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The erosion and dispersal of massive molecular clouds by young stars

Ant. Whitworth *Department of Applied Mathematics and Astronomy, University College Cardiff, Cardiff CF1 1XL, Wales*

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Summary. We evaluate the efficiency with which O stars disperse the molecular clouds from which they form. An O star near the surface of an extended molecular cloud ionizes a H II region which is radiation-bounded on the inner side (towards the cloud centre) and density-bounded on the outer side; consequently the ionized gas can stream away into space on the outer side, and this in turn enables the ionization front on the inner side to advance faster into the cloud, thus eroding a large cavity around the O star. This process may be very effective in destroying molecular clouds; if ~ 4 per cent of a cloud's material were converted into new stars with a Salpeter Initial Mass Function, the remaining 96 per cent could be broken up and dispersed by the ionizing radiation from the O stars.

1 Introduction

Massive molecular clouds are concentrated in the plane of the Galaxy, and the formation of stars from these clouds occurs predominantly in the spiral arms, where a large-scale shock acts to assemble and compress the clouds, thereby inducing gravitational instability against condensation and the consequent formation of new stars. Star formation must be completed – in the sense that relatively unobscured main sequence stars are revealed – on a short time-scale, $\lesssim 10^7$ yr, since otherwise the spiral arms would not be delineated as observed by luminous, extreme Population I objects.

However Oort (1974) has calculated that, on average, only a small fraction (~ 0.02) of the interstellar medium is irrevocably lost to star formation at each spiral-arm passage; this fraction does not include the material converted into stars but subsequently returned to the interstellar medium by various mass-loss processes. Scoville & Solomon (1975) have stated that, since a large part of the interstellar medium presently resides in massive molecular clouds, their lifetime against conversion into stars must be much longer than a free-fall time. In short, the continuing existence of a significant interstellar medium after a galactic age of $\sim 10^{10}$ yr implies that conversion into stars proceeds on a time-scale much longer than the interval between consecutive spiral-arm passages, $\sim 2 \times 10^8$ yr, or the free-fall time in a massive molecular cloud, $\sim 2 \times 10^6$ yr.

These considerations prompt two questions; (a) With what probability p does a massive molecular cloud on passing through a spiral arm become unstable against star formation, and in the event of instability what fraction f of the cloud's mass is converted into new stars? (there is only one question here, since we know that $pf \sim 0.04 \pm 0.02$). (b) If f is small, does the remainder of the cloud survive as such (this might have interesting consequences for its molecular chemistry, since the cloud would then be repeatedly 'annealed' by successive bursts of star formation and this could promote the formation of complex molecules), or is the remainder of the cloud dispersed by the action of the new stars? In this paper we argue that a single burst of star formation with $f \sim 0.04$ can disperse the remainder of the cloud.

Observations indicate that O stars form in the outer layers of massive molecular clouds (not necessarily all O stars, but some). These stars are sufficiently hot and luminous to ionize extensive H II regions, and the ionized gas will then tend to expand, thus dispersing the residual gas around the newly formed star. If the H II region is everywhere radiation-bounded (i.e. limited in extent by the supply of ionizing photons from the central star, rather than by the availability of hydrogen gas to ionize), the H II region is contained by an ionization front (IF) outside which the gas is neutral, atomic and/or molecular hydrogen; as the H II region expands, a shock front (SF) advances into the neutral gas building up a dense layer of neutral gas just ahead of the IF. If the H II region becomes density-bounded (i.e. moving out along a particular line of sight from the central star, there are ionizing photons left over but no more hydrogen to ionize), then there is no IF and the ionized gas can stream away from the ionizing star freely.

In the situation envisaged here (see Fig. 1) the H II region around a newly formed O star remains radiation-bounded on the inner side, towards the interior of the molecular cloud; but the H II region soon becomes density-bounded on the outer side where the IF has broken through the surface of the molecular cloud. When this happens, ionized gas can stream away into space through the hole in the IF on the outer side of the H II region. This relieves the pressure in the H II region and reduces the recombination rate, so that fewer ionizing photons are needed to maintain ionization within the volume of the H II region and more ionizing photons are available at the IF to produce first-time ionizations. Consequently the IF can advance faster into the cloud and thereby erode a larger cavity around the O star.

