stellar masses, Poveda (1) found that the vertical line tangent to this curve lies exactly at type K1, which is, as I have said, the earliest spectral type found by us for the flare stars in Orion. Another example: the H-burning ages of the various aggregates and the ages derived for the flare stars in them by the Hayashi theory, are of the same order. And finally, our empirical evidence which relates the UV Ceti stars of the solar neighbourhood to the flare stars in young aggregates can easily be understood through the theoretical work of Hayashi and his collaborators and of Kumar, if we accept the general picture of gravitational contraction for star formation.

[Explanatory note by *G. H. Herbig:* It may be useful to clarify here a matter of nomenclature that has given rise to some confusion among non-specialists in this field: namely, the difference between *flare* and *flash* variables. The *flare stars* are well-known objects: found originally among the dMe stars (although a few show no strong emission spectrum) in the solar neighbourhood, there is no question but that these flare stars have no connection whatsoever with nebulosity at the present time. They are often known as UV Ceti variables, after one of the most active examples. About 1953, however, Haro and his collaborators began to find in young aggregates such as the Orion Nebula and the Taurus dark clouds a type of low-luminosity variable that, photometrically, showed the same kind of short-lived outbursts as the flare stars. But these spectra showed clearly that although the stars were of K and M type, almost without exception they had *no* strong H or Ca II emission between outbursts, unlike most UV Ceti variables. Since these non-emission objects were clearly associated with the nebulae, it was felt best to keep them clearly separate, at least in name, from the flare variables of the solar neighbourhood until some clearer evidence of their physical connection with UV Ceti-like objects could be found. Hence these rapid variables in the nebulae were given the name *flash stars.* It is now beginning to appear, mainly as the result of work by Haro and his colleagues, that in older aggregates which are now completely free of nebulosity, one still finds variables of the flash type, giving rise to the old suspicion that the dMe flare stars of the solar neighbourhood are no more than low-mass examples of the flash family that long ago escaped from their parent aggregates. Consequently, if this concept survives, the necessity for a distinction between flash and flare stars may soon disappear.]

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5. PHYSICAL CONDITIONS IN THE GAS OF THE NEBULA

T. K. Menon

Since the early days of astronomical spectroscopy, a large number of spectroscopic and photometric investigations have been made of the Orion Nebula. Among the more detailed ones may be mentioned those due to Campbell and Moore (1), Wyse (2), Wurm and Rosino (3), Osterbrock and Flather (4), Wilson, Münch, Flather, and Coffeen (5), Aller and Liller (6), Menon (7), and Boyce (8). These investigations have provided us with a wealth of data using spectroscopic, spectrophotometric, photoelectric, photographic and radio frequency techniques. In this paper we shall summarize the information on the physical conditions in the gas of the Orion Nebula obtained from the above studies.

Though there is some uncertainty in the distance to the Nebula, we shall adopt for the purposes of further discussion a distance of 450 pc. At that distance then 1 minute of arc corresponds to 0·131 pc. The Nebula has an approximate total diameter of 48′ or 6·29 pc. However, high resolution radio frequency measurements have shown that the half-intensity width of the Nebula is only about 2′6, thus indicating the high concentration of emission towards the center. Both optical and radio observations indicate a high degree of circular symmetry in the emission from the Nebula. Infra-red photographs show that there is a remarkably symmetrical star cluster co-extensive with the Nebula.

The distribution of matter in the Orion Nebula has been studied by Osterbrock and Flather (**4**), Dokuchaeva (**9**), Boyce (**8**) using optical data, by Rishbeth (**10**), Parijskii (**11**), Menon (**7**), and Lequeux (**12**) using radio data. Osterbrock and Flather (**4**) utilized the intensity ratio of the [O II] lines $\lambda\lambda$ 3726, 3729. Then using the most reliable cross sections of O^+ as given by Seaton and Osterbrock (**12a**) and assuming an electron temperature of 10 000°K, they derived the projected density. From the projected density on the assumption of a spherical model with radius 24′, they derived the radial density distribution. Dokuchaeva, and also Boyce, measured the Balmer line fluxes at various distances from the center of the Nebula. Boyce, after correcting for absorption, derived the projected variation of intensity of Hβ with radius. The models derived from radio observations are based on a combination of high resolution studies and total flux measurements. Menon's procedure consisted of first obtaining a mean projected intensity distribution at 3·75 cm by combining interferometric data on intensity distribution obtained by Twiss, Carter and Little (**13**) and single-dish observations at 3·75 cm. Since the optical depth of the Nebula at 3·75 cm is quite small the intensity distribution at 3·75 cm can be used to obtain the intensity distribution at other wavelengths and then the fluxes obtained for an assumed electron temperature. A comparison of the computed and observed fluxes showed that the major part of the Nebula must have an electron temperature of the order of only 6000°K and not the 10 000°K generally assumed in the literature. The earlier computations by the above procedure were repeated recently using more accurate values for the fluxes and the earlier results were essentially confirmed. A further check on this result was obtained by computing the fluxes directly from the obtained contour diagram at 3·75 cm instead of assuming a mean distribution.

