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OPTICAL IDENTIFICATION OF DUST WITHIN THE CRAB NEBULA'S FILAMENTS

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ABSTRACT

We present optical continuum images of the Crab Nebula which reveal numerous, small "dark spots" across the face of the Crab's amorphous synchrotron nebula. These spots range in size from being unresolved at 0".8 resolution to ≈5", exhibit $\Delta m_{4770} = 0.08$–0.44, and are most visible in the shorter wavelength continuum images. Comparisons with images taken using interference filters centered on various nebulae emission lines indicate that these dark features are coincident with [O I], [C I], and [S II] bright cores of selected filaments. This positional coincidence plus a wavelength dependence similar to that exhibited by conventional interstellar dust establishes the presence of dust within at least some of the Crab Nebula's filaments. Dust condensation in the Crab's ejecta probably occurred early in the evolution of the remnant when the filament cores were relatively dense and had cooled to below 1000 K.

Subject headings: interstellar: grains — nebulae: Crab Nebula — nebulae: supernova remnants — stars: supernovae

I. INTRODUCTION

Dust condensation in the metal-rich ejecta of supernovae (SNs) was first proposed by Cernuishi, Marsicano, and Codina (1967) and Hoyle and Wickramasinghe (1970). Soon afterward, Falk, Lattimer, and Margolis (1975), Lattimer, Schramm, and Grossman (1978), and Clayton (1975, 1979) suggested that SNs may in fact be important sites for carbon, silicate, and metallic iron grain formation, assuming the ejecta adiabatically cool to 10^3 K or less in time scales of about a year.

Recent studies have indicated that dust formation may occur within some SNs. Infrared observations of SN 1979C in M100, SN 1980K in NGC 6946, and SN 1982E in NGC 1332 taken within 1 yr of outburst showed infrared excesses consistent with a warm dust interpretation (Merrill 1980; Dwek *et al.* 1983; Graham *et al.* 1983). Furthermore, recent data on SN 1987A indicate that a modest amount of dust did condense in this supernova within less than 2 yr following outburst (Lucy *et al.* 1989). These observations, plus the analog of nebulae around ordinary novae where dust forms quite rapidly and in considerable amounts (Bode 1982), suggest that SNs are possibly major sites of dust formation in a galaxy (Dwek and Scalo 1980; Dwek 1989).

Despite all this, there has been little observational evidence in support of the presence of dust grains inside young supernova remnants. Analysis of the strong infrared emissions from Tycho, Kepler, and Cas A have yielded only upper limits on dust amounts (Wright *et al.* 1980), while more recent studies of Cas A are only suggestive of dust formation in some of its metal-rich knots of ejecta (Mezger *et al.* 1986; Dwek *et al.* 1987; Dinerstein *et al.* 1987). Perhaps the best evidence for dust formation in SN ejecta comes from the study of the Crab Nebula (SN 1054). The unexpectedly low iron abundance in the Crab filaments is consistent with a partial depletion into dust grains (Dennefeld and Pequignot 1983). While star counts show no evidence of any substantial extinction within the nebula itself (Trimble 1977) over the interstellar reddening of $A_v = 1.46 \pm 0.12$ (see Davidson and Fesen 1985), dust that formed need not be uniformly distributed in the nebula. An excess of infrared emission in the Crab's continuum around $\lambda \approx 50$ μm due to thermal emission from dust grains indicates a mass of dust within the nebula of between 0.005 and 0.05 $M_\odot$ (Harvey, Gatley, and Thronson 1978; Dwek and Werner 1981; Marsden *et al.* 1984; Davidson and Fesen 1985; Mezger *et al.* 1986). Although the upper mass limit is suggestive of dust formation within the remnant, the lower limit is only a bit above that amount of interstellar dust estimated to have been swept up by the expanding ejecta.

Recently, strong additional support for the presence of dust within the Crab Nebula has been reported by Woltjer and Véron-Cetty (1987) who found evidence of optical absorption in one of the Crab Nebula's filaments. A continuum image of the Crab obtained using an interference filter 64 Å wide (FWHM) centered at 5354 Å showed the presence of absorption at a position coincident with an [O III] bright filament located some 40" west of the pulsar. Since some of its filaments lie in front of the inner synchrotron continuum nebula, the Crab provides a unique opportunity to investigate dust formation in a young supernova remnant via optical absorption.

In this *Letter*, we present subarcsecond optical images of the Crab Nebula taken both on and off filamentary emission lines of varying ionization states. The images show clear evidence for the presence of dust associated with many of the remnant's filaments. The images are described in § II with results and discussion given in § III.

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II. OBSERVATIONS

Optical interference filter images of the Crab Nebula were obtained in 1987 November and 1988 November using an 800 × 800 pixel Texas Instruments CCD camera at the prime focus of the 4 m telescope at Kitt Peak National Observatory. The system produces a field of view which is 3'.9 square, with a pixel size of 0".30.

The following interference filters and integration times were used to obtain images showing the nebula's emission structure in various emission lines: an [O I] filter (λ_0 = 6320 Å, FWHM = 200 Å; 500 s), an Hα + [N II] filter (λ_0 = 6576 Å, FWHM = 104 Å; 640 s), a [S II] filter (λ_0 = 6737 Å, FWHM = 75 Å; 604 s), and a [C I] filter (λ_0 = 9870 Å, FWHM = 100 Å; 1200 s). In order to image the Crab's synchrotron emission nebula free from any filamentary line emission, the following continuum filters and integration times were used: λ_0 = 4770 Å (FWHM = 100 Å; 640 s), λ_0 = 6100 Å (FWHM = 150 Å; 500 s), λ_0 = 6478 Å (FWHM = 74 Å; 640 s), and λ_0 = 8100 Å (FWHM = 400 Å; 300 s). The telescope's prime focus f/2.7 ratio produces a passband shift 10–15 Å to the blue for all filters (Jacoby 1987).

Seeing was excellent in both the 1987 and 1988 observing runs, with measured FWHMs of star images ranging from 0".65 to 1".1. Image data reduction included bias subtraction and dome flat-field corrections. The 1988 images were obtained in a drift scanning mode in which the image is allowed to drift slowly while the CCD is moved synchronously on a precise stage by single-pixel increments, so that the same part of the image falls on the same charge packet. Due to a faulty guide probe, guiding during the integration of the 4770 Å was temporarily lost resulting in a bright and slightly wavy star trail being recorded across the image frame.