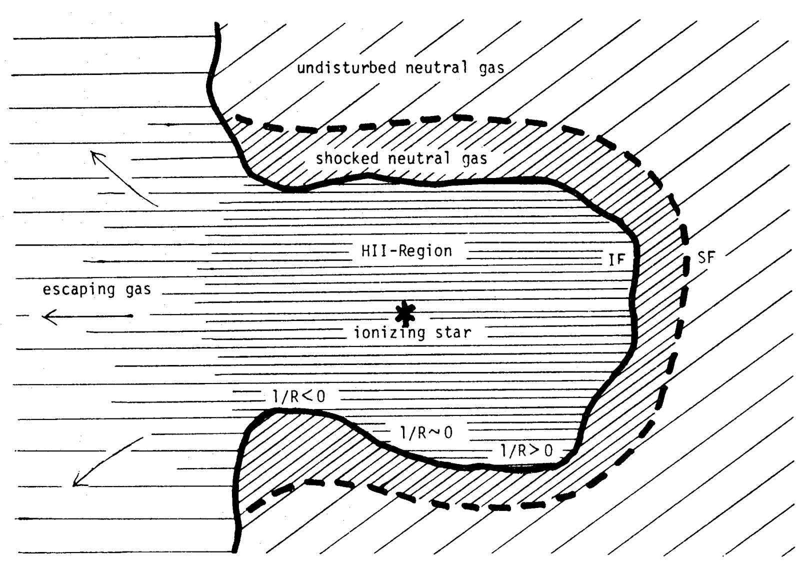

Figure 1. An O star eroding a cavity in the side of a massive molecular cloud.

That this situation frequently occurs seems indisputable. Some good cases in point are Orion, M17, W3 and K3-50 (see, e.g. Balick, Gammon & Hjellming 1974; Elmergreen & Lada 1977; Colley & Scott 1977). The question is: how much of the background cloud is eroded in this way?

2 Model and equations

The dynamical evolution of a H II region depends strongly on its geometry. If we define a radius of curvature for the IF with respect to the ionized gas, R, we can distinguish the following well-studied, one-dimensional, spherically symmetric configurations; (a) $1/R > 0$: the orthodox Strϕmgren Sphere (Strϕmgren 1939), a H II region centred on the ionizing star and surrounded by neutral gas, (b) $1/R < 0$: a globule/bright-rim (Dyson 1968; Kahn 1968), where the H II region and ionizing stars surround a central neutral condensation, (c) intermediate between these two, $1/R = 0$: a plane-parallel IF (Kahn 1954). The essential difference between these configurations involves the way in which the flux of ionizing photons reaching the IF is (or is not) diluted by geometry, and/or by absorption – because the ionized gas flowing off the IF is (or is not) trapped on the line of sight between the IF and the ionizing star. However, the configuration illustrated in Fig. 1 is two-dimensional, axially symmetric *and* it involves a combination of both positive and negative $1/R$ values, so that none of the above treatments are directly applicable. The structure and evolution of a two-dimensional, axially symmetric H II region/IF is very difficult to compute (e.g. Dyson 1973) and so very heavy-handed modelling may be justified.

At any stage the H II region has a linear dimension L such that the volume of the cavity in which recombination uses up ionizing photons is $\sim L^3$, the area of the IF is $\sim L^2$ and the ionized gas must travel a distance $\sim L$ before escaping into space on the density-bounded side. We therefore envisage a cylindrical flow region of cross-section L^2 in which all flows are parallel to the cylinder axis and positions are measured along the axis by a variable l (see Fig. 2). At $l = 0$ is a two-dimensional star with surface area L^2 emitting a parallel flux of ionizing photons

$$F_* = \mathscr{L}_*/L^2 \tag{1}$$

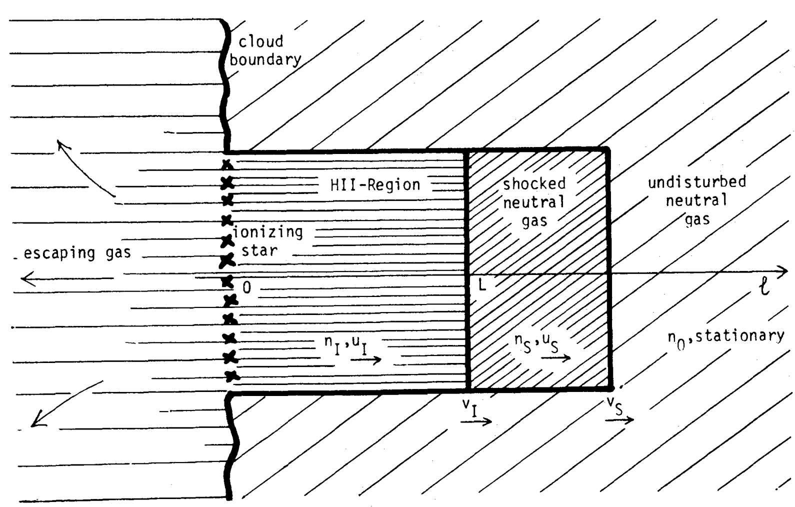

Figure 2. Geometry and parameters of model for O star eroding cavity in side of massive molecular cloud.

