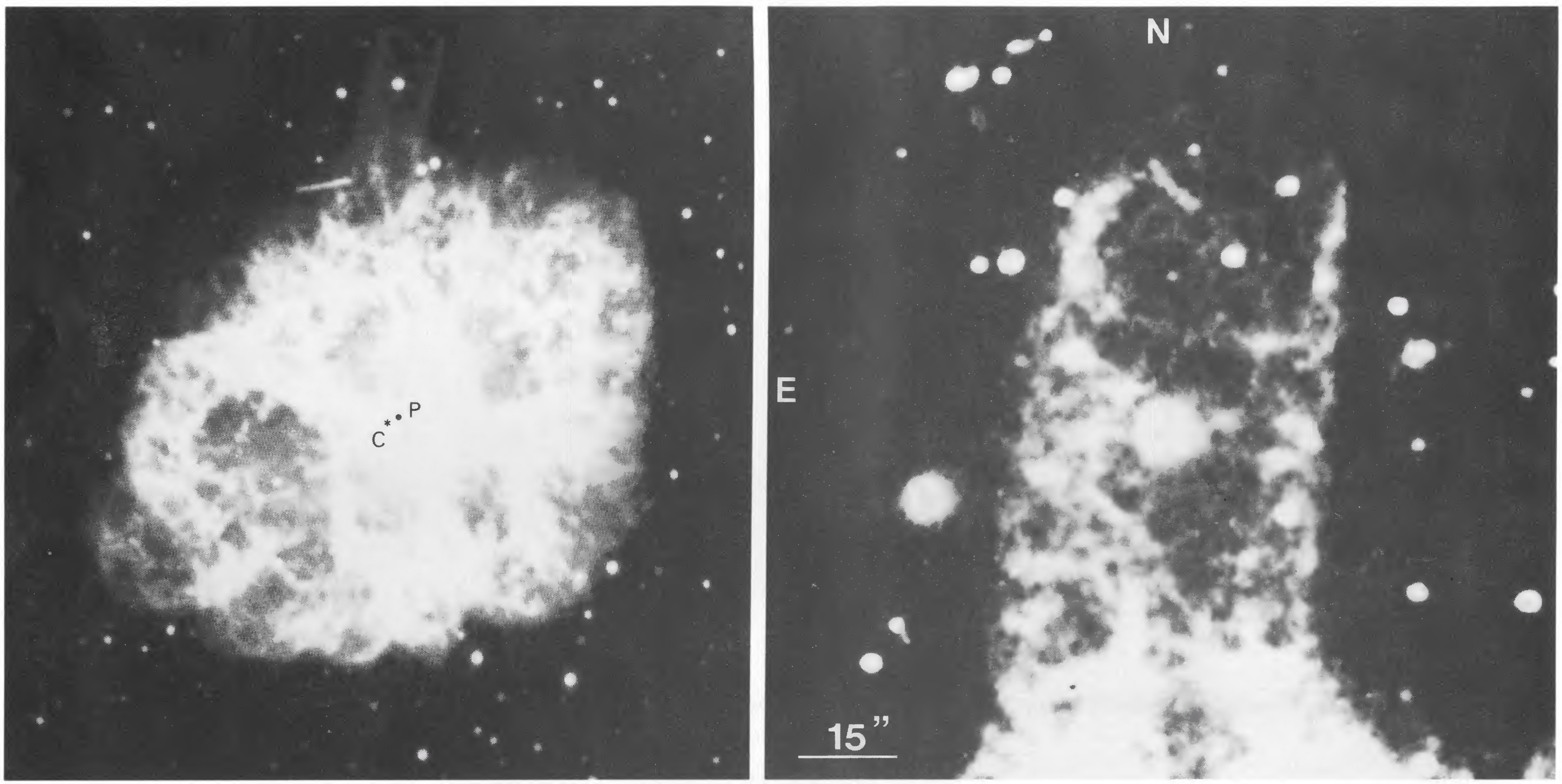

FIG. 1.—(*a*) Left panel: deep [O III] photograph of the Crab Nebula obtained by Gull and Fesen (1982) showing location of jet with respect to remnant's expansion center (C) and pulsar (P). (*b*) Right panel: a deeper and higher resolution video camera image of the jet showing its detailed structure.

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uncertainty was considerable due mainly to the poor detection of the knot on the 1974 image.

