5.4 RADIATIVE IONIZATION OF THE FILAMENTS IN THE CRAB NEBULA

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Abstract. We have attempted to explain the observed excitation conditions in the filamentary system of the Crab Nebula in terms of ionization and heating by high frequency radiation. It was found that it is possible to reasonably fit most of the observed lines by assuming either (1) an ultraviolet continuum which smoothly joins the optical and X-ray data and a gas composition in which the number densities of hydrogen and helium are equal, (2) a spectrum which drops off about as steeply as ν^{-2} and therefore does not smoothly fit the X-ray spectrum, or (3) an ultraviolet continuum which smoothly joins the optical and X-ray data plus strong emission-line features near 20 eV. A UV continuum which is much larger than in these models results in too much ionization in the filaments. The calculations suggest that most of the filaments consist of outer ionized regions with cores of neutral gas, so that the mass of the filamentary shell may be considerably larger than the 1.45 $M_\odot$ required to explain the emission line intensities.

1. Introduction

In this communication we summarize attempts to explain the observed excitation conditions in the filamentary system of the Crab Nebula in terms of ionization and heating by high frequency radiation. For a more detailed discussion of this work see Davidson and Tucker (1970).

2. The Calculations

The incident source spectra of four models are shown in Figure 1. Also shown are the observed optical (Minkowski, 1968 and references cited therein) and X-ray spectra Gorenstein *et al.*, 1970) renormalized by a factor of 2.95×10^6 (corresponding to a reduction in distance from 1700 pc to 1 pc; i.e., applicable to a filament which is apparently 2′ from the center of the Nebula). For the optical observations, a particular value for the interstellar extinction must be assumed. The visual extinction is probably about $A_v \approx 2$ magnitudes (Minkowski, 1968).

The geometry of each model is rather simplified – each case is plane-parallel with a boundary upon which a beam of ionizing radiation is normally incident. The gas pressure is uniform in each case (this should be a better approximation than would uniform density). The electron density of the region containing O II is about 1000 cm^{-3} in each case.

Model 1 is a simple power-law spectrum that smoothly connects the optical and X-ray data. It is rather similar to a model considered by Williams (1967). It encounters

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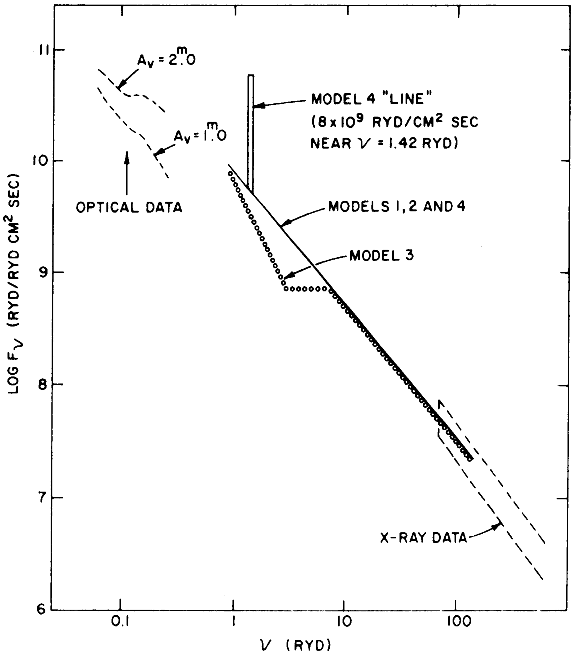

Fig. 1. Incident source spectra assumed for four calculated models. Observed optical and X-ray spectra are also shown, multiplied by 2.95×10^6 (i.e., appropriate to a filament which is 2′ from the center of the Nebula). Optical data are due to O'Dell (1962); for X-ray data, see Gorenstein *et al.* (1970). The relative abundances by number for the various models are $n(Z)/n(\mathrm{H}) = 1.0$ (H), 0.45 (He) 4×10^{-4} (C), 1.1×10^{-4} (N), 9×10^{-4} (O), and 5×10^{-4} (Ne) for models 1, 2 and 3 and $n(Z)/n(\mathrm{H}) =$ 1.0 (H), 1.0 (He), 0.0002 (C), 0.0002 (N), 0.0006 (O), and 0.0005 (Ne) for Model 2.

the difficulty that the ionization ratio O II/O III is several times too small to explain the ratio of the forbidden lines ([O II] λ3727)/([O III] λ5007).