III. RESULTS AND DISCUSSION

Our 4770 Å continuum image of the Crab Nebula (Fig. 1 [Pl. L13]) shows several dark spots across the whole of the remnant's synchrotron emission nebula. Close examination of the 4770 image reveals nearly two dozen of these small spots of apparent absorption. Their positions relative to Wyckoff and Murray's (1977) "star 16" (i.e., the central north following star) are listed in Table 1. The features are labeled alphabetically by region (1 = west, 2 = south, 3 = east, and 4 = north) starting usually with the most prominent spot. Feature 1A, west of the pulsar, is the most prominent spot and is the likely absorption feature reported by Woltjer and Véron-Cetty (1987). The reality of these features is confirmed by Hester *et al.* (1989) who report optical and near-infrared observations which show several of the more prominent dark spots.

The features exhibit Δm_{4770} from 0.44 mag down to our detection limit of 0.08 mag. Individual spot extinction estimates at 4770 and 6478 Å are listed in Table 1 and were estimated by means of N-S and E-W cross-cut plots through the 4770 and 6478 images. Measurement errors are estimated to be 20%–40% due to the nonuniform background brightness of the amorphous region. Dimensions of the features were also determined from FWHM measurements. Spots range in size from being unresolved at 0".8 resolution to ≈5", with many appearing distinctly noncircular (e.g., 1A, 2A).

The spectral properties and positions of these dark spots suggest that they are not synchrotron emission "holes" around filaments but rather extinction features due to dust located in the central regions of selected filaments that lie in front of the nebula's inner synchrotron emission nebula. The observed wavelength dependence of the absorption is similar to that seen for normal interstellar dust. The average ratio of absorption at 4770–6478 Å for the five stronger spots is 1.6, close to the value of 1.5 for interstellar reddening (Seaton 1979). Comparison with emission-line images of the nebula show that the absorption spots coincide precisely with centers of filaments. While many of the coincident filament positions do not have measured radial velocities, features 1A, 1C, 1E, 3A, 3C, and 4A correspond to filaments 198/199, 226, 201, 208, 207, and 138, respectively (Trimble 1968), all of which exhibit negative radial velocities (−403 to −733 km s^{-1}) indicating locations on the remnant's expanding front hemisphere.

TABLE 1

CATALOG OF ABSORPTION SPOTS IN THE CRAB NEBULA

Spot ID	Position[a]	Δm_{4770}	FWHM (4770)	Δm_{6478}	FWHM (6478)
1A	39".1W, 25".8S	−0.44	2".3	−0.26	1".9
1B	41.8W, 18.5S	−0.17	2.2	−0.12	1.2
1C	41.8W, 16.4S	−0.20	2.2	−0.13	1.6
1D	54.5W, 18.2S	−0.16	1.9	−0.11	2.1
1E	67.3W, 7.3S	−0.21	1.2	−0.17	1.3
2A	0.0E, 72.4S	−0.35	3.9	−0.20	2.2
2B	3.5W, 64.5S	−0.16	1.5	−0.14	1.6
2C	6.1E, 51.5S	−0.12	1.8	−0.09	1.2
2D	12.1E, 53.3S	−0.10	1.4	−0.10	1.0
2E	16.5E, 36.5S	−0.14	2.2	−0.08	1.2
2F	36.4E, 36.7S	−0.24	2.9	−0.21	1.3
2G	60.9E, 40.6S	−0.30	1.9	−0.15	1.2
3A	16.7E, 6.1S	−0.13	0.9	≤−0.05	...
3B	24.2E, 5.4S	−0.32	3.0	−0.10	1.8
3C	26.4E, 2.4S	−0.25	4.8	−0.09	1.2
3D	31.2E, 2.7S	−0.17	2.5	−0.15	1.6
3E	35.5E, 0.3S	−0.11	1.8	−0.07	1.3
3F	40.6E, 2.1S	−0.12	1.5	−0.08	≤1.0
3G	44.5E, 2.7N	−0.19	1.5	−0.14	1.4
4A	13.3W, 63.3N	−0.28	1.9	−0.19	1.2
4B	14.3W, 49.7N	−0.10	1.3	−0.08	1.7
4C	19.1W, 43.3N	−0.08	1.0	≤−0.05	1.1
4D	63.0W, 54.2N	−0.12	1.6	−0.12	2.2
4E	56.4W, 54.8N	−0.12	1.0	−0.12	0.9

[a] Positions are 1988 offsets relative to star 16 (Wyckoff and Murray 1977).

The absorption spots also appear systematically smaller with increasing wavelength (see Table 1). This effect can be seen by comparing the four continuum images for region 1 obtained at 4770 Å, 6100 Å, 6478 Å, and 8100 Å (Fig. 2 [Pl. L14]). The absorption features gradually decrease both in strength and size from the 4770 image to the 8100 Å image where they are only weakly visible; e.g., feature 1A's diameter changes from 2".3 at 4770 Å, to 1".9 at 6478 Å, and to just over 1" at 8100 Å. Continued visibility in the 8100 Å continuum image of some of the stronger absorption features suggests a high concentration of dust in at least a few filaments. If the filamentary dust is centrally concentrated, then the optical extinctions we report here probably represent lower limits on the maximum extinction values. Although dense filament cores have long been invoked to explain the wide range of ionization states seen in individual filaments (Davidson 1973), additional support has recently come from the detection of H_2 inside some Crab filaments (Graham, Wright, and Longmore 1990).

An obvious question is why were these features not reported earlier? Baade, Minkowski, and others repeatedly photographed the Crab over a wide spectral range and yet never reported seeing any absorption in the nebula. The answer is