into the cloud. (The plane $l = 0$ also defines the cloud boundary.) The IF is at $l = L$ and has velocity

$$v_{\rm I} \equiv \dot{L}. \tag{2}$$

Throughout most of the evolution there is a SF at $l > L$ with velocity $v_{\rm S}$, i.e. preceding the IF into the neutral gas. It is in the spirit of this model that no attempt will be made to introduce numerical factors to take account of; (1) the location of the star within (rather than on) the cloud boundary, (2) the emission of ionizing photons in both (all) directions (both into and out of the cloud), (3) erosion from the side walls of the cavity, (4) the consequent convergent flow of gas in the cavity (and divergent flow outside the cavity). Such numerical factors are too difficult to evaluate here. The net effect of these considerations may well be to enhance erosion, but this conclusion is not clear and could only be established by long and involved hydrodynamic computations.

The undisturbed gas beyond the SF has density n_0 (protons per unit volume), zero velocity and isothermal sound-speed

$$a_0 \lesssim 0.9 \times 10^5 \text{ cm/s (atomic hydrogen at 100 K)}. \tag{3}$$

The shocked neutral gas has density $n_{\rm S}(> n_0)$, velocity $u_{\rm S}$ and the same isothermal sound-speed a_0. In other words, the shock is assumed to be isothermal, but the conclusions do not depend sensitively on this assumption, nor on the exact value of a_0. The ionized gas in $0 < l < L$ has density $n_{\rm I}(< n_0)$, velocity $u_{\rm I}$ and isothermal sound-speed

$$a_{\rm I} \sim 1.3 \times 10^6 \text{ cm/s (ionized hydrogen at } 10^4\text{ K)}. \tag{4}$$

All velocities are measured in the direction of increasing l. Any ionized gas striking the stellar surface from the right (i.e. through $l = 0$ with $\dot{l} < 0$) is presumed to escape and disperse in the region $l < 0$.

Following the notation of Kahn (1954) and Axford (1961) the evolution of a H II region should start with a short phase in which the IF is weak R type and advances quickly straight into the undisturbed neutral gas; a large fraction of the ionizing photons reach the IF and thus ionize new material. As more and more ionizing photons are used maintaining ionization against recombination within the volume of the H II region, the number reaching the IF decreases and its advance slows down. Eventually the IF becomes R-critical. At this stage a SF develops ahead of the IF and adjusts the flow so that conditions at the IF are D critical with

$$v_{\rm I} - u_{\rm I} = (5/3)^{1/2} a_{\rm I}. \tag{5}$$

This phase of the flow (with a SF preceding the IF into the neutral gas) probably persists until the ionizing star evolves off the main sequence and ceases to emit a significant flux of ionizing photons. The equations governing the evolution of the H II region during this main phase are (along with (5)):

$$\mathscr{L}_* = \beta_2 n_{\rm I}^2 L^3 + n_{\rm I}(5/3)^{1/2} a_{\rm I} L^2, \tag{6}$$

$$n_{\rm I}(5/3)^{1/2} a_{\rm I} = n_{\rm S}(v_{\rm I} - u_{\rm S}), \tag{7}$$

$$8 n_{\rm I} a_{\rm I}^2/3 = n_{\rm S}(a_0^2 + (v_{\rm I} - u_{\rm S})^2), \tag{8}$$

$$n_{\rm S}(v_{\rm S} - u_{\rm S}) = n_0 v_{\rm S}, \tag{9}$$

$$n_{\rm S}(a_0^2 + (v_{\rm S} - u_{\rm S})^2) = n_0(a_0^2 + v_{\rm S}^2). \tag{10}$$

(6) is the equation of overall ionization balance (input of ionizing photons equals recombinations plus first-time ionizations). We have invoked the 'on the spot' approximation, so that β_2 is the recombination coefficient for atomic hydrogen into excited states only,

$$\beta_2 \sim 2 \times 10^{-13}\,\mathrm{cm^3\,s^{-1}}. \quad (11)$$

(7) and (8) are equations for conservation of matter and momentum respectively, across the IF. (9) and (10) are the corresponding equations for the SF. The energy balance in both neutral and ionized gas involves rapid interaction with the radiation field; the basic result is to maintain approximate isothermality at $\lesssim 100$ K in the neutral gas, and at $\sim 10^4$ K in the ionized gas, so that (3) and (4) are essentially energy equations.