Pronyk (**14**) had already suggested a possible variation of T_e through the Nebula. Aller and Liller (**6**) suggest a temperature of 9000°K at the center of the Nebula. The radio studies definitely indicate that the major portion of the Nebula is at a much lower temperature. That some nebulae can have such low temperatures is also suggested by observations of some nebulae at 85 Mc/s by Mills, Little and Sheridan (**15**). High resolution observations at low frequencies should provide us with invaluable data on temperatures of emission nebulae.

From the mean intensity distribution at 3·75 cm the radial density distribution was derived, assuming the Nebula to consist of concentric shells and for a value of electron temperature of 9000°K. The dependence of the derived density on the electron temperature is weak and hence the assumption of a constant T_e for the whole Nebula is a good approximation. In Fig. 1 are plotted the density distributions obtained by the above method and that due to Osterbrock and Flather.

A comparison of the density distributions obtained from optical and radio data shows that the optical values are everywhere significantly greater than that obtained from radio observations. Osterbrock and Flather suggested that the discrepancy could be easily explained as being due to the existence of density fluctuations. The maximum and minimum values of N_e from the optical data are $1{\cdot}8 \times 10^4$ cm^{-3} and $2{\cdot}6 \times 10^2$ cm^{-3}, whereas the radio data give $2{\cdot}7 \times 10^3$ cm^{-3} and 10 cm^{-3}, respectively. If we assume that the condensations are distributed at random and if R is the radius of a condensation and D is the mean distance between condensations, then we can show that (see Chandrasekhar (16))

$$\frac{R}{D} = 1{\cdot}12\,\alpha^{1/3}, \qquad (1)$$

where α is the square of the ratio of electron densities from the radio data to those from the optical data. We see from Fig. 1 that this ratio reaches a minimum at a distance of about 4′ from the center and increases inwards and outwards from this point. The existence of fluctuations in the central parts of the Nebula had been known for a long time and is particularly striking in a photograph reproduced by Münch and Wilson (17). Wurm and Rosino remark that outside the central region the density is more homogeneous. The outer parts again show extreme filamentary structure. There thus seems to be a difference in the type of condensations in the central parts and in the outer parts of the Nebula. These conclusions are further strenthened by the recent discussion of Münch and Wilson who show that the interpretation of the He I λ 3889 absorption line requires the existence of density fluctuations with varying dimensions. The volume occupied by the condensations can be estimated to be of the order of 1/20 of the total volume. It is quite likely that some of the apparent condensations seen in photographs are not related to the density fluctuations discussed above but have somewhat of an independent existence. More detailed spectroscopic studies are needed to clarify the nature of these condensations.