In an effort to improve this proper motion measurement, we digitized the original 1974 plate, using a PDS microdensitometer and processed it using the Comtal Display System of the Astronomical Data Analysis Facility at Goddard Space Flight Center. An intensity transform window set just above the sky background level and just below the detected brightness of the nebula's outer filaments was used to display the image. This permitted a better determination of the knot's center as well as more accurate corrections for the considerable small-scale geometric distortion produced by the image tube and the slight E-W misguiding of the exposure. A comparison of this digital data to the 1983 image yielded a smaller but more accurate proper motion estimate of $0''.22 \pm 0''.05$ yr^{-1}. Although larger than that observed along the Crab's northern boundary (=minor axis), this value is comparable to the largest observed proper motions along the major axis (Trimble 1968) and implies an expansion velocity of 2100 ± 500 $(D/2$ kpc) km s^{-1}. (A proper motion value of $\sim 0''.2$ yr^{-1} is also consistent with the knot's location on a KPNO 4 m prime focus plate, No. 690, obtained by A. Millikan on 1973 November 29 which very weakly detected this knot.) Unfortunately, unless detected on some other previous plate, a better determination of the jet's proper motion must await additional high resolution and deep images.

IV. DISCUSSION

The [O III] images and proper motion estimate presented above, when combined with recent radio and spectroscopic observations, help to clarify the jet's fine-scale structure and general properties. These data also place important constraints on possible formation mechanisms. Below, we briefly review the jet's known properties and compare these with those predicted by several jet models. While our knowledge of the jet is still quite incomplete, the "shadowed flow" model proposed by Morrison and Roberts (1985) seems to agree best with existing data.

a) Jet's Observed Properties

Despite its complex structure of delicate filaments and emission knots, the jet possesses a highly organized morphology. Its sharply defined and virtually parallel east-west edges with negligible radio or optical emission outside these boundaries, is in striking contrast to other filamentary regions of the remnant. Concentration of optical emission along the jet's edges suggests a limb-brightened cylindrical structure—an impression supported by spectroscopic data revealing a hollow, ± 360 km s^{-1} velocity ellipse (Shull *et al.* 1984).

From its 2100 km s^{-1} transverse velocity estimated above and 275 km s^{-1} central radial velocity of its velocity ellipse (Shull *et al.* 1984), one can estimate the jet's line-of-sight orientation. Taking the nebula's radial velocity to be essentially zero (Trimble 1970; Clark *et al.* 1983), the observed velocities imply a tilt of $\sim 8^\circ$ into the plane of the sky. Thus, the jet's apparent dimensions are very nearly those of its actual dimensions, i.e., $\sim 0.5 \times 0.9$ pc.

Spectroscopy of the jet's filaments suggests a lower helium abundance compared to the majority of the Crab's bright filaments (Davidson 1978, 1979). However, the quality of the data is not high and most filaments studied were along the jet's base. Also, Clark *et al.*'s spectra indicate that low helium abundances may be common in the remnant's outlying filaments. Thus, the magnitude and significance of the jet's lower helium abundance is difficult to assess.

Nonthermal radio emission associated with the jet appears well-correlated to its optical emission and shows high polarization, implying a uniform magnetic field. The jet's estimated magnetic field strength of 2–3 $\times 10^{-4}$ G is close to the nebula's average value of 4×10^{-4} G, suggesting that the jet's magnetic field originates from within the remnant (Wilson, Samarasinha, and Hogg 1985). Magnetic and cosmic pressures appear to be significantly larger than those of the jet's thermal gas. Assuming equipartition of energy between cosmic rays and magnetic fields, Wilson, Samarasinha, and Hogg (1985) estimate pressures of 3–9 $\times 10^{-9}$ dyn cm^{-2} in the jet. Filaments with densities of 100–500 cm^{-3} and temperatures of 10^4 K will produce much lower pressures of 0.3–1.4 $\times 10^{-9}$ dyn cm^{-2}.

A major difficulty in understanding the jet's origin has been the apparent nonradial alignment of its major symmetry axis. However, there are indications that the jet's individual emission features may in fact be expanding in a simple radial fashion away from the remnant's expansion center. High-resolution radio observations have recently shown the magnetic field lines at the jet's base to be radially aligned and consequently slightly misaligned with the jet's eastern edge (Wilson, Samarasinha, and Hogg 1985). Since the nonthermal radio emission is closely associated with the jet's optical filaments via enhanced magnetic fields surrounding the filaments (as is the case in the rest of the nebula), this suggests some degree of radial alignment of individual eastern filaments. The jet's very straight western edge of filaments is also in very good radial alignment with the nebula's center of expansion.

