EVOLUTION OF GASEOUS NEBULAE

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The study of the density distribution of ionized hydrogen in the vicinity of early-type clusters of different ages can provide important information regarding the evolution of gaseous nebulae. We do not at present have any detailed knowledge about the early stages in the formation of a cluster. It seems reasonable to assume that the gaseous remnant of the original interstellar cloud will, after the formation of a cluster, have a distribution with a maximum at the center. However, in the presence of early-type stars capable of ionizing this gas, the distribution will be gradually altered as a consequence of the ionization and pressure discontinuities which they set up. Recent theoretical and observational work1,2 provides us with some insight into the evolution of gaseous nebulae.

We have detailed information about the distribution of density of ionized hydrogen in the case of the Orion Nebula and the Rosette Nebula (Fig. 1). These values were derived from high resolution studies of their radiation at wavelengths of 3.75 cm and 10 cm, respectively. It should be pointed out that these distributions, though approximately corrected for finite resolving power, can have sharper features than those shown in the figure.

The Orion Nebula has an r.m.s. density of about 2500 electrons/cm² at the center and about 10 electrons/cm² at the boundary. This distribution is in striking contrast to that found in the Rosette Nebula, which has a low central density and a maximum of 20 electrons/cm² at a distance of about 0.35 R₁, where R₁ is the radius of the ionization boundary. It has been shown elsewhere² that the observed boundary in the case of the Orion Nebula is most likely a density boundary, whereas
in the case of the Rosette Nebula it is an ionization boundary. The total mass of ionized matter is about $100 \, M_\odot$ for the Orion Nebula and about $11,000 \, M_\odot$ for the Rosette Nebula.

Now Goldsworthy has found some possible solutions for the motion in expanding H II regions. He has considered, *inter alia*, spherically symmetrical model nebulae in which the interstellar gas is initially cool and nonionized and has a pronounced density peak at the center. At time $t = 0$ an early-type star begins to shine, and to ionize and heat the surrounding gas. There results an unbalanced pressure gradient, and the gas begins to move.

The motion in general has discontinuities at the ionization front, which bounds the H II region, and at a shock front. If the ionization takes place slowly, the shock moves ahead of the ionization front into the neutral gas beyond; the density within the H II region is then almost uniform. If the ionization takes place rapidly, the ionization front precedes the shock. In this case the density distribution between the shock and the ionization front is not much changed from that which prevailed previous to the ionization. However, a partial vacuum appears behind the shock, and so a pronounced density minimum occurs at the center of the H II region. The brightness of the star and the density of the surrounding gas determine the speed of the ionization front, and thereby the ratio of the radius of the shock to that of the ionization front; the ratio becomes very small when the ionization occurs very rapidly. One would therefore judge from the curves in Figure 1 that the process of ionization is fairly fast in the Rosette Nebula; in the Orion

![Density Distribution in the Orion and Rosette Nebulae](image)
Nebula it is extremely fast so that the shock and the partially evacuated region have a very small radius, and cannot be resolved.

Figure 2 illustrates the nature of the flow and is adapted from Goldsworthy’s Figure 9.

\[
\frac{D_0}{\eta} \frac{d\eta}{d\eta} = \omega(1 - \omega)^2 - \frac{3}{2}(2\omega - 1)\eta^2 \quad (1)
\]

and

\[
\frac{D_1}{\omega} \frac{d\omega}{d\eta} = \frac{3}{2}\eta^2 - \frac{1}{2}\omega(1 - \omega), \quad (2)
\]

where

\[
D_1 = (1 - \omega)^2 - \eta^2. \quad (3)
\]

Here

\[
\omega = \frac{t}{r}, \quad \eta = \frac{ac}{r}, \quad \omega = \rho r^{3/2},
\]

\[ r \] = distance from star,

\[ t \] = time since beginning of the ionization process,

\[ \rho \] = gas density,

\[ \omega \] = gas velocity, assumed radial,

\[ a_c \] = isothermal speed of sound in ionized hydrogen.

It should be explained that the O+ ions in the H II region keep the ionized gas very nearly isothermal even when it is in motion. We adopt a temperature of \(10^4\) °K for it. The curves of Figure 2 show some possible relations between \(\omega\) and \(\eta\). For a case of very rapid ionization the appropriate solution curve begins at \(I_3\), where \(\eta = 0\) and consequently \(r = \infty\). The ionization front is then infinitely distant from the star. We follow the curve to \(S_3\) and there make a transition onto the curve \(S_3C\), which we follow to the center of the H II region, at \(C\). If the process of ionization is less rapid, we begin with the ionization front at \(I_3\), say, which corresponds to a nonzero value of \(\eta\), and therefore a finite radius \(R_i\) for the front. We follow the solution curve to \(S_3\), whence an isothermal shock takes us to
S′, on S3C, and then we again follow that curve to C. If ηs and ηi are the η-coordinates of the shock and ionization fronts, then the radii of these are in the ratio $R_s : R_i = \eta_s : \eta_i$. Some typical values are given in the table below.