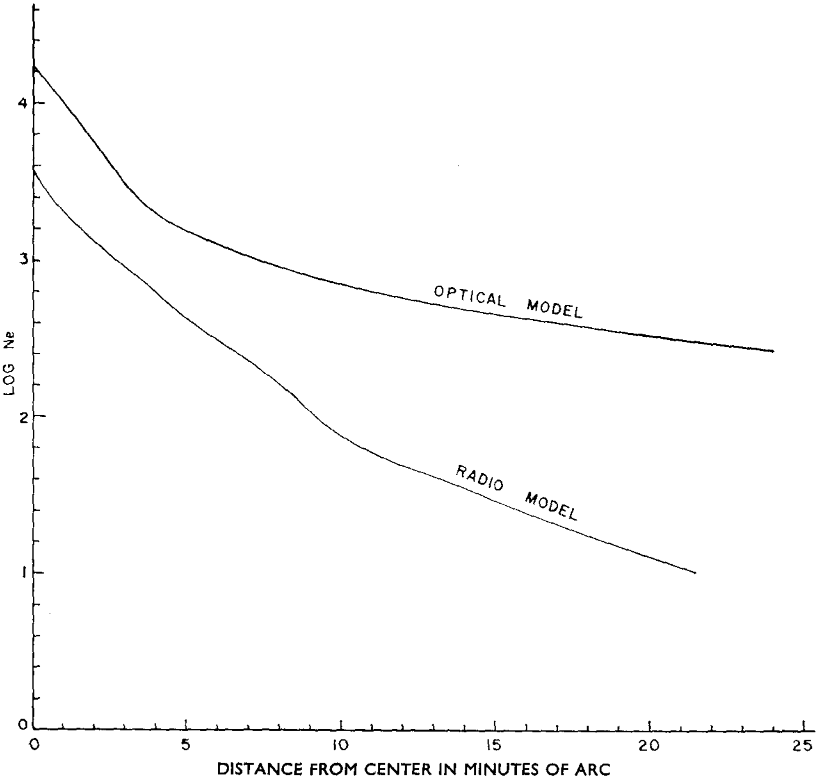

Fig. 1. Models of electron density distribution in the Orion Nebula.

Since the radio radiation from the Nebula is entirely due to free-free transitions it is more appropriate to compare the radio flux with the Balmer line fluxes since this would provide a good check on recombination theory. Recently Boyce has measured the total Hβ flux from the Orion Nebula and also measured the variation of Hβ intensity with radius in the unobscured part of the Nebula. These measurements confirm the radial symmetry of the emission referred from radio data. The measured Hβ (for a uniform absorption correction of $0^{m}.8$) flux agrees to within 3 per cent with the value predicted on the basis of recombination theory from the observed radio flux at 2000 Mc/s for an electron temperature of 10 000°K. However, a more realistic correction taking into account the variation of absorption with radius gives a value of Hβ flux which is about 25 per cent higher than predicted for a temperature of 10 000°K. This discrepancy can be eliminated by assuming a lower electron temperature.

Boyce has also compared the radial variation of the measured Hβ intensity with the values predicted from the electron density distribution derived by Menon from radio data and the agreement is very good except at the center where the observed points fall above the predicted values. At the center the radio data do not provide accurate information because of low resolution, and hence the densities could very well be somewhat higher than shown at the center in Fig. 1. The mass of the Nebula computed from the above distribution, taking into account the helium abundance found by Mathis (**18**), is about $100\odot$.

The problems of the conditions of ionization and excitation of the Orion Nebula have been discussed at length by many authors. It is clear that the major ionizing agent is the ultraviolet radiation from two of the stars of the Trapezium cluster of spectral type O6 and O9; however, there are a number of aspects of the problem that require comment. A study of the variation of ionization and excitation with radius is of importance in determining whether the Nebula is density bounded or ionization bounded. From their filter photographs Wurm and Rosino draw a number of interesting conclusions. They point out that even though the lines of lower ionization potential gain intensity, relatively to those of higher ionization potential, with increasing distance from the center, all emissions have their maximum at the center. The observation of the rapid decrease of surface brightness with radius of the collisionally excited line [S II] λ 6731 is taken to mean that there is a real decrease of pressure with radius. They also find that there are several structures near the outermost border of the Nebula which are relatively strong in the [O III], indicating that the ionization of the Nebula is still relatively high at the outermost border. From this they conclude that the Nebula is most likely a density-bounded object. This conclusion is further supported by Menon from a comparison of the theoretically predicted extent of the ionization boundary from Strömgren's theory and the observed density boundary. According to Aller and Liller, the chemical composition of the Nebula is the same as that of the involved stars.

The questions of the presence and the amount of absorbing matter in the Nebula have been the subject of a number of investigations. Definitive results on these questions have been rather difficult to obtain because of the uncertainties in the law of reddening for the case of the Trapezium stars. According to Johnson (quoted by Boyce) the ratio of total to selective absorption is quite high over the whole Orion region, that $A_V/E_{(B-V)}$ is as high as 5 over a region 20 degrees in diameter and that the ratio approaches 7 in the center of the Orion Nebula. However, Borgman (**19**) finds only small deviations from the standard Whitford curve for the Trapezium stars. Because of this uncertainty the observed Balmer line ratios cannot be used to determine the absorption. One further point concerns the optical depth of Hα and its effect on the Hα/Hβ ratio. Boyce has recently shown that effects of self-absorption are negligible. Seaton's (**20**) hypothesis regarding the existence of an H I envelope around the Nebula is not confirmed either by Boyce's data or the radio data.