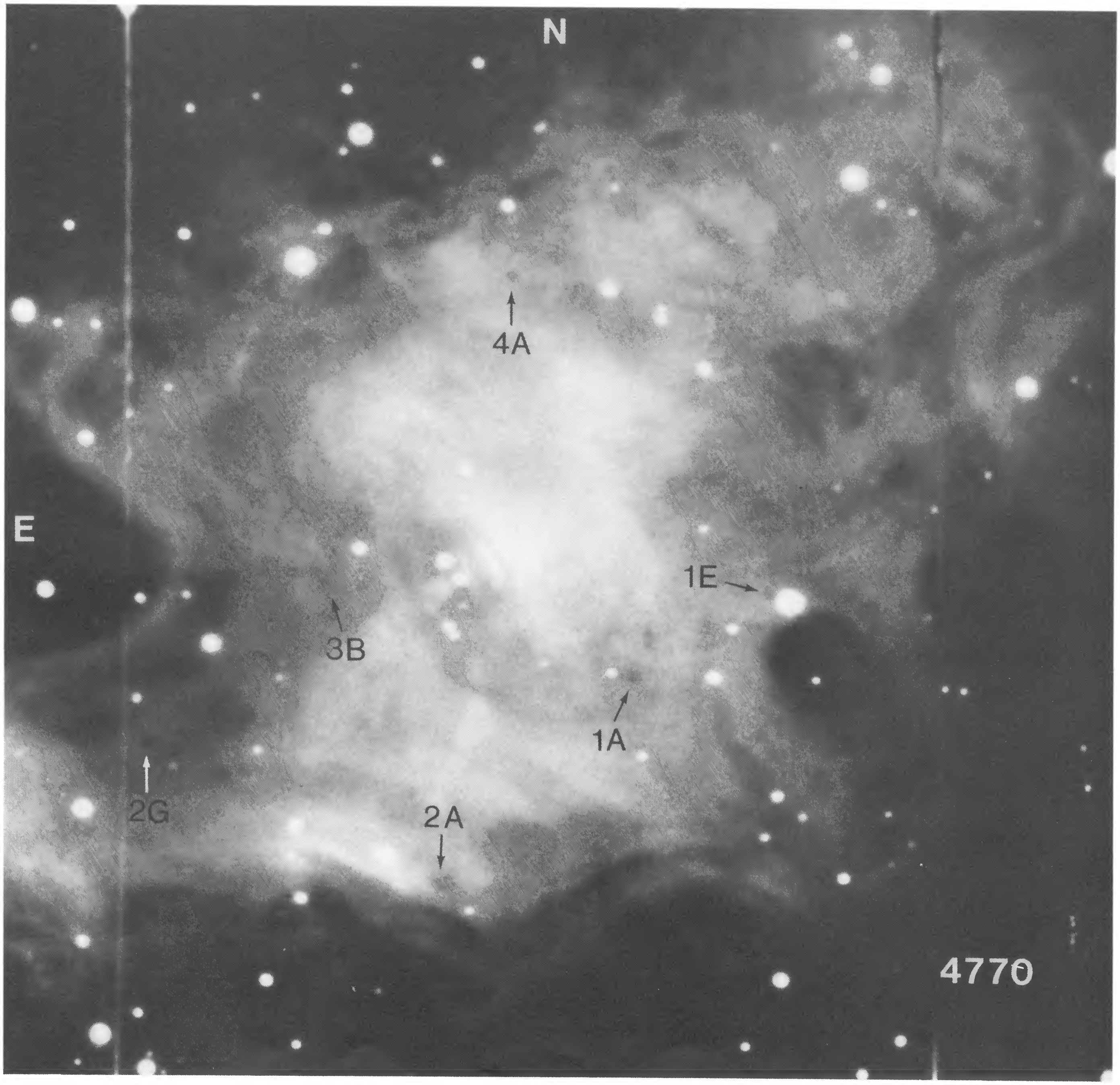

FIG. 1.—A 4700 Å continuum image of the inner 80% of the Crab Nebula showing the presence of numerous dark spots in the nebula's diffuse synchrotron emission. Some of the stronger features are labeled. Image size is 3'.9 × 3'.7.

FESEN AND BLAIR (*see* **351**, L46)

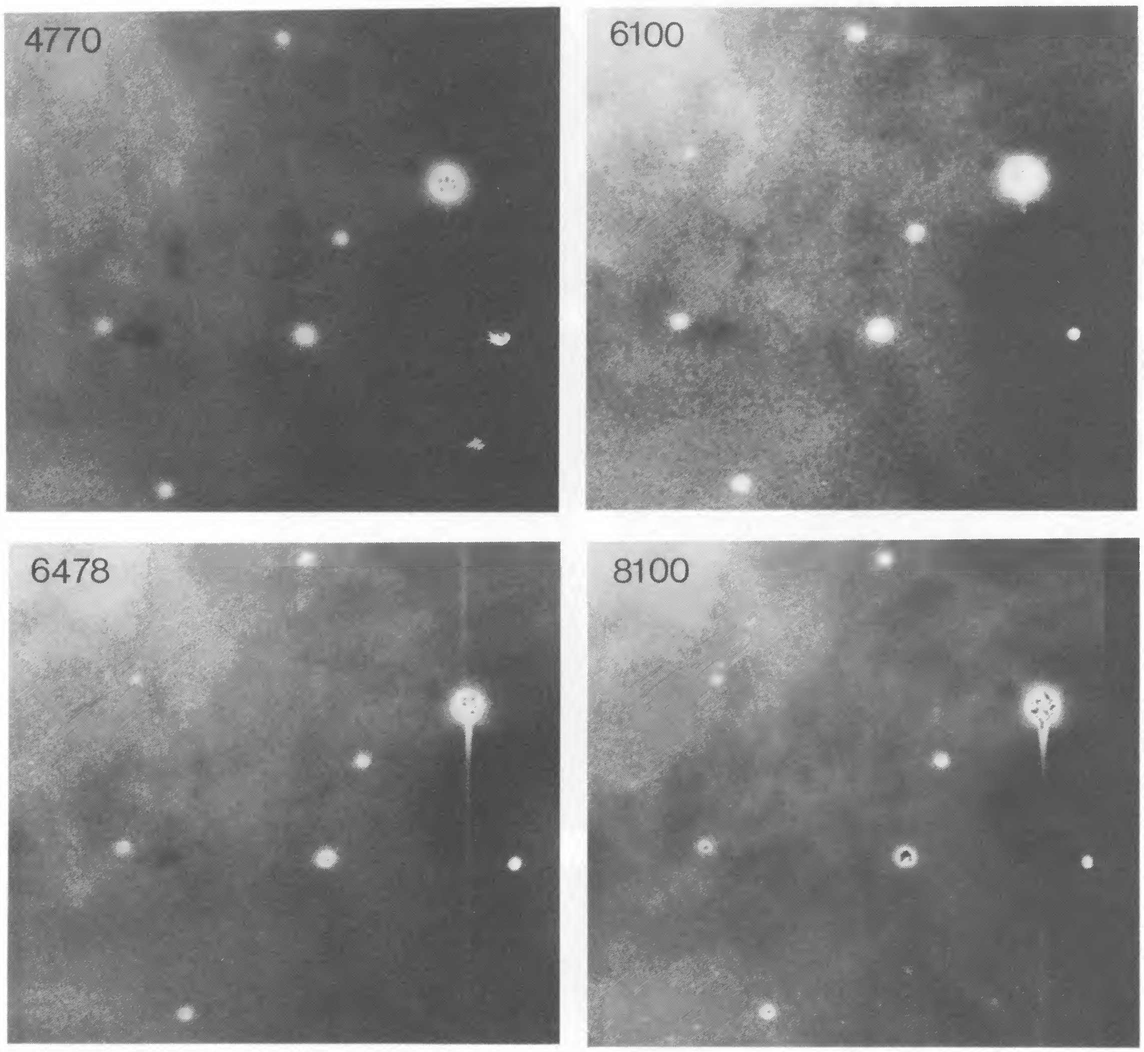

FIG. 2.—A series of continuum images for the region due west of the Crab's pulsar (=region 1). Size of field as shown is ~1′ a side. Note the general weakening and size reduction of the absorption features with increasing wavelength. North is up; east is to the left.

FESEN AND BLAIR (*see* **351**, L46)

that these researchers simply lacked sufficiently narrow filters to eliminate the filamentary line emission that filled in the absorption spots. Baade's excellent continuum images (Baade 1942) were obtained using broad filters centered near 8000 Å, where the spots are only weakly visible. Also, our images were obtained under excellent seeing conditions ($\leq 1''$), allowing us to more easily detect even weak features. We note that variations in the observed Hα/Hβ ratio among individual filaments (Fesen and Kirshner 1982) might be attributed in part to the presence of filamentary dust.

Despite sizes near the resolution limit of the images, and the nonuniform brightness level of the Crab's amorphous synchrotron nebula, one can obtain a rough estimate for the mass of dust required to produce the observed extinction of a typical absorption feature. Dust extinction in magnitudes can be given by $\Delta m = 1.086 N_g \pi a^2 Q_e$, where N_g is the total column density of scattering dust grains of radius a, and Q_e is the extinction efficiency factor, which is a function of wavelength and grain size. Choosing a grain size of 7.5×10^{-6} cm (e.g., SiC grains) appropriate for optical and infrared extinction, a value of 2 for Q_e, and a dust density of 2–3 g cm^{-3}, we estimate a dust mass of 2×10^{-6} $M_\odot$ for an absorption feature 2″ in diameter with $\Delta m_{4770} = 0.20$ mag and a distance of 2 kpc. Assuming the 24 features listed in Table 1 represent only a fraction (0.3) of the total filaments in the remnant with similar dust masses, then the nebula's dust mass easily visible at 4770 Å is 1.4×10^{-4} $M_\odot$.

This mass is considerably less than the 5–50 $\times 10^{-3}$ $M_\odot$ estimated from infrared measurements. Possible reasons for our lower mass estimate include. (*a*) a serious underestimate of the amount of dust due to a steep concentration within a small region in the filament cores, (*b*) much larger grain sizes than the 7.5×10^{-6} cm assumed above, and (*c*) additional but less concentrated dust spread throughout the remnant's other filaments but producing an extinction below our Δm limit of 0.08 mag. This last possibility is supported by examination of the 4770/6478 ratio image (Fig. 4 [Pl. L19]). Along with the already noted dark spots, much fainter more extended absorption "bands" can be seen which appear to connect features 4A to 1A and then on to 3A/3B–3F. These regions of weaker optical extinction lie coincident with chains of filaments. Even though the extinction is low in these areas, their large spatial extents might indicate a substantial amount of dust. Therefore, if a majority of the Crab filaments contain at least this level of dust, then the total mass derived from observed optical extinctions might approach the 10^{-2} $M_\odot$ value estimated from IR measurements.

While there is little or no correspondence with bright Hβ emission filaments or as suggested by Woltjer and Véron-Cetty (1987) with [O III] line emission, there is excellent positional agreement with filaments strong in low-ionization emission lines, especially [S II]. This is illustrated in Figure 3 (Plates L15–L18), where we show the 4770 continuum image together with [O I] 6300, [S II] 6717, 6731, [C I] 9850, Hβ, and [O III] 5007 line emission images for the four regions studied. For example, while there is certainly bright [O III] emission at the position of the strong feature 1A (see Fig. 3*a*), there is little correlation between the locations of dust spots and filament [O III] brightness. On the other hand, the absorption spots appear to coincide exactly with the bright centers of filaments which are strong in lower ionization lines such as [S II], [O I], and [C I]. Knots best demonstrating this correspondence include knots 1E, 2A, 2E, and 4D. The strong connection between absorption features and filament cores suggests that the dust resides largely inside the filaments and thus is unlikely to be swept-up circumstellar or interstellar dust, although this cannot be completely ruled out.

Dust formation in the Crab's filaments probably occurred early in the remnant's development. Ejecta temperatures below 1000 K plus relatively high densities of metal-rich material favorable for dust condensation would have been present within a year or so after the SN outburst. The existence of dust in lower density filaments, as suggested by the absorption bands seen in the ratio image (Fig. 4 [Pl. L19]), supports the notion of dust forming early on when the ejecta density was appreciably higher. The recent discovery of H_2 emission in some of the remnant's filaments (Graham, Wright, and Longmore 1990) indicates both the presence of dust grains in the filaments as a way of producing the H_2 molecule and also the rapid formation of dust within the first few decades after the SN event. Since the Crab Nebula is a Type II supernova remnant produced by the explosion of a fairly massive star ($\approx$10–30 $M_\odot$: Nomoto *et al.* 1982; Hillebrant 1982; MacAlpine *et al.* 1989), the observed dust probably consists of iron and silicate grains.

The optical detection of dust in the Crab's filaments is perhaps the most direct evidence for dust production in a Galactic supernova remnant. It suggests that dust may form fairly rapidly in even ejecta that is not particularly rich in heavy elements. Why more filaments do not show stronger absorption features is unclear. Perhaps differences in initial density or heavy-element abundances which are particularly favorable for dust formation occurred in only a fraction of the filaments. The correlation of dusty filaments with those particularly bright in [S II] emission does suggest some abundance differences may be present. Although the mass of dust in the Crab inferred from even infrared observations is probably insufficient to suggest supernovae as major sources of dust, it does suggest that dust, once formed, can survive at least for 10^3 yr in a relatively hostile environment around a very active pulsar.

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REFERENCES

Baade, W. 1942, *Ap. J.*, **96**, 188.
Bode, M. F. 1982, *Vistas Astr.*, **26**, 369.
Cernushi, F., Marsicano, F., and Codina, S. 1967, *Ann. d'Ap.*, **30**, 1039.
Clayton, D. D. 1975, *Ap. J.*, **199**, 765.
———. 1979, *Space Sci. Rev.*, **24**, 147.
Davidson, K. 1973, *Ap. J.*, **186**, 223.
Davidson, K., and Fesen, R. A. 1985, *Ann. Rev. Astr. Ap.*, **23**, 119.
Dinerstein, H. L., Lester, D. F., Rank, D. M., Werner, M. W., and Wooden, D. H. 1987, *Ap. J.*, **312**, 314.
Dennefeld, M., and Pequignot, D. 1983, *Astr. Ap.*, **127**, 42.
Dwek, E. 1989, in *IAU Symposium 135, Interstellar Dust*, ed. L. Allamandola and A. G. G. M. Tielens (Dordrecht: Kluwer), in press.
Dwek, E., Dinerstein, H. L., Gillett, F. C., Hauser, M. G., and Rice, W. L. 1987, *Ap. J.*, **315**, 571.

1990ApJ...351L..45F

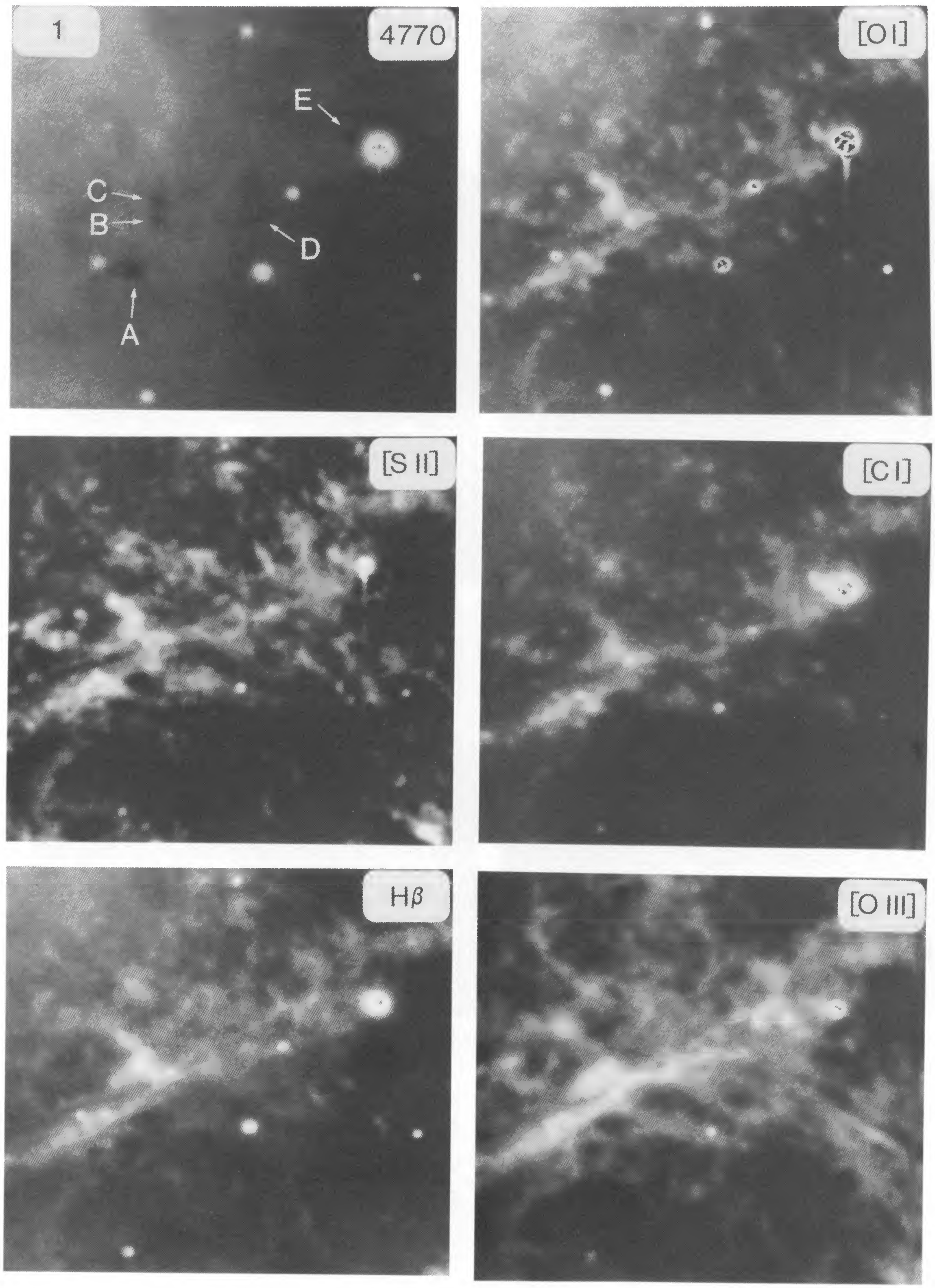

FIG. 3a

FIG. 3.—Mosaic of continuum and emission line images for regions 1–4. Scale and orientation are the same as Fig. 2 except for Fig. 3*d* where the field size is 70″ in the E-W direction.

FESEN AND BLAIR (*see* **351**, L47)