A particular configuration is specified by giving the density n_0 in the undisturbed neutral gas, and the type of ionizing star (or stars), i.e. a two-dimensional free-parameter space. For the purpose of numerical illustration, we shall adopt a density

$$n_0 \to 10^3\,\mathrm{cm^{-3}} \quad (12)$$

and an O6 star with

$$\mathscr{L}_* \to 2.4 \times 10^{49}\,\mathrm{s^{-1}} \quad (13)$$

$$t_* \to 1.5 \times 10^{14}\,\mathrm{s}\ (5 \times 10^6\,\mathrm{yr}) \quad (14)$$

where t_* is the main sequence lifetime.

Two useful length-scales are the linear size of the initial H II region before dynamical motions introduce density changes

$$L_0 = (\mathscr{L}_*/\beta_2 n_0^2)^{1/3} \to 5 \times 10^{18}\,\mathrm{cm}\ (1.7\ \mathrm{pc}) \quad (15)$$

and the distance travelled by a sound wave in the ionized gas during the main sequence lifetime of the ionizing star

$$L_a = a_I t_* \to 2 \times 10^{20}\,\mathrm{cm}\ (70\ \mathrm{pc}). \quad (16)$$

These are effectively lower and upper bounds to the size of the H II region during its dynamical evolution.

A particular stage in the evolution of a configuration is fixed by choosing a value for L in $L_0 < L < L_a$. Then there are six equations (5)–(10) in six unknowns (n_I, u_I, v_I, n_S, u_S, v_S). The duration of any stage is given by

$$dt/d\ln(L) = L/v_I. \quad (17)$$

3 Solution and approximations

From (6)

$$n_I = -(5/3)^{1/2}(a_I/2\beta_2 L) \pm ((5/3)(a_I/2\beta_2 L)^2 + (\mathscr{L}_*/\beta_2 L^3))^{1/2}. \quad (18)$$

(Reality requires $n_I > 0$ and so only the plus sign need be considered.) Eliminating $(v_I - u_S)$ between (7) and (8),

$$n_S = (1 \pm (1 - 15a_0^2/16a_I^2)^{1/2})(4a_I^2/3a_0^2)\,n_I. \quad (19)$$

(The minus sign is invalid here because the shocked gas must be more dense, and the ionized gas less dense, then the undisturbed neutral gas: $n_S > n_0$, $n_I < n_0$, therefore $n_S > n_I$.) Eliminating $(v_S - u_S)$ between (9) and (10),

$$v_S = (n_S/n_0)^{1/2} a_0. \quad (20)$$

Substituting back into (9),

$$u_S = (1 - (n_0/n_S))v_S. \tag{21}$$

Substituting back into (7),

$$v_I = u_S + (n_I/n_S)(5/3)^{1/2} a_I. \tag{22}$$

Finally, from (5),

$$u_I = v_I - (5/3)^{1/2} a_I. \tag{23}$$

Equations (18) to (23) can be further simplified using the following three approximations; that they are justified during the more important later stages of the evolution (when $L \gg L_0$) will – if not self-evident – be demonstrated later.

(a) Almost all the ionizing photons are used maintaining ionization against recombination in the volume of the H II region; so on the right-hand side of (6) the second term can be ignored by comparison with the first, and consequently (18) reduces to

$$n_I \sim (\mathcal{L}_*/\beta_2 L^3)^{1/2} = (L/L_0)^{-3/2} n_0. \tag{24}$$

(b) From (3) and (4), $(a_0/a_I)^2 \lesssim 5 \times 10^{-3} \ll 1$, so (19) and (20) become

$$n_S \sim (8a_I^2/3a_0^2)\, n_I; \tag{25}$$

$$v_S \sim (8/3)^{1/2} (L/L_0)^{-3/4} a_I. \tag{26}$$

(c) The shock is strong with $n_S \gg n_0$, so (21), (22) and (23) give

$$v_I (\equiv \dot{L}) \sim u_S \sim v_S \sim (8/3)^{1/2} (L/L_0)^{-3/4} a_I; \tag{27}$$