The major difficulty in determining reddening from emission line intensities is due to the possibility of dust being mixed with the gas of the Nebula. Hall's (**21**) polarization measurements, Sharpless's (**22**) data on variation of color excess with radius, Wurm and Rosino's (**23**) filter photographs discussed earlier and Boyce's data on nebular lines all indicate that reddening increases towards the center of the Nebula. These observations imply that dust is mixed with gas and its density increases towards the center. Wilson *et al.* (**5**) suggest that the non-appearance of the emission lines from the farther side of the Nebula can be accounted for on the basis of the presence of dust in the Nebula. The nature of the dust grains which can exist at a temperature of about 10 000°K raises a number of interesting questions. According to Greenberg (quoted by Boyce) the grains do not become as hot as might be expected and the grains could exist for some time within the Nebula. Hoyle and Wickramasinghe (**24**) have suggested that the interstellar grains may be made of graphite particles expelled from cool stars and graphite being a refractory material would not evaporate in an H II region. In this case the original distribution of dust within the Nebula will be maintained.

The similarity between the distribution of gas and stars and an isothermal distribution has been commented upon by some authors. In Fig. 2 are plotted the gas distribution from radio data, stellar distribution from Johnson (**25**) and an isothermal distribution. The similarity among these distributions may be taken as an indication of the short time scale of the Nebula.

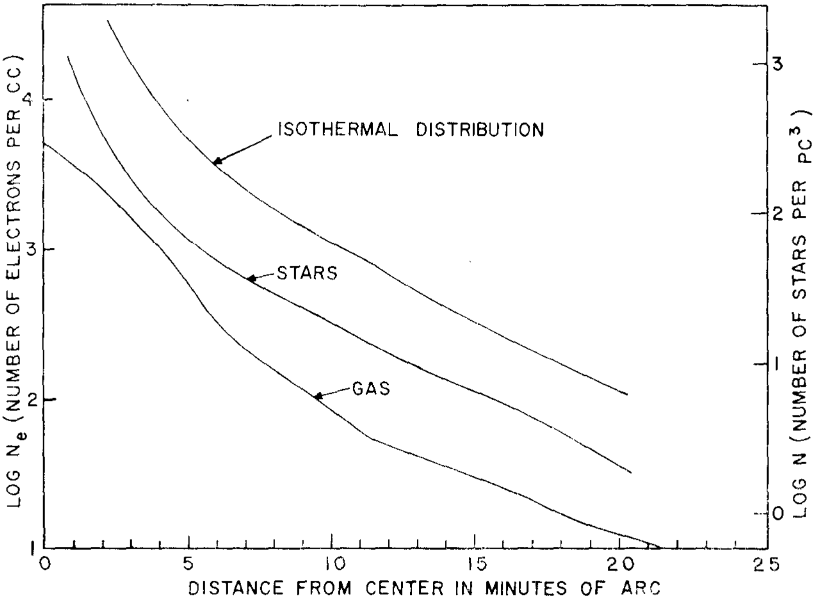

Fig. 2. Distribution of gas and stars in the Orion Nebula compared to an isothermal distribution.

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DISCUSSION

G. Münch. I wish to comment on Menon's remark regarding the low temperatures in emission nebulae. The most direct determination of temperature is based upon measurement of the contours of emission lines of elements of different mass. This involves no complicated assumptions, theories, cross-sections, models, etc.: only well-known Maxwell-Boltzmann statistics. In the Orion Nebula, the emission-line contours of H, He I, and [O II] or [O III] lead to a value near 9600°K. It happens that the temperature obtained from the intensity ratio between the λ 4363 and the N1, N2 lines of [O III] agrees very well with this value. The collision cross-sections for excitation, therefore, must be nearly correct. This intensity ratio is so sensitive to temperature that if $T_e \cong 6000$°K, the λ4363 line would be completely unobservable. In every galactic emission nebula that has been observed, λ4363 appears with nearly the same relative strength with respect to N1, N2. A spectrogram taken with the slit crossing the Orion Nebula near θ^2 Ori A shows conspicuous variations in the relative strength of λ4363, but these correspond to temperature fluctuations of only about 200°–300°K. For these reasons, I feel that we should look elsewhere than to the large temperature fluctuations mentioned by Menon for the source of these difficulties.