In Model 2 the radiation spectrum is the same as in Model 1, but the abundance of helium is taken to be equal to that of hydrogen. This will affect the line ratios, since most of the photons having energies above the ionization potential of helium will be quickly absorbed, so the zone where helium is ionized will be smaller than in Model 1. Since this is the region where O III should occur, we would expect the O II/O III ratio to be larger in Model 2 than in Model 1.

Models 3 and 4 have the same abundances as Model 1, but have different radiation spectra. In Model 3 the ionizing spectrum from 1 to 3 Rydbergs is a steep power law with spectral index 2, becomes level at 3 Rydbergs, and resembles the Model 1 spectrum above 7.6 Rydbergs. In this model there is no direct connection between the X-ray and optical spectra. The O II/O III ratio should be larger in this model than in Model 1 since there are fewer photons capable of ionizing O II.

Model 4 has the same source spectrum as Model 1 plus a 'line' at 1.42 Rydbergs (19 eV). This line is below the ionization threshold of O II but above that of O I, so the amount of O II is increased without producing additional O III. The peak in the spectrum could be produced by $2s-2p$ transitions in oxygen ions in a diffuse gas having an electron temperature of about 200000K. The total luminosity in the peak is about 2×10^{37} erg/sec, so for a diffuse gas filling the nebula, this requires an electron density of about 20 cm^{-3} (Cox and Tucker, 1969). Such a gas would add about 20 pc cm^{-3} to the dispersion measure of the pulsar NP 0532. The expansion of the Crab Nebula should cause this 'internal' dispersion measure to decrease by about 0.2%/yr, giving a possible check on the presence of diffuse-ionized gas in the Nebula.

TABLE I

Calculated and observed emission line intensities for typical crab nebula filaments**

Model	1	2	3	4	Observed
Region producing [O II] λ3727:					
n_H(cm^{-3})	810	1100	760	1040	–
n_e(cm^{-3})	1030	1020	900	1020	1000
T_e(K)	9960	9360	9900	8740	–
Ionized thickness (10^{16} cm)	2.9	2.3	2.1	5.0	–
Relative line intensities:					
[O II] λ3727	7.2	10.5	10.0	10.0	9.7
[Ne III] λ3868*	4.9	1.7	3.8	2.8	1.5
He I λ4471	0.17	0.21	0.16	0.09	0.18
He II λ4686	0.27	0.24	0.25	0.13	0.7
H I λ4861	1.00	1.00	1.00	1.00	1.00
[O III] λ5007*	30.5	16.2	22.3	17.9	14.6
[N II] λ6580*	3.9	12.5	5.3	4.7	13.3
Ne II 12.8μ	1.7	1.0	1.8	2.1	–

* Two well-separated lines, e.g., [O III] λ5007 means λ5007 + λ4959. Observed relative intensities are taken from Woltjer (1958).

** These models overestimate the H I-cooling rate; as a result the quoted values for the temperature and forbidden line intensities are too low by about 5% and 25%, respectively.

The filament parameters and the calculated relative emission line intensities of the models are listed in Table I. The observed relative intensities are also listed. The observed ratio ([O III] λ5007)/([O II] λ3727) is 1.5; note that this does not include a correction for the amount of extinction which is now thought to be present – such a correction might reduce the ratio to about 1.0.

The calculated value for the ratio of the oxygen lines is 4.2 in Model 1. This is roughly the same discrepancy found by Williams (1967).

In Model 2, in which the hydrogen and helium abundances are assumed to be equal, the ratio of the oxygen lines is in good agreement with the observations, as are the relative intensities of the Ne III and N II lines and the 4471 Å line of helium.

Models 3 and 4 represent attempts to obtain the correct line intensity ratios by adjusting the ionizing radiation spectrum. The relative line intensities in these models are also in good agreement with the observations.

A major difficulty with all the models involves the He II $\lambda 4686$ recombination line; its observed intensity is several times larger than the predicted value. To drastically increase the intensity of this line, it would seem necessary to increase the incident flux above 4 Rydbergs (in order to increase the amount of He III). The observational measurement of He II $\lambda 4686$ may be somewhat confused by a nearby [Fe III] line (Woltjer, 1958). Fe III should be found in the same region as O II; hence, relatively strong [Fe III] emission would not be surprising, given the prominence of the [O II] doublet. This may require a larger than average iron abundance, which is consistent with the popular theory that the large natural abundance of iron is due to the decay of ^{56}Ni following the expulsion of silicon-burning zones from supernovae (see Bodansky *et al.*, 1968, and references cited therein). In any case, further measurements of the intensity of the He II $\lambda 4686$ line would be extremely useful in helping to determine the physical conditions in the filaments.

Note that the helium-line intensities produced by Model 2 are nearly the same as those in Model 1, despite the great difference between the helium abundances of the two models. This is because these are recombination lines. Therefore, if the helium abundance is sufficiently great, the intensity of He II $\lambda 4471$ depends only on the total absorbed flux of ionizing photons involved, and not on the helium density.

These models and other similar calculations not discussed here show that a large increase in the ionizing flux is unacceptable, since too much ionization in the filaments would result. Assuming any plausible gas density and helium abundance, increasing the flux by a factor of more than about three beyond that which we have assumed would result in at least some filaments consisting entirely of ionized-helium zones producing very little [O II] and [N II] line emission.

Note that the thickness of the ionized zone in Models 2 and 3 is about half the total thickness of a typical filament. This may suggest that most of the bright filaments consist of ionized outer regions with cores of non-ionized gas. Such a model is supported by the fact that the intensity of [O I] $\lambda 6360$ is equal to or somewhat greater than that of Hβ (Trimble, 1970). This observation is difficult to explain unless the filaments have neutral cores. In addition there seems to be no strong correlation between the spectra and the thickness of the filaments. If the radiation field were strong enough to ionize all the gas in a filament, then such a correlation should exist. The presence of neutral cores must raise the total mass of the filamentary system by an amount which is difficult to estimate because the calculations become very uncertain in this region.

The mass of the ionized portion of the filaments can be estimated from O'Dell's (1962) measurements of the Hβ flux from the Crab Nebula. He finds that the total Hβ flux is about 1.24×10^{-11} erg/cm^2-sec, which for a distance of 1720 pc and a visual extinction $A_v = 2$ magnitudes, would require about 1.5 $M_\odot$ in Models 2 and 3, and about 0.9 $M_\odot$ in Model 1. If we include the mass of the possible neutral filamentary cores of Models 2 and 3, then this estimate must be increased by more than a factor of two, raising the total mass of the filaments to more than 3 $M_\odot$.

3. Summary

In all the models the observed high intensity of the He II λ4686 line continues to pose problems. Additional observations should decide whether the theory or the observations are at fault on this point. In Models 2 and 3 the thickness of the ionized part of the filaments is less than the observed diameter of the filaments. This suggests that most of the filaments consist of ionized outer regions with cores of neutral gas.

The acceptance of any of the above models has interesting implications. Model 2 requires a helium abundance equal to that of hydrogen, a value which is about a factor 7 greater than the 'cosmic' abundances. A large abundance of helium is consistent with the idea that the filaments were formed by the shell ejected during the supernova explosion which produced the Crab Nebula. According to Model 2 the filaments should have neutral 'cores', so that the total mass of the shell may be considerably larger than previous estimates of about a solar mass.

In Model 3 there is no direct connection between the X-ray and optical spectrum, as is generally assumed. The most obvious explanation for the spectral shape of Model 3 is that it is due to synchrotron radiation from at least two ensembles of electrons having different energy distribution functions. In view of the difference in the radiative lifetime for the relativistic electrons producing the low frequency (radio-optical) and high frequency (X-ray) synchrotron radiation, this is a reasonable hypothesis. In this case the nice fit of the extrapolated X-ray spectrum to the optical data is purely coincidental.

Model 4 requires strong emission line features such as are produced by a 200000 K plasma. The total luminosity required is $\sim 2 \times 10^{37}$ erg/sec and represents a major source of energy loss from the Nebula. This hypothesis may be subject to test by means of the dispersion measure of NP 0532.

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Discussion

L. H. Aller: The structure of the filaments is not uniform and there is a range of structure in each filament. Data from (S II) lines should be included in any future study.

V. Trimble: The filaments are necessarily ejected material as there is not enough material to be swept up. The abundances of N and O in the filaments are normal.

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Model 4 would require a plasma and this would stop the filaments expanding at the observed rate. Model 2 seems promising.

J. A. Roberts: The change in dispersion measure predicted for Model 4 would be observable. It is in the opposite sense to the change which is observed.

L. Sartori: I am glad to see evidence for an abundance of He in supernovae as this supports our fluorescence theory.

E. M. Kellogg: Any increase in the helium abundance might destroy the good agreement with other line emissions.