<table>
<thead>
<tr>
<th>$\eta_s$</th>
<th>$R_s/R_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>0.47</td>
<td>0.60</td>
</tr>
<tr>
<td>0.28</td>
<td>0.33</td>
</tr>
<tr>
<td>0.25</td>
<td>0</td>
</tr>
</tbody>
</table>

The curves of Figure 1 suggest that $R_s/R_i$ takes the values 0 and 0.35 for the Orion and Rosette Nebulae, respectively; the corresponding values of $\eta_s$ are 0.25 and 0.28. We shall now compute roughly how the density varies in the region bounded by the shock. To do so we rewrite equations (1) and (2) in the form

$$D_1 \frac{d}{d\eta} \frac{u}{\eta} = \frac{1}{2} (3 - 4u),$$

and

$$D_1 \frac{d}{d\eta} \log \omega^{3/2} = \frac{1}{2} \eta (3 - 4u) (1 - u),$$

so that, on division,

$$d(\log \omega^{3/2}) = \frac{1 - u}{\eta} d\left(\frac{u}{\eta}\right).$$

This is to be integrated along S3C; on this curve u varies from $\frac{3}{4}$ to $\frac{1}{2}$, and the product $u (1 - u)$ from $\frac{3}{16}$ to $\frac{1}{4}$. For the purpose of this estimate we set $u (1 - u)$ equal to $\frac{7}{25}$, and find

$$\log \omega^{3/2} = \text{const} + \frac{7}{64 \eta^2}.$$  

In physical variables

$$\rho \propto \frac{1}{(a_s d)^{3/2}} \exp \left(\frac{7}{64 \eta^2}\right) = \frac{1}{(a_{s'} d)^{3/2}} \exp \left(\frac{7r^2}{64 a_{s'}^2 \eta^2}\right).$$

There is thus a marked density minimum at the center of the H II region. The density increase in the outward direction comes to a halt when the shock is reached, at $\eta = \eta_s$, and formula (8) ceases to apply. On passing outward through the shock, one encounters a decrease in density by a factor $(1 - u_{s'})/(1 - u_s)$, where $u_{s'}$ and $u_s$ are the values taken by u on the inner and outer sides of the shock. According to our estimation the shock transition in the Rosette Nebula is approximately represented by $S_2 \rightarrow S_2'$, in Figure 2. The corresponding ratio $(1 - u_{s'})/(1 - u_s)$ is about $5/6$, and is probably too small to be observed. In the Orion Nebula the density change becomes very small since the shock transition is very weak, being represented in Figure 2 by the single point $S_3$.

We can therefore speak of the density at the shock front, without specifying the side of the shock, and we find that it is larger than the density at the center of the nebula by a factor $\exp \left(\frac{3}{4} \eta^2\right)$. With our estimates for $\eta_s$ this equals 4.06 and 5.75, respectively, for the Rosette and Orion Nebulae. The prediction for the Rosette Nebula agrees quite well with observation, but no density drop is observed in the
Orion Nebula. Presumably the shock front has so small a radius there that the inner section of the H II region cannot be resolved. With a limit of resolution of 3 minutes of arc and an estimated distance of 500 pc between us and Orion, this means that the radius of the shock must be less than 0.5 pc, so that

\[ R_s = \frac{a_s}{\eta_s} < 0.5 \text{ pc} = 1.5 \times 10^{14} \text{ cm}. \]

Since \( \eta_s = \frac{1}{4} \) and \( a_s = 1.4 \times 10^6 \text{ cm/s} \), it follows that the age \( t \) of the ionized region must be less than \( 3 \times 10^{11} \text{ s} \), or 10,000 years. In the Rosette Nebula \( R_s = 2.45 \) pc; the corresponding age \( t \) is about 50,000 years.

The age of the Trapezium Cluster in the Orion Nebula has, for comparison, been variously estimated to be 10,000 years and up to 300,000 years by Parenago\(^3\) and by Strand.\(^4\) The cluster NGC 2244 immersed in the Rosette Nebula has not been studied in sufficient detail to provide us with a reliable estimate of its age. The present investigation seems to indicate that dense H II regions tend to be extremely young objects.

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**AN EVALUATION OF STUDIES ON ULTRASTRUCTURE OF SIEVE PLATES**

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Botanists interested in the translocation of organic solutes in plants are constantly seeking support for their concepts of this phenomenon in the structure of the presumed principal conduit in the phloem tissue, the sieve element. Electron microscopy offers a means of extending this search.

Among the various features of the sieve element, the strands connecting the superimposed sieve elements with one another through the sieve plates and the limiting layer between the cytoplasm and the vacuole (that is, the tonoplast) are receiving especial attention because the nature of these structures might be casually related to the ability of phloem tissue to conduct the solutes at the observed high velocities. Absence of the tonoplast and some peculiar structure of the connecting strands—for example, a structure permitting an intervacuolar connection—would enable one to think of the translocation in terms of mass flow; lack of such specializations would suggest support for the concept of molecular movement.