Proper-motion measurements of filaments within or near the jet southern boundary also suggest radial expansion. The estimated transverse velocity of ~ 2100 km s^{-1} from the proper motion ($\mu = 0''.22 \pm 0''.05$ yr^{-1}) of its brightest emission knot is consistent with a homologous expanding remnant (i.e., $V_{\mathrm{exp}} \propto$ radius), and is similar to the largest values observed along the Crab's major axis (Trimble 1968). Although a strong visual impression of nonradial filamentary motion is given by a relatively faint "inverted Y" shaped filament located near the jet's southern boundary, this seems to be not real. While looking as if its motion were northward along the jet's central symmetry axis, proper motion of its central emission knot shows normal radial motion away from the remnant's expansion center (filament 122; Trimble 1968). Furthermore, comparisons of recent and archival plates reveal no nonradial proper motions for other filaments near the jet/nebula boundary. Therefore, in spite of its clearly nonradial alignment, the evidence favors an ordinary radial expansion of its filamentary emission.

b) Comparison to Models

Models proposed to explain the jet's origin and peculiar structure can be organized into four groups.

i) Red-giant mass-loss wake.—Blandford *et al.* (1983) proposed an intriguing model which suggested the jet is a long (10 pc) tubelike train of stellar-wind material from the Crab's SN red-giant precursor. However, the jet's estimated transverse velocity of ~ 2000 km s^{-1}, strongly polarized nonthermal radio emission, and ± 360 km s^{-1} velocity ellipse are all inconsistent with this model. Furthermore, it seems unlikely for such a feature to maintain straight and parallel walls over a time span of 10^5 yr while drifting with respect to the nebula (Kundt 1983; Benford 1984; Morrison and Roberts 1985).

ii) Relativistic plasma beam models.—Benford (1984) proposed the jet might have formed via a small fraction of magnetic-field energy emitted by the remnant's pulsar in an ordered beam early in the Crab's history. Although possessing a very high initial outward velocity ($V_J \approx c$), nebula entrainment would slow it down to its currently observed radial velocity of 100 km s^{-1} (implying an orientation out of the plane of the sky) and permit eventual overtaking by the nebula. Entrained nebula material would produce the jet's observed optical emission, with any counterjet lost in the remnant's main emission. However, the jet's large transverse velocity and small radial velocity constrain it to lie close to the plane of the sky, making a counterjet difficult to hide. Also, this model predicts a filled synchrotron emitting tube which is not indicated by the radio observations. The jet's observed velocity ellipse, radial alignment of magnetic field lines, yet nonradial axial symmetry, pose problems for this model in which the jet's walls are collimated through magnetic tension. Similar difficulties are encountered by Michel's (1985) relativistic wind termination model, which proposes oppositely directed jets as by-products of the pulsar's wind interaction with surrounding nonrelativistic filamentary matter.

iii) A "break-out" along the nebula/plasma interface.—Since the Crab's filaments are being accelerated, internal relativistic plasma pressures must be greater than those of the thermal filaments. Thus, the jet's synchrotron emission and high filament velocities rather naturally suggest that it might have been produced by a leak of high-pressure plasma through the filamentary envelope that otherwise seems to completely bound the relativistic gas. Models along this line have been proposed by Bychkov (1975), Kundt (1983), and Shull *et al.* (1984). In these models, the jet's optical emission is due either to swept-up, low-density filaments or halo material. Besides possible difficulties with cooling the shocked material sufficiently rapidly to permit optical emission, these models do not straightforwardly explain why the jet should possess such a collimated structure, especially considering the large internal pressures required and the likely radial expansion of the jet's filaments.

iv) High-velocity mass stripping.—Based upon the similarity of the jet's strong [O III] emission like that seen elsewhere in the remnant's periphery, Chevalier and Gull (1975) suggested the jet might be a sheet of filamentary material produced by high-velocity relativistic particles causing differential acceleration or Rayleigh-Taylor instabilities, or both, in low-density envelopes of outlying filaments. This model does not, however, explain the jet's nonradial symmetry. A somewhat related model was proposed by Morrison and Roberts (1985) in which an isolated interstellar cloud located by chance near the precursor at time of outburst intercepted a portion of a rapidly expanding but tenuous hydrogen-rich halo. Such a halo has been proposed to exist on theoretical grounds by Chevalier (1977) and reportedly detected by Murdin and Clark (1981). Mass stripping by the halo along the cloud's edges would produce a "shadowed flow" of halo/cloud material in the form of a radially aligned cone. The jet's nonradial alignment would be produced by the superposition of a succession of nested cones due to the cloud's drift velocity relative to the nebula. This model, however, requires the existence of an as yet unconfirmed halo, as well as rapid cooling of the shocked flow in order to produce its observed optical emission. It also requires a relatively high-density cloud ($n_e \approx 100$ cm^{-3}) located fairly close the Crab some 200 pc from the galactic plane and possessing well-defined edges and a transverse velocity of ~100 km s^{-1}.

Despite the initial attractiveness of the plasma-leak models, the somewhat ad hoc cloud scenario suggested by Morrison and Roberts (1985) describes surprisingly well many of the jet's observed properties. This model can explain the jet's western edge alignment with the Crab's expansion center, its thin walls and hollow structure, velocity ellipse, and the jet's abrupt northern termination. In their picture, the jet's structure is a cone rather than a straight tube. Thus, its transverse and radial velocities are simply components of the jet's outward expansion (Morrison and Roberts 1985; Wilson, Samarasinha, and Hogg 1985). Assuming a transverse velocity of 2100 km s^{-1}, one requires an opening cone angle in the line-of-sight of ~20° to produce the reported ±360 km s^{-1} velocity ellipse. While this is nearly twice as large as the 12° angle subtended by the jet at its base, somewhat smaller values are possible considering uncertainties in both transverse (2100 ± 500 km s^{-1}) and radial velocities (720 ± 90 km s^{-1}). High-velocity mass stripping off the edges of a dense cloud would produce a hollow, thin-walled tubular structure like that observed in the jet much more naturally than any other proposed model. Moreover, the abrupt termination of the jet's observed emission at a distance of 4′.2 north of the nebula's center is close to the halo's 5′ detected extent in the NE sector (Murdin and Clark 1981). This difference is what one might expect if the ablated cloud flow velocities were close to but just below those of the unimpeded halo (Morrison and Roberts 1985).

To explain the jet's apparent nonradial alignment despite radially moving filaments, Morrison and Roberts gave the cloud a transverse velocity of ~100 km s^{-1} to the SE. This would produce a superposition of ablated flow cones, thereby altering the apparent position angle of the eastern emission edge. Taking the jet's northeastern emission knot as the initial cone's eastern tip (P.A. = 5°), one requires an angular change of ~10° in order to make the jet's eastern edge appear collimated with its western edge (P.A. = 354°). Such a series of projected cones should be visible for both the jet's western edge as well as its eastern edge.

Remarkably, this is what appears to be observed. In Figure 2, one sees that the jet's western limb consists of a well-defined, conical emission structure which tapers smoothly to a point coincident with the very northern tip of the jet's western edge. The eastern extent of this emission appears very well delineated, showing little deviation along the jet's entire length. The angle of this emission cone is ~11°, precisely that required to produce a parallel-appearing east-west structure. The presence of such a well-defined structure possessing the correct angle, direction, and apex location is strong evidence that at least a model similar to the Morrison and Roberts's high-velocity flow-drift model is likely to have been involved in the jet's formation process. Although much broader [O III] emission is seen along the jet's eastern edge, this could be the result of a more irregular eastern edge to the cloud.

Assuming a homologous expansion for the jet, we can estimate the cloud's transverse velocity. Since the proper motion velocity of filaments along the jet's base is ~1800 km s^{-1} (Trimble 1968), with ~2100 km s^{-1} for the bright knot about halfway up (this work), we estimate a $\Delta V_T \approx 500$ km s^{-1} for the transverse velocity difference across the entire jet's length. The interstellar cloud's transverse velocity, V_C, is then just $V_C = \Delta V_T \sin \alpha / \cos \beta$, where α is the projected angle of successive cones (i.e., ~11°) and β = P.A. + α − 90°. For position angles 90° and 120°, the cloud's transverse velocity would be 97 and 126 km s^{-1}, respectively, very close to Morrison and Roberts's suggested value of 100 km s^{-1}.

Although a 100 km s^{-1} velocity is large for interstellar clouds, some of this relative motion may be attributable to the nebula itself. It is quite clear that we do not know the nebula's proper motion (see Trimble 1970), but there is some suggestion that it might be substantial and directed toward the northwest, the exact opposite direction required for the cloud's motion. If one *assumes* that the present geometric center of the remnant (which is only very poorly known) coincides with its center of mass, then the remnant's proper motion is ~ 100 km s^{-1} in the direction of P.A. $\approx 340°$ (Trimble 1968). (Note: The pulsar's transverse velocity is 123 ± 38 km s^{-1} in the direction of P.A. $= 293° \pm 18°$; Wyckoff and Murray [1977].) In any case, some portion of the required interstellar cloud velocity could be due to nebula's own motion. However, the cloud must then also possess a fairly high density of ~ 100 cm^{-3} in order to prevent the halo from flowing through it and yet be relatively small in size (diameter ≈ 0.5 pc) with a sufficiently steep density gradient to produce such well-defined edges. The existence of a high-velocity halo surrounding the Crab is itself quite uncertain. Reportedly detected by Murdin and Clark (1981), Dennefeld and Pequignot (1983), and Clark *et al.* (1983), a halo would help reconcile many of the Crab's properties with Type II SN models (Chevalier 1977, 1985). Nonetheless, it has gone undetected in several recent radio, optical, and X-ray searches (Wilson and Weiler 1982; Velusamy 1984; Mauche and Gorenstein 1985; Fesen and Ketelsen 1985). The Murdin and Clark data are suggestive of a line-emitting halo gas, but continuous synchrotron emission is not ruled out. However, weak radio emission from presumably leaked relativistic plasma has only been detected outside the nebula's [O III] boundary in the NW region (Velusamy 1984). (Note: Deep broad-band optical images do detect synchrotron emission outside the nebula's northwestern filamentary boundary coincident with the faint radio emission. This suggests that for at least this region relativistic plasma leaked out the main nebula without disturbing the outer filaments.)

Despite these difficulties, the interaction of an interstellar cloud with the Crab's expanding envelope/ejecta might explain some other properties of the remnant. The jet's optical emitting material of ablated cloud/envelope gas would be expected to show a lower helium abundance compared to the filamentary eject. As noted above, existing spectroscopy of the jet's emission do support nearly cosmic helium abundances. Interaction of the cloud with the denser, slower moving, but optically bright ejecta could also have impeded their otherwise free expansion and increased their H/He ratio. Radial velocity mappings of the Crab's filaments by Clark *et al.* (1983) do indicate a "hole" in the remnant's filamentary shell in the velocity range ± 100 km s^{-1} in the jet's direction. Moreover, several filaments with atypical low-helium abundances for the Crab lie in near-perfect radial alignment between the remnant's expansion center and the jet's base (Fesen and Kirshner 1982; Uomoto, MacAlpine, and Henry 1985). If true, the cloud would have to have been located interior to these filaments implying a distance of 0.6 pc or less from the center of expansion. Finally, the data of Clark *et al.* also show an isolated, low radial velocity filament ($V_r = +60$ km s^{-1}) lying well within the remnant's low radial velocity shell and just east of the jet's direction (38″ east, 30″ north of pulsar). Although the Clark *et al.*'s data sampled only $\sim 10\%$ of the nebula, low radial velocity filaments near the pulsar appear quite rare and it is conceivable that this filament might be associated with the cloud that originally formed the jet.

Obviously, eventual acceptance of this or any other model will require additional observations. Though consistent with many of the jet's observed properties, the Morrison and Roberts shadowed flow model is viable only if a rapidly expanding halo medium exists. Therefore, much more sensitive optical halo searches at or below flux levels reported by Murdin and Clark (1981) can provide a crucial test for this model as well as the halo itself. A possible sharp boundary for the halo coincident with the jet's northern termination could be exploited both as an initial search area and as a discriminating tool for low-level instrumental scattering effects. Additional long slit spectra across the jet like those obtained by Shull *et al.* should also show a small decrease in the observed radial velocity ellipse toward the jet's base if it truly possesses a conelike structure. More accurate 5876/Hβ intensity ratios for the jet's filaments, relative to other periphery filamentary regions of the remnant, should also help resolve the question of atypically low helium abundances associated with the jet. If the shadowed flow model is indeed correct, it then raises several interesting questions regarding the nature and kinematics of such a dense cloud lying some 200 pc off the galactic plane and so close to the precursor at time of outburst.

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