$$u_I \sim -(5/3)^{1/2} a_I. \tag{28}$$

Integrating (27) we obtain the size of the cavity as a function of time

$$L \sim 1.8 (L_0^3 (a_I t)^4)^{1/7}, \tag{29}$$

where we have put $L = 0$ at $t = 0$. The erosion rate (protons per unit time) is

$$\dot{\mathcal{N}} = L^2 n_I (5/3)^{1/2} a_I \sim 1.7 (L_0^6 (a_I t))^{2/7} n_0 a_I, \tag{30}$$

and the net erosion,

$$\mathcal{N} = \int \dot{\mathcal{N}}\, dt \sim 1.4\, (L_0^4 (a_I t)^3)^{3/7} n_0. \tag{31}$$

Thus the total amount of gas eroded by the star at the end of its main sequence lifetime is given by

$$\mathcal{N}_f \sim 1.4\, (L_0^4 L_a^3)^{3/7} n_0 \to 2.1 \times 10^{61} \text{ protons} \equiv 2.3 \times 10^4 M_\odot, \tag{32}$$

where we have substituted numerical values from (15) and (16).

From (30) the erosion rate increases monotonically with time, so we should check our approximations by evaluating parameters at the end of the evolution. From (29) and (24),

$$L_f \sim 1.8 (L_0^3 L_a^4)^{1/7} \to 7.5 \times 10^{19} \text{ cm (25 pc)}; \tag{33}$$

$$n_{If} \to 18 \text{ cm}^{-3} \ll n_0. \tag{34}$$

The ratio of the first to the second term on the right-hand side of (6) is then

$$\beta_2 n_{If} L_f/(5/3)^{1/2} a_I \to 160. \tag{35}$$

and so approximation (a) is justified. Approximation (b) is self-evident. From (25),

$$n_{\mathrm{Sf}} \rightarrow 10^4\,\mathrm{cm}^{-3} \gg n_0, \quad (36)$$

so the strong shock approximation (c) is also justified. From (27), (21) and (22),

$$u_{\mathrm{If}} \rightarrow -1.4 \times 10^6\,\mathrm{cm/s}; \quad (37)$$

$$v_{\mathrm{If}} \sim u_{\mathrm{Sf}} \sim v_{\mathrm{Sf}} \rightarrow 3 \times 10^5\,\mathrm{cm/s}; \quad (38)$$

$$v_{\mathrm{Sf}} - v_{\mathrm{If}} \sim v_{\mathrm{Sf}} - u_{\mathrm{Sf}} \sim (3/8)^{1/2}\,(L_{\mathrm{f}}/L_0)^{3/4}\,(a_0/a_{\mathrm{I}})a_0 \rightarrow 3 \times 10^4\,\mathrm{cm/s}, \quad (39)$$

$$v_{\mathrm{If}} - u_{\mathrm{Sf}} \sim ((15)^{1/2} a_0/8a_{\mathrm{I}})\,a_0 \rightarrow 3 \times 10^3\,\mathrm{cm/s}. \quad (40)$$

4 Consequences and discussion

Substituting in (31) from (15) and (16) we see that the total mass eroded by an O star in this way is very insensitive to the ambient density n_0, and depends most critically on the star's main sequence lifetime,

$$(M_{\mathrm{f}}/2.3 \times 10^4 M_\odot) \sim (t_*/1.5 \times 10^{14}\,\mathrm{s})^{9/7} (\mathscr{L}_*/2.4 \times 10^{49}\,\mathrm{s}^{-1})^{4/7} (n_0/10^3\,\mathrm{cm}^{-3})^{-1/7}. \quad (41)$$

Mezger, Smith & Churchwell (1974) have estimated that if a stellar association of total mass M_{t} forms according to the Salpeter Initial Mass Function, it will initially generate ionizing photons at a rate

$$\mathscr{L}_{\mathrm{t}} \sim (M_{\mathrm{t}}/M_\odot) \times 2.2 \times 10^{46}\,\mathrm{s}^{-1} \equiv (M_{\mathrm{t}}/10^3 M_\odot)\ \mathrm{O6\ stars} \quad (42)$$

(the main contribution being most probably from stars of spectral type around O6). Consequently, if a burst of star formation converts a fraction 0.04 of a massive molecular cloud into a new stellar association, the ionizing radiