ELECTRON DENSITIES IN FILAMENTARY NEBULAE

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The Cygnus Loop, the brightest parts of which are NGC 6960, NGC 6992, and NGC 6995, is a well-known filamentary nebula quite different in structure from typical diffuse or planetary nebulae. There are a very few other filamentary nebulae of the same general type as the Cygnus Loop; a total of five objects of this class, of which the Cygnus Loop is the brightest, have been discussed by Minkowski. The second brightest is IC 443, which is apparently considerably more distant than the Cygnus Loop. In the Cygnus Loop no hot star has been found that might be responsible for the excitation and ionization of the nebula; there are some B-type stars in the vicinity of IC 443, but since the nebula lies in the Milky Way at $b = +5^\circ$, these may well be projected field stars. Both the Cygnus Loop and IC 443 are radio sources, and thus these two objects are different in several ways from the more common types of emission nebulae.

Oort has suggested that the energy radiated by the Cygnus Loop is derived ultimately from its expansion energy, the heating mechanism being the collision of the expanding shell with interstellar matter. Minkowski has made a thorough observational study of the velocities and line intensities in the Cygnus Loop, and has concluded that his results agree with Oort's interpretation. Pikelner has worked out a somewhat similar, but not identical, theory, in which the energy is derived from the dissipation of shock waves propagating out from the center through a nebula with a fluctuating density distribution. Although the main idea of conversion of kinetic energy to heat seems fairly well established, the details of the Cygnus Loop and IC 443 are by no means completely understood, and further observations and interpretations of them and of similar objects are of value. A limited program of observations of the [O II] $\lambda 3729/\lambda 3726$ intensity ratio...
for the determination of electron densities, undertaken for these reasons, is reported on here.

The observations were all made at a dispersion of 66 Å/mm with the Newtonian-focus spectrograph of the 100-inch telescope, as described in more detail in a previous paper. Observations of individual points in the Loop are collected in Table I. In each case the slit was along a bright filament, and the position angle of the slit, together with the coordinates of its center with respect to a nearby star, are given to identify its position. The intensity ratios $r = \frac{\lambda 3729}{\lambda 3726}$ depend in most cases on only one observation, except for two filaments for which two plates each were obtained. The electron densities in the Cygnus Loop were computed from the measured intensity ratios according to the formula of Seaton and Osterbrock, with an assumed electron temperature of 40,000°. This temperature, considerably higher than the electron temperature of an ordinary gaseous nebula, is approximately that which follows from the intensity ratio

$$[\text{O II}]\, \frac{\lambda 3726 + \lambda 3729}{[\text{O III}]\, \lambda 4959 + \lambda 5007} = 1.74$$

measured by A. D. Code, together with the collisional excitation and ionization theory of Miyamoto. Other evidence cited by Pikelner and Minkowski also points to a relatively high electron density.
temperature in the luminous filaments of the Cygnus Loop. For the one filament observed in IC443 the electron density was computed using an assumed temperature of 20,000°, chiefly because in the spectra of IC 443 the [O III] and [Ne III] lines are weaker with respect to the [O II] lines than in the spectra of the Cygnus Loop. The quantity essentially determined by the observed intensity ratio is $N_e/T_e^{1/2}$, so any error in the assumed electron temperature causes a percentage error approximately one-half as large in the derived electron density. It is likely that neither of the assumed temperatures is in error by a factor greater than two; the errors in the densities caused by the uncertainties in the temperatures are therefore not over 40%.

In Table I the electron densities are not given for points 1 and 3 because the observed intensity ratios for these points are higher than the largest ratio to be expected at the assumed temperature, namely $r = 1.45$ in the limit of very low density. The computed maximum value of the intensity ratio depends on the temperature; it is 1.50 in the limit of very low temperature, 1.49 at 10,000°, and 1.45 at 40,000°. Thus, if we had assumed a lower temperature for the nebula, say 10,000°, we could have derived finite densities for all the points listed. The observational evidence mentioned above, however, is so overwhelmingly in favor of a higher temperature that this assumption cannot be made, and it is likely that the observed ratios are too high merely as a result of random errors. In fact the uncertainty of a single observation of $r$ listed in Table I is probably of the order of ±0.06; this figure is an estimate based on the internal consistency of observations of this same ratio in other nebulae (chiefly the Orion Nebula and IC 418) made with several different spectrographs and several different calibration devices. When this random error is taken into account it is seen that the observed ratios at points 1, 3, and 6 indicate relatively low densities, but do not contradict the theory used to derive the densities. The true values of the ratio at points 1 and 3 must be close to 1.45, the predicted maximum value for the estimated temperature, so these observations serve to check rather closely the theoretical result on which this prediction is based, namely that the excitation cross sections for the $^2D_{5/2}$ and $^2D_{3/2}$ levels are in the ratio 1.5 to 1.
A rough estimate of the mass of an individual filament in the Cygnus Loop may now be made, using the mean density resulting from Table I, together with the volume of a filament. Measurements of the apparent widths of all the filaments listed in the table have been made on a series of excellent direct photographs taken by Dr. A. R. Sandage. These plates, taken in good seeing with the 100-inch telescope diaphragmed to 58 inches, show diameters of about 1.6 for the images of faint stars, while the mean width of the filaments, as measured directly on the plates, is about 2.4. This last figure must be corrected for the finite image size to give the true width of the filaments; the correction is uncertain but the best scheme is probably to take the square root of the difference of the squares as the true width. The result is a width of 1.8, or at the distance of 770 parsecs derived by Minkowski, a diameter of the filaments of about $7 \times 10^{-3}$ parsecs. Many of the filaments in the Cygnus Loop can be followed for a length of 4.5, corresponding to a distance of 1 parsec, so we shall calculate the mass of a single cylindrical filament with this length and with a diameter of $7 \times 10^{-3}$ parsecs. For the mean electron density we take 200 per cubic centimeter, corresponding to the median of the seven ratios listed in Table I, or under the assumption that the material is chiefly ionized hydrogen, $3.3 \times 10^{-22}$ gm/cm$^3$, and the result is approximately $2 \times 10^{-4} m_\odot$ for the mass of a filament. This value is considerably smaller than the mass derived by Minkowski, both because the densities which I quoted to him were incorrectly too large (they were based on eye estimates of intensity ratios, rather than photometric measurements, and were also computed with too low an assumed temperature), and because the width he took, following Oort, as representative for the filaments is larger than the value given above. There are probably some hundreds or possibly a few thousands of filaments in the Cygnus Loop, but the mass of an average filament is somewhat less than the value derived above, because the filaments for which spectra were obtained are especially selected bright ones. The mass of the whole system of luminous filaments is therefore probably of the order of or less than one-tenth of the mass of the sun. The result is not incompatible with the idea that the Cygnus Loop is an expanding supernova shell which has swept up a much larger...
mass of interstellar material, for the spectroscopic observations refer only to the matter that is now emitting forbidden lines, while the bulk of the mass may have cooled and may now be dark. In fact, as Oort and Minkowski have pointed out, the nebula is so large (40 parsecs in diameter), that the mass of interstellar matter in the volume which it now occupies must have been quite large. Even for an interstellar density as low as 0.1 hydrogen atoms per cubic centimeter, the mass of interstellar matter would be of the order of 100 solar masses, and we must conclude that the bulk of the material that has been swept up is not luminous at the present time. Woltjer, in discussing the somewhat similar case of the Crab Nebula, has already emphasized that the filaments give only a lower limit to the total mass.\footnote{L. Woltjer, \textit{B.A.N.}, 14, 39, 1958 (No. 483).}

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\begin{itemize}
  \item \textsuperscript{1} R. Minkowski, Cambridge symposium on “Gas Dynamics of Cosmic Clouds,” 1957, in press.
  \item \textsuperscript{2} R. Minkowski, in \textit{Gas Dynamics of Cosmic Clouds} (Amsterdam: North Holland Publishing Co., 1955), p. 106.
  \item \textsuperscript{3} G. A. Shaïn and V. F. Gaze, \textit{Pub. Crimean Astrophysical Obs.,} 7, 87, 1951.
  \item \textsuperscript{4} D. Walsh and R. Hanbury Brown, \textit{Nature,} 175, 808, 1955.
  \item \textsuperscript{6} S. B. Pikelner, \textit{Pub. Crimean Astrophysical Obs.,} 12, 93, 1954.
  \item \textsuperscript{8} M. J. Seaton and D. E. Osterbrock, \textit{Ap. J.,} 125, 66, 1957.
  \item \textsuperscript{9} S. Miyamoto, \textit{Zs. f. Ap.,} 38, 245, 1956.
  \item \textsuperscript{10} M. J. Seaton, Cambridge symposium on “Gas Dynamics of Cosmic Clouds,” 1957, in press.
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