K. Wurm. On a large number of spectrograms covering the whole Orion Nebula obtained at Asiago, we found only occasionally a small increase in the [O III] ratio λ4363/λ5007. These changes corresponded to a variation in T_e of not more than 100° to 200°. We conclude from this that T_e remains rather constant, in agreement with Dr Münch.

T. K. Menon. I see no way of reconciling the spectrum computed from the high-frequency contours with the observed fluxes unless T_e is significantly lower than 10 000°K.

A. R. Thompson. An east-west profile of the Orion Nebula obtained by T. Krishnan and myself with the 1′0 beam of the Stanford compound interferometer at 9·1 cm shows a principal peak coinciding in right ascension with the Trapezium stars, but a subsidiary peak, containing about 14 per cent of the total flux, coincides with θ^2 Ori A. Under the assumption that the central peak is circularly symmetric, the mean value of the emission measure over a central area of radius 0′65 is approximately $7{\cdot}6 \times 10^6$, in agreement with Strömgren's optical measurement.

K. Wurm. However, θ^2 Ori A contributes little to the excitation of the Nebula immediately around it: only the continuum increases in intensity there.

G. Münch. But the effect of θ^2 Ori A upon the ionization equilibrium of nebular matter in its neighborhood, and hence upon the recombination spectrum there, is not independent of its contribution to the dust-scattered continuum. The reddening produced by the dust on the recombination spectrum can in principle be determined from the recombination lines alone. Therefore, if we know the albedo of the scattering particles, we should be able to relate the scattered spectrum to the recombination spectrum. The integration along the line of sight is always a difficulty, but I fail to see how the observation of scattered light from θ^2 Ori A rules out the possibility that this star also contributes to the ionization.

Y. Parijsky. Recent radio observations at Pulkovo show that the very center of the Nebula is much brighter than found previously. This means that the density fluctuations in the central region are much smaller. There is no hole in the emission at a scale $\geqslant 0'.5$, nor is there indication of the secondary maximum observed at Stanford.

G. Courtès. Mr P. Cruvellier has recently measured the electron densities over the Orion Nebula from the [O II] doublet ratio, using a highly accurate photo-electric method and Fabry-Pérot dispersion. With the 77-inch reflector (at the coudé focus), he obtained a spectral resolution of 0·3 Å over a field of 30″. The profiles of both Hβ and the [O II] lines were determined in order to separate temperature and turbulent effects. The large number of measured points permitted the construction of contours of equal electron density, and it was found that these contours follow a smooth elliptical shape, probably bearing a relation to the direction of the magnetic field.

6. ON THE INTERNAL STRUCTURE OF THE ORION NEBULA

K. Wurm

The investigations which I intend to describe here have the aim of arriving at a better understanding of the optical surface structure of the Orion Nebula. It was hoped to obtain by such a study some idea about the arrangement of the visible masses of the Nebula in space, and also about the positions of the brightest stars in the field relative to these masses.

The Nebula has a very intense kernel. This kernel appears in all monochromatic pictures with equal shape, as well in the stronger emission lines and also in continuous light. There can scarcely be a doubt that the bright kernel owes its shape to absorbing masses in the foreground. However, these absorbing masses belong to the Nebula itself, and they become easily visible in emission by increasing the exposure time. If one compares the distribution of the surface brightness with the distribution of the star density, it becomes clear that there exists a correlation between these two quantities. The star density is highest at places of highest emission density, and low where the emission is weak. That part of the Nebula which I have designated as the bright kernel coincides with the region of high star density. It follows from this property that we are looking deepest into the cluster connected with the Trapezium in the vicinity of this group of stars. The correlation between surface intensity and star density is one of chance. It originates from the distribution of matter at that border of the Nebula which we face from our position on the Earth.

There exists yet a second correlation between two observable quantities (1), namely between the surface brightness in the Balmer lines and the projected electron density measured after the method proposed by Seaton. This correlation is linear. In a recent paper (2), I have shown that this result finds an explanation, if one takes account of the continuous extinction