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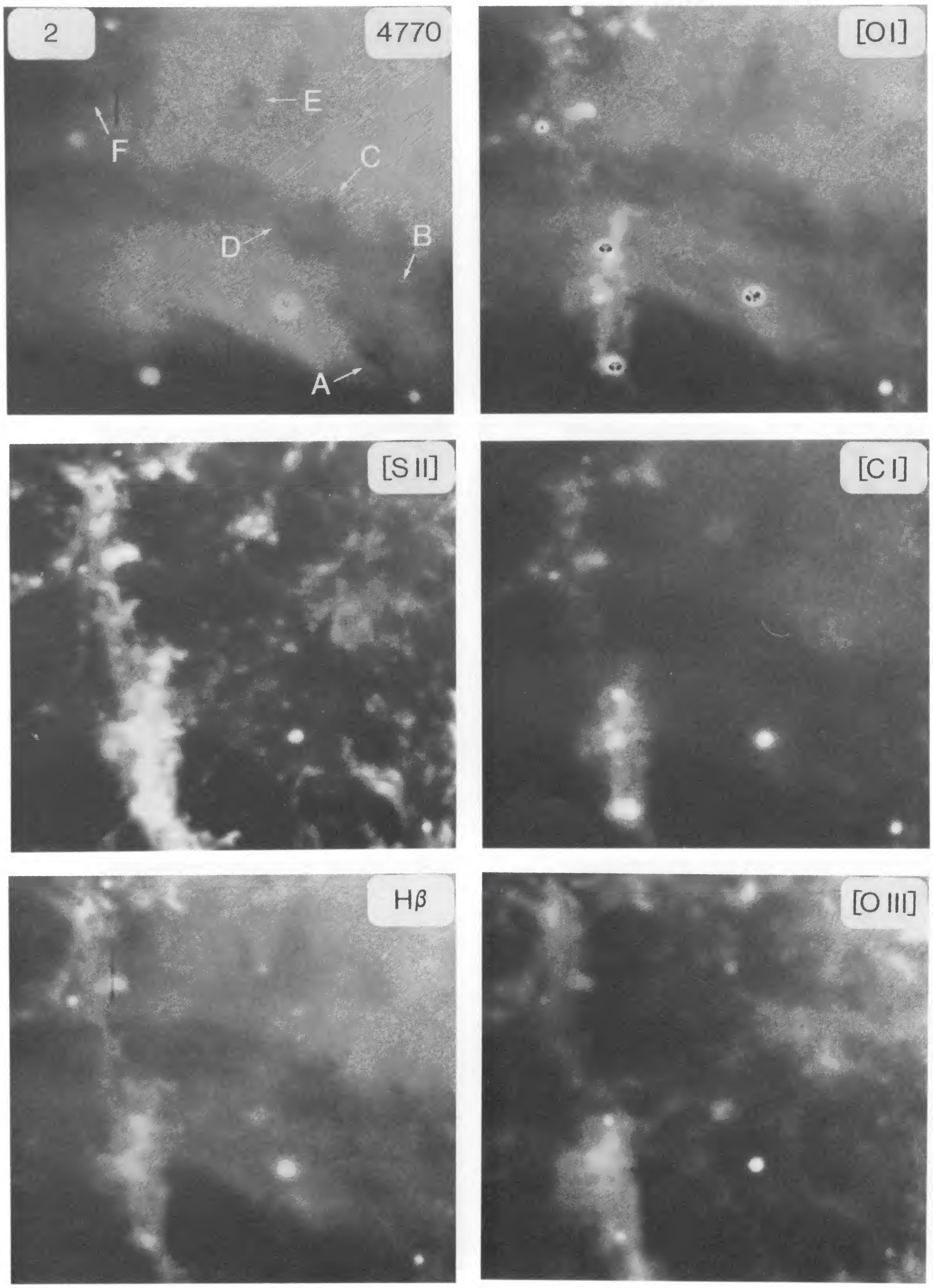

FIG. 3*b*

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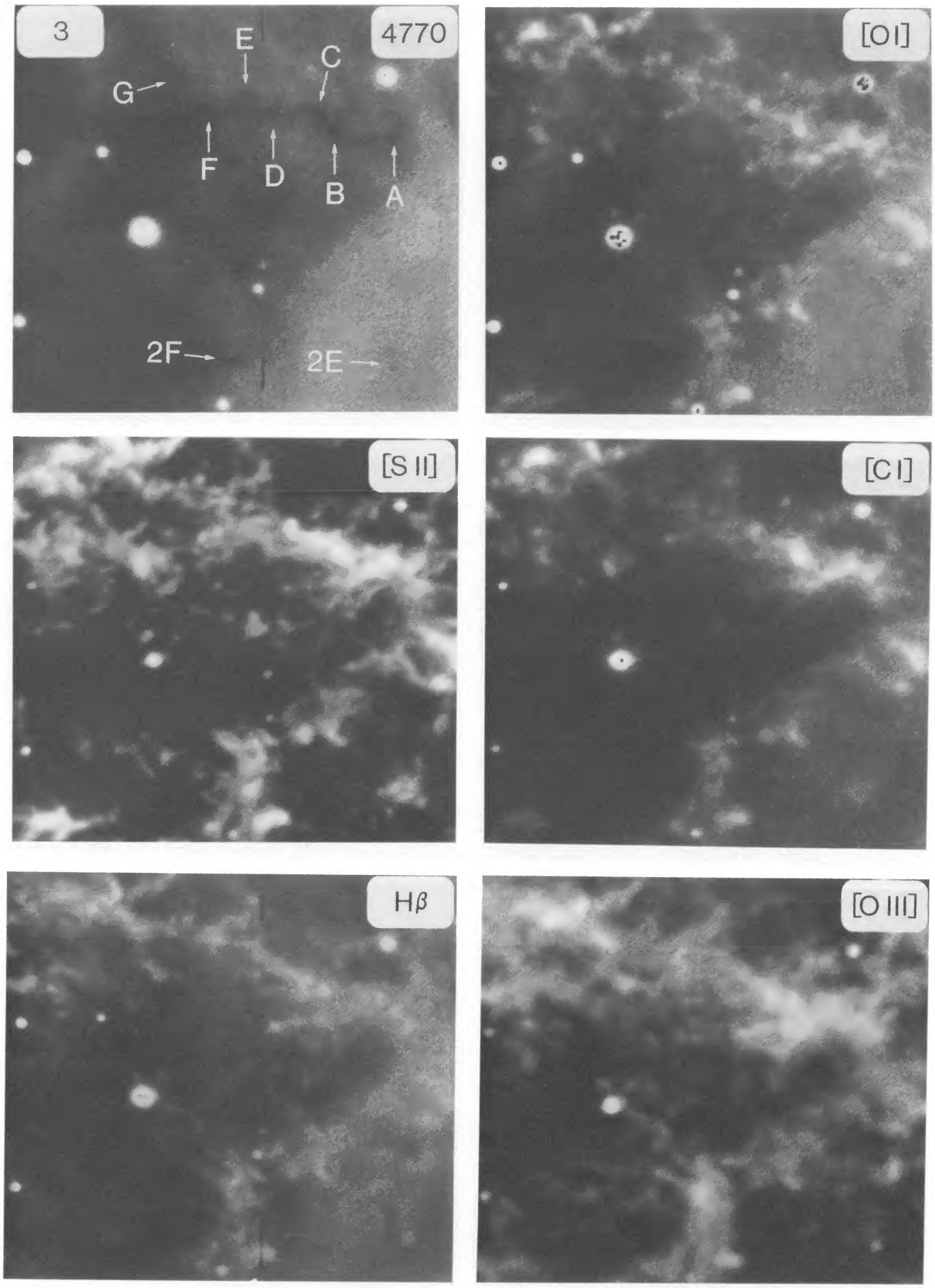

FIG. 3c

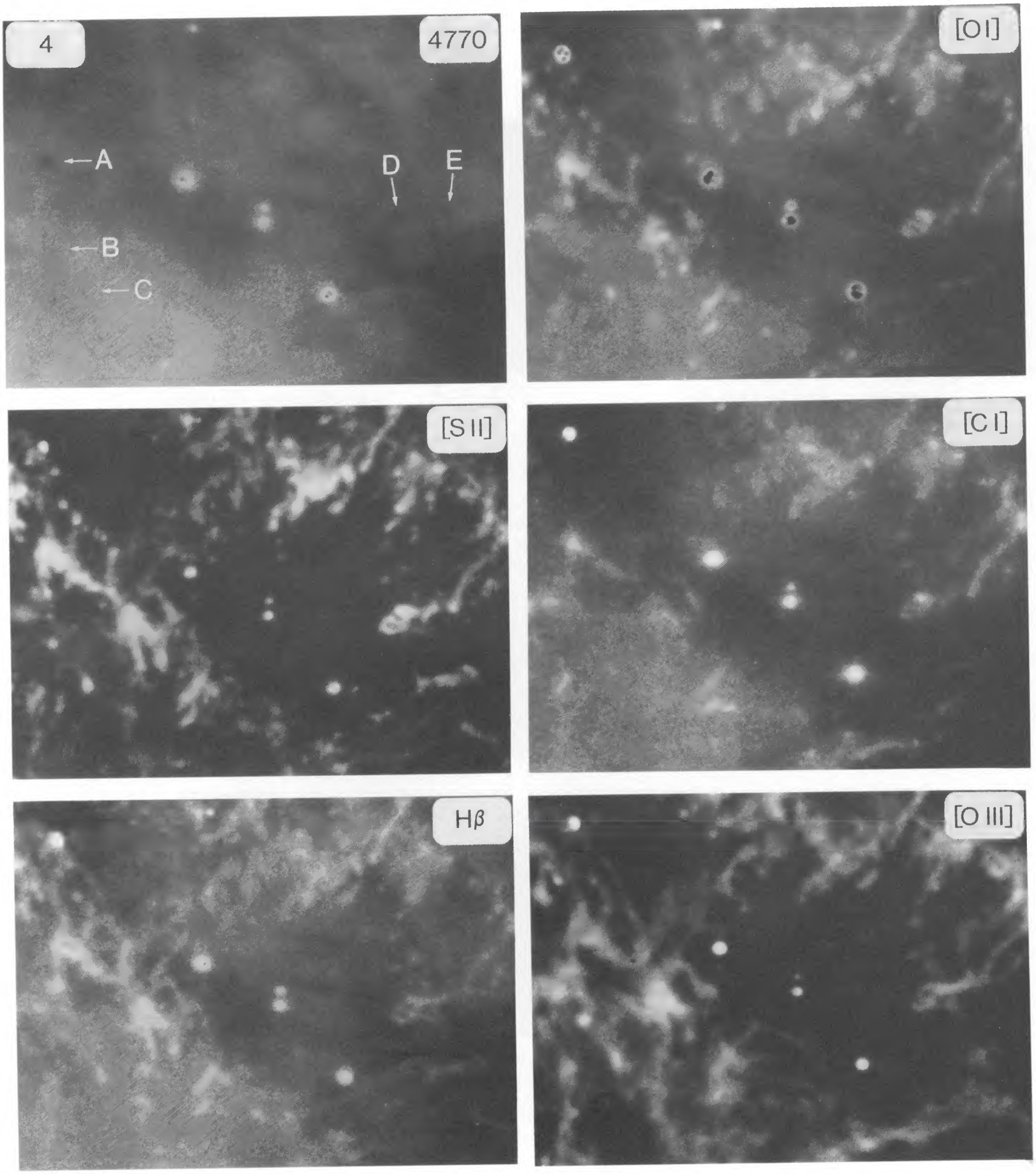

FIG. 3*d*

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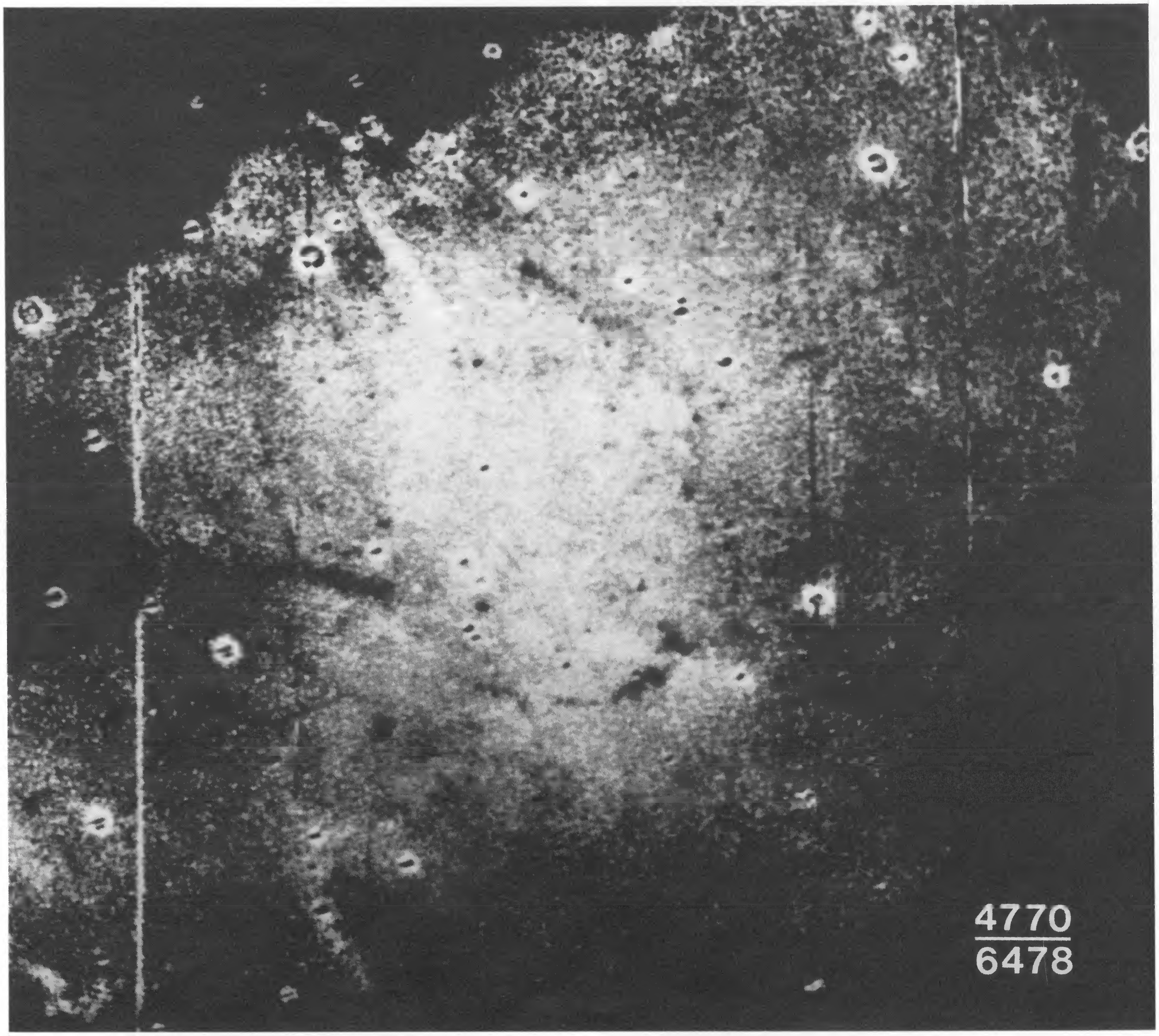

