SESSION 1

OBSERVATIONS OF THE CRAB NEBULA

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1.1 OPTICAL OBSERVATIONS OF THE CRAB NEBULA

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Abstract. The continuum radiation from the Crab Nebula has a great deal of structure, the majority of which is strongly polarized. Wisps in the vicinity of the pulsar at the centre of the nebula move noticeably in a few months. The appearance of the nebula changes markedly when photographed in different emission lines, as a result of the variations of physical conditions from place to place within the nebula.

1. Introduction

The optical emission from the Crab Nebula (Plate I) consists of two distinct components, line emission and continuum synchrotron emission. On a color photograph the two are readily separable. The line emission, coming from gas at densities near $10^3\ \mathrm{cm}^{-3}$ and temperatures near $10^4\ \mathrm{K}$, is red due to the predominance of Hα and [N II]. A more recent and probably more accurate color photograph by J. Miller at Lick Observatory shows many of the filaments (line emitting features) as green due to [O III] radiation at λ5007. Other strong lines are produced by [S II], [O II], [O I], He I and II, [Ne III], and hydrogen. The white light, more strongly concentrated toward the center than the filaments, is the synchrotron continuum emission, which we also see in the radio, infrared, and (probably) X-ray regions of the spectrum.

2. The Continuum Emission

The outermost isophotes of the nebula as shown, e.g. by Woltjer (1957), are roughly elliptical. It has been suggested by Shklovskii (1966) that one would expect material to be ejected from an explosive event in the form of a prolate ellipsoid and by Münch (1958) that the interstellar magnetic field (given that the major axis of the ellipse is approximately parallel to the galactic equator) might have perturbed a symmetric explosion into the prolate shape. The most intense continuum emission regions trace out a crude S-shape. The arms of the S extend in the same general direction as continuum features are observed to move, and the shape is probably related in some way to the electrodynamics of the pulsar.

The continuum emission (Plate II) is frequently spoken of as amorphous, but this is far from the case. There are obvious large-scale features – a sort of hole near the center (this has perhaps been swept clean by agency of the pulsar), two indented bays on the east and west sides of the object, and regions of higher and lower intensity, especially in the northwest quadrant. Changes in these regions were first noted, with some surprise, by Lampland (1921). Near the center are the rapidly changing wisps, first mentioned by Baade (Oort and Walraven, 1956) and studied by Scargle (1969a). And, in very good seeing, the continuous emission appears to be largely

Davies and Smith (eds.), The Crab Nebula, 3–11.

Plate I. Photograph of the Crab Nebula (originally in colour) by W. Miller (courtesy Hale Observatories, Carnegie Institute of Washington).

concentrated in thin, thread-like features which are entangled in a sort of basket weave or cotton wool structure. Polarization data indicates that these fibers are aligned with the magnetic field lines. Their formation is not satisfactorily understood; neutral sheets in the magnetic field, thermal instability driven by the synchrotron radiation, and self-pinching relativistic current tubes have been suggested. At any rate, the traditional equipartition way of estimating magnetic field strength and relativistic electron energy from the synchrotron intensity should be modified to take this non-homogeneity into account. See M. Rees (this symposium, p. 407) concerning circular polarization and the possible absence of a magnetic field.

The work of Scargle (1969a) indicates that the nebula is rather bluer at the center than at the edges. This is what one would expect if relativistic particles are largely injected near the center, given that electrons responsible for optical radiation have synchrotron lifetimes of the order of the age of the remnant. The blueness of the center is also in accord with the difference between the radio and optical objects; although the outermost detectable contours in the two spectral regions are about the same size, the radio emission is less strongly peaked at the center than is the optical emission. It is possible that this correlation continues into the X-ray region and that the nebula is significantly smaller at high energies. This variation of color with position implies that the frequency dependence of the volume emissivity varies with location in the

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nebula. The apparent inflection of the integrated optical continuum after correction for reddening (see the spectrum given by Baldwin elsewhere in this volume, page 22) may, therefore, be the result of summing unlike spectra and not indicative of an inflection in the real volume emissivity. If, on the other hand, the spectrum really

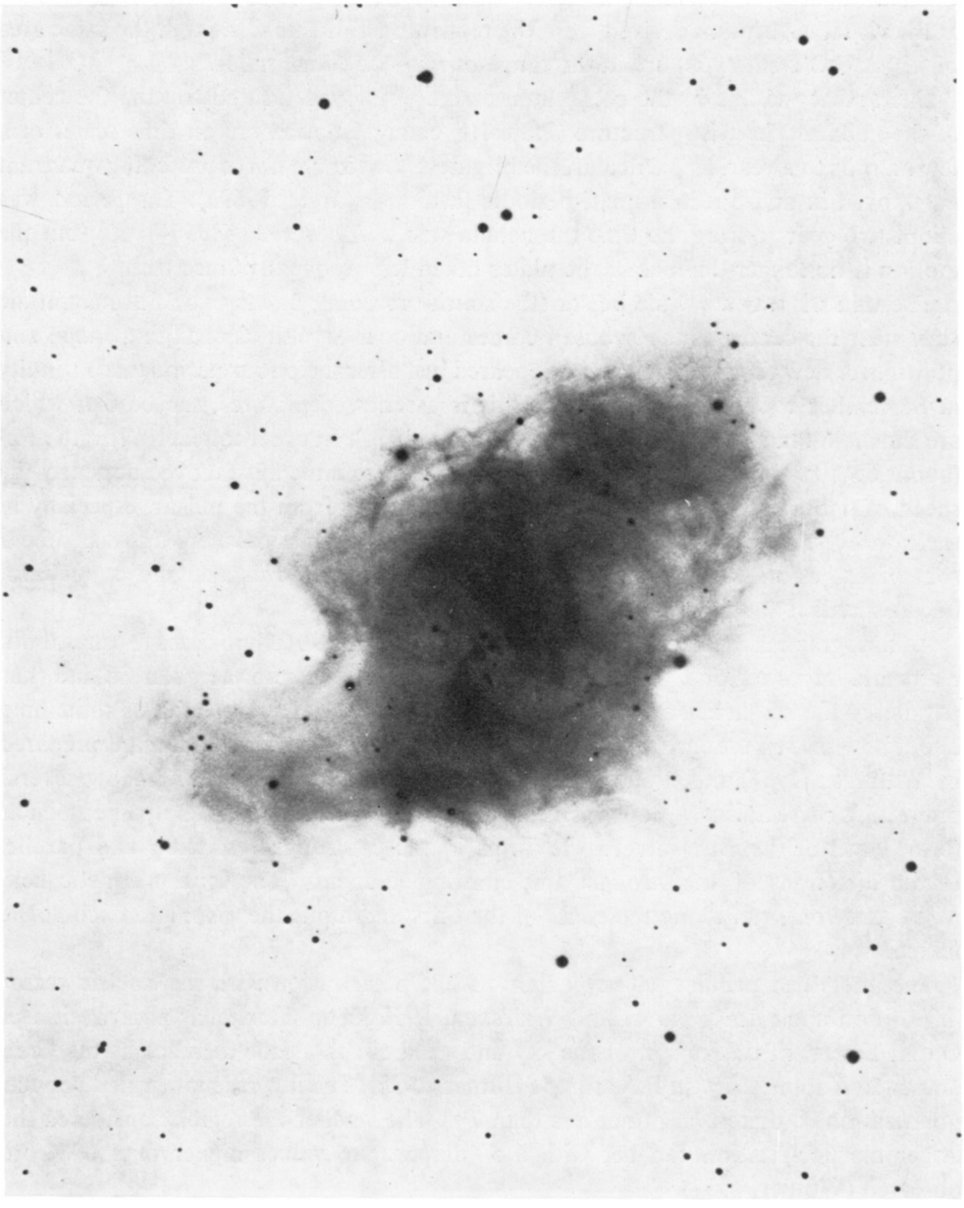

Plate II. Continuum emission photograph of the Crab Nebula taken by W. Baade (courtesy Hale Observatories).

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has a relative maximum in the blue, this is most likely a feature of the volume emissivity in some part of the nebula (Minkowski, 1968).

The uncertainty in the shape of the optical spectrum results from our lack of knowledge of the reddening of the object. It ought to be possible to estimate this directly from the observed ratio of the [SII] lines in the red and the blue (whose emitted intensity ratio is known theoretically), but this has not been done. Guesses at the visual absorption derived from the reddening of O and B stars in the same area of the sky (O'Dell, 1962) are in the range one to two magnitudes.

The activity visible in the continuum emission is concentrated toward the center of the nebula. The wisp structure (Plate III) changes noticeably on time scales of a few months to a year. In particular, the brightest wisp in the north preceding quadrant has moved in and out in a quasi-periodic fashion (Scargle, 1969a). The period was about two years during the time the nebula was well observed (1955–1960), but the motion is no longer obvious in the plates taken less frequently since then.

The thin wisp, nearest the pulsar (the south preceding of the two 16th magnitude stars near the center of the nebula), comes and goes as well as changing shape and position. A new thin wisp may have appeared just after the pulsar period discontinuity in September 1969. The evidence for this is a series of pictures, the best of which are shown in Plate III (from Scargle and Harlan, 1970). In order to reach a length of 2″ (about 6×10^{16} cm) in a couple of months, the feature must have moved at nearly the speed of light. Less rapid changes can be seen further from the pulsar, especially in the northwest quadrant. Regions of strong and weak emission there appear to be a sort of extension of the series of wisps near the center and also move outward, but at speeds $\lesssim 0.1$ c.

A photograph taken through polaroid (e.g. Scargle, 1969b) emphasizes features, both fibers and larger regions, which are elongated perpendicular to the polaroid and thus parallel to the magnetic field in their vicinity. This must be trying to tell us something about how the features are produced. The detailed optical polarization maps prepared by Walraven (1957) and Woltjer (1957); see Figure 1 in Conway (1971) show several interesting correlations with intensities. The electric vectors tend to be perpendicular to the edges of the bays and to the wisps in the continuum emission and parallel to the directions of the stronger line-emitting filaments. The local magnetic field must, therefore, run along the edges of the bays and along the wisps and encircle the filaments.

The integrated nebular emission shows 9.2% polarization with the electric vector in position angle 159°.6 (Oort and Walraven, 1956). The interstellar polarization of O and B stars in this region of the sky and at about the same distance as the Crab amounts to about 2.4% in P.A. 148°.5 (Hiltner, 1956). The intrinsic integrated nebular polarization is, therefore, rather less than 7%. The smaller the region considered the larger the polarization can be; with a 5″ diaphragm, values higher than 60% are observed (Woltjer, 1957).

Unlike the radio continuum emission (for which a high resolution map discussed by Wilson elsewhere in this volume (page 68) shows intensity maxima near some of the

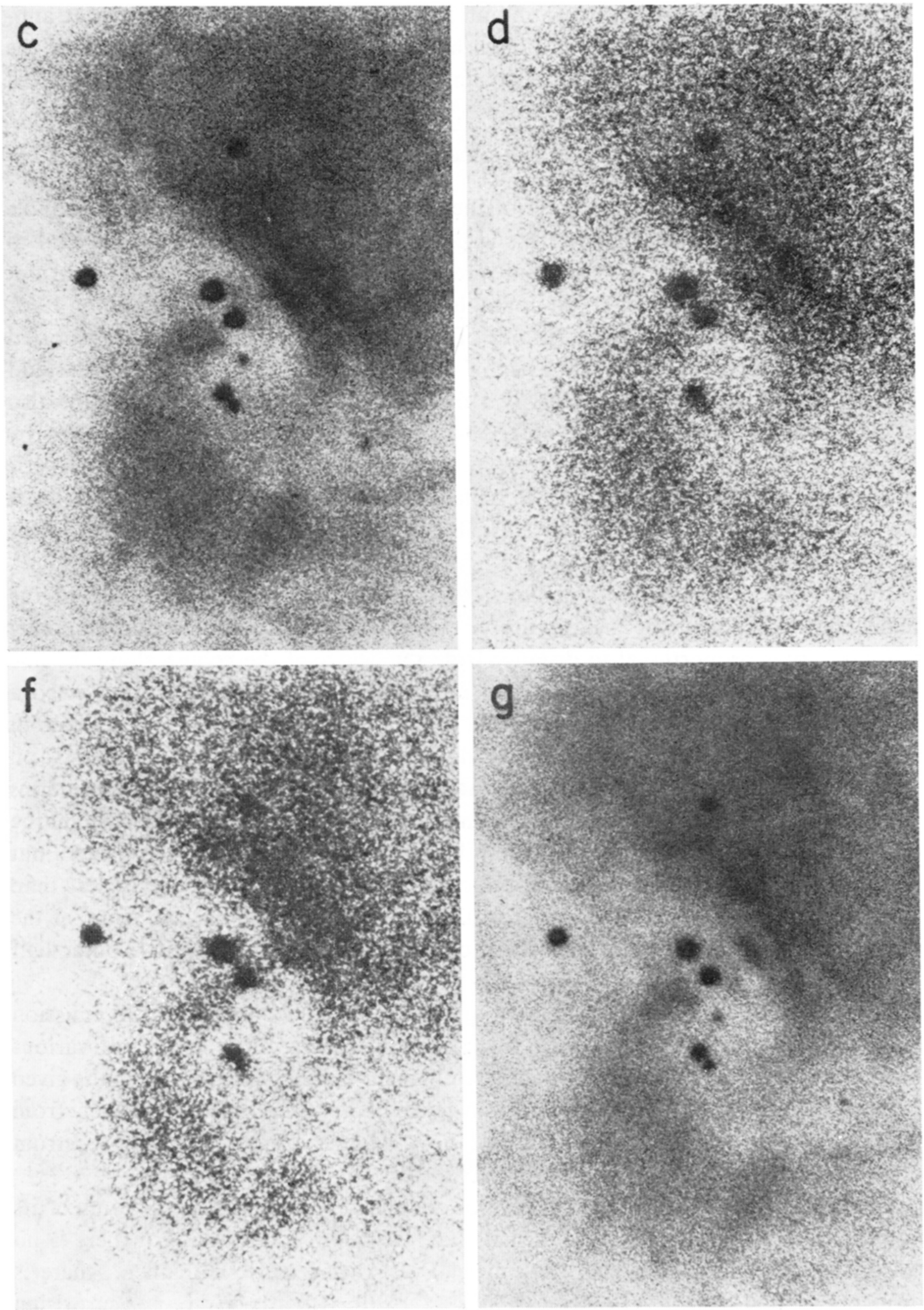

Plate III. Changes in the wisp structure at the center of the Crab Nebula (from Scargle and Harlan, 1970).
(By courtesy of the Astrophysical Journal and University of Chicago Press)

stronger filaments) the optical continuum seems, if anything, to be somewhat anti-correlated with the line emission, though both are weak near the center. One of the bays, for instance, is almost bisected by an intense filament.

3. The Line Emission

A very heavily exposed photograph of the line emission (obtained using a suitable color or interference filter) shows a sharply defined edge, quite nearly elliptical in shape except for a bulge on the south preceding edge. An accidentally burned out [O II] λ3727 interference filter photograph, taken by the author in January 1967, also shows the faint jet on the north side of the Crab Nebula which was first reported by van den Bergh (1970) on the basis of a broader band photograph. This would appear, therefore, to be at least partly a line emission feature, but there seems also to be an indication of it in the outermost continuum emission isophote given by Woltjer (1957).

The line emission is concentrated in a filamentary structure (Plate IV), the strongest features being extremely irregularly distributed and the fainter ones scattered over most of the surface of the nebula.

It is possible to determine something of the three dimensional structure of the filamentary component by making use of radial velocity information and assuming that velocity is proportional to distance from the center of the nebula along the line of sight as it is in the plane of the sky. Mayall (1962) has in this way obtained a three dimensional reconstruction in which all the features appear to be connected in intertwined ribbons. The radial velocity data given by Trimble (1968) suggests, on the other hand, that the line-emitting material is at least partially in discontinuous clumps. It is clear in any case that the filaments are not confined to a thin shell on the outside of the object. Only a few faint filaments are found near the center, but about half of the features with radial velocities given by Trimble (1968) are less than two-thirds of the way from the center to the surface of the nebula, and some of the strongly emitting filaments extend more or less radially outward in the outer half of the object.

There are striking differences in the appearance of the nebula in various emission lines (Plate IVa, b, c), or alternatively, striking differences in the spectra of various filaments. The latter can be seen quantitatively from the line emission strengths given by Woltjer (1958) for a number of positions in the nebula and more qualitatively from the emission line ratios given by Trimble (1970). Woltjer also gives a mean spectrum of relative intensities averaged over the nebula.

The spectrum of a particular volume of gas must be explainable in terms of its unique composition, temperature, density, and degree of ionization, but there is no reason why the mean spectrum should be. Even within a single filament, there is probably a good deal of stratification (Miller, 1970). It is, therefore, not surprising that theoretical calculations (e.g. Davidson and Tucker, 1970) of the behaviour of a slab of gas of fixed density and composition exposed to a given flux of ionizing ultra-

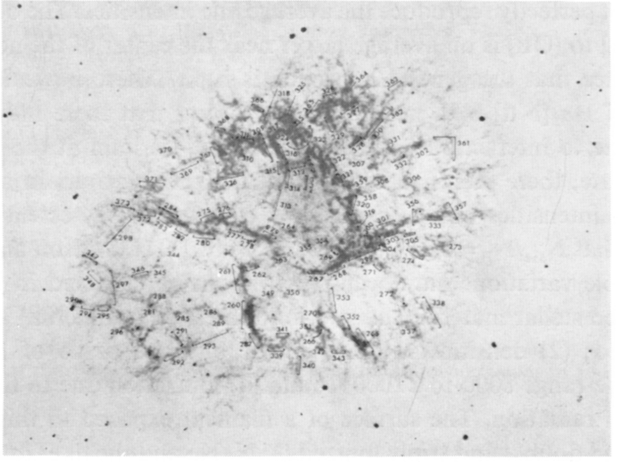

Plate IVa.

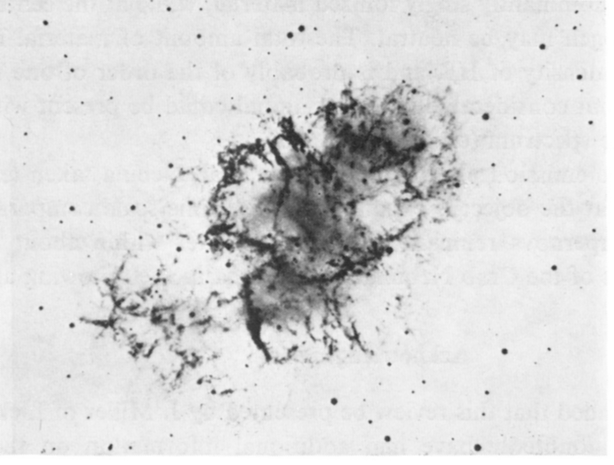

Plate IVb.

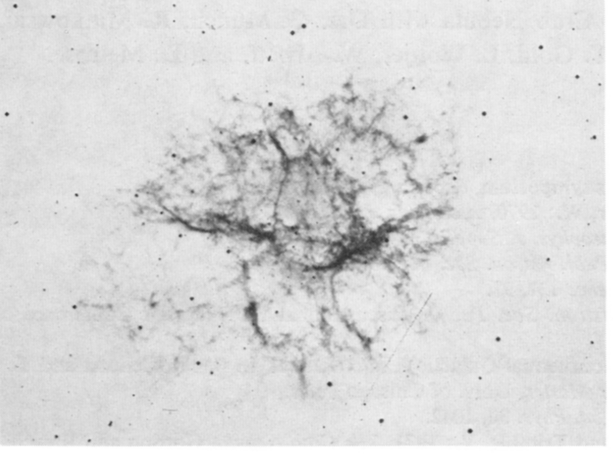

Plate IVc.

Plate IVa–c. The Crab Nebula in the line emission of (a) Hα + (N II), (b) (S II), (c) (O II). Taken by G. Münch (a and c) and W. Baade (b) on the 200″ telescope. (Courtesy Hale Observatories.)

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violet radiation do not perfectly reproduce the average line intensities. The observation that the ratio of [O III] to [O II] is on average larger near the center of the nebula than at the surface indicates that the general approach is right. There is weak evidence from the variation of Hα/[N II] with position in the object that there may be some additional heating due to interaction with the interstellar medium at the surface of the nebula. At any rate, there seems to be no difficulty, in principle, in accounting for the range of line intensities observed in terms of gas with (1) essentially solar composition, except that $N_{He}/N_H = 0.45$ (Woltjer, 1958) to 1.0 (Davidson and Tucker, 1970), but considerable variations may occur (and might be expected in gas which is a mixture of expelled stellar material and swept up interstellar material) and would not be easily detected; (2) densities within a factor of three or so of 10^3 cm^{-3}; (3) temperatures in the range 8000 to 27000 K; and (4) ionization due to the nebular ultraviolet continuum radiation. The surface of a filament exposed to this flux will contain H^+, He^{+2}, and doubly and triply ionized O, N, Ne and the like; intermediate regions will have predominantly singly ionized material, while at the center of dense filaments even hydrogen may be neutral. The total amount of material required is estimated from the intensity of Hβ, and is probably of the order of one solar mass (Minkowski, 1968), but considerable neutral material could be present without contributing much to the spectrum (except [O I] λ6300).

Comparison of line emission photographs of the Crab Nebula taken ten or more years apart shows that the object is expanding with a time scale comparable to the known age of the supernova remnant and from a center within about 10″ of the pulsar. The dynamics of the Crab Nebula are discussed in the following article.

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Discussion of this paper was deferred until after the following paper by the same author.