FIG. 4.—A ratio image of the 4770 Å/6478 Å continuum images of the Crab Nebula. Some stellar residues appear as black dots. Note the diffuse nature of the faintest dust absorption, indicating that at least some of the dust is distributed in a more extended component.

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Dwek, E., and Scalo, J. M. 1980, *Ap. J.*, **239**, 193.
Dwek, E., and Werner, M. W. 1981, *Ap. J.*, **248**, 138.
Dwek, E., *et al.* 1983, *Ap. J.*, **274**, 168.
Falk, S. W., Lattimer, J. M., and Margolis, S. H. 1977, *Nature*, **270**, 700.
Fesen, R. A., and Kirshner, R. P. 1982, *Ap. J.*, **258**, 1.
Graham, J. R., Wright, G. S., and Longmore, A. J. 1990, *Ap. J.*, **352**, 172.
Graham J. R., *et al.* 1983, *Nature*, **304**, 709.
Harvey, P. M., Gatley, I., and Thronson, H. A. 1978, *Pub. A.S.P.*, **90**, 655.
Hester, J. J., Graham, J. R., Beichman, C. A., and Gautier, T. N., III 1989, *Ap. J.*, submitted.
Hillebrant, W. 1982, *Astr. Ap.*, **110**, L3.
Hoyle, F., and Wickramasinghe, N. C. 1970, *Nature*, **226**, 62.
Jacoby, G. 1987, *NOAO Newsletter*, No. 9, p. 15.
Lattimer, J. M., Schramm, D. N., and Grossman, L. 1978, *Ap. J.*, **219**, 230.
Lucy, L. B., Danziger, I. J., Gouiffes, C., and Bouchet, P. 1989, preprint.
MacAlpine, G. M., McGough, S. S., Mazzarella, J. M., and Uomoto, A. 1989, *Ap. J.*, **342**, 364.
Marsden, P. L., Gillett, F. C., Jennings, R. E., Emerson, J. P., De Jong, T., and Olnon, F. M. 1984, *Ap. J. (Letters)*, **278**, L29.
Merrill, K. M. 1980, *IAU Circ.*, No. 3444.
Mezger, P. G., Tuffs, R. J., Chini, R., Kreysa, E., and Germund, H.-P. 1986, *Astr. Ap.*, **167**, 145.
Nomoto, K., Sparks, W. M., Fesen, R. A., Gull, T. R., Miyaji, S., and Sugimoto, D. 1982, *Nature*, **299**, 803.
Seaton, M. J. 1979, *M.N.R.A.S.*, **187**, 73P.
Trimble, V. 1968, *A.J.*, **73**, 535.
———. 1977, *Ap. Letters*, **18**, 145.
Woltjer, L., and Véron-Cetty, M.-P. 1987, *Astr. Ap.*, **172**, L7.
Wright, E. L., Harper, D. A., Loewenstein, R. F., Keene, J., and Whitcomb, S. E. 1980, *Ap. J. (Letters)*, **240**, L157.
Wyckoff, S., and Murray, C. A. 1977, *M.N.R.A.S.*, **180**, 717.

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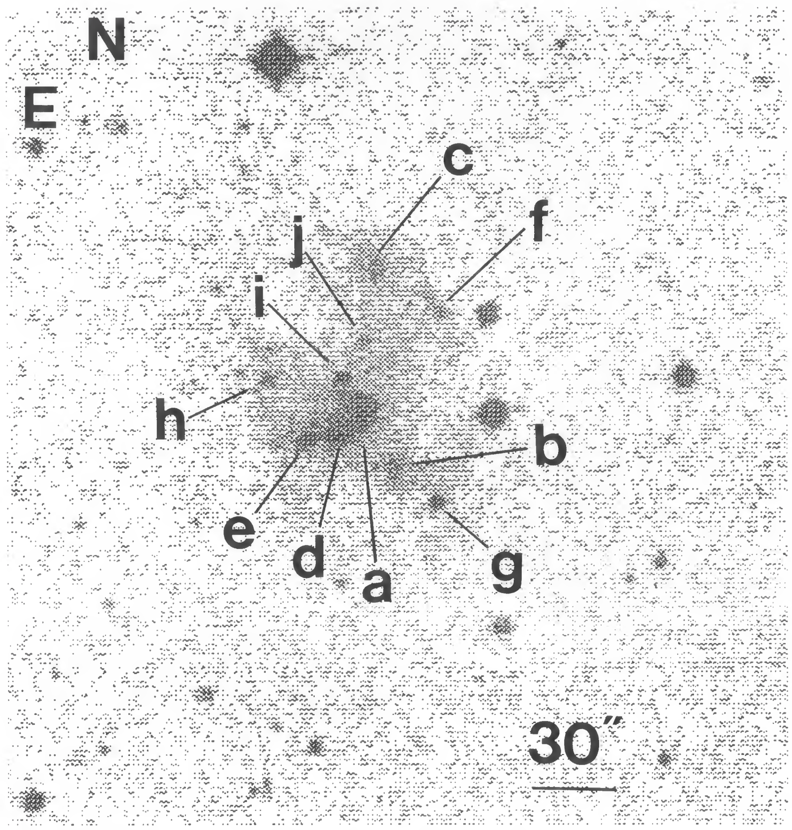

FIG. 3.—Gray-scale digitization of the UK Schmidt photograph, with principal features in the dwarf irregular marked. The field size is 5′ × 5′.

IMPEY, BOTHUN, MALIN, AND STAVELEY-SMITH (*see* **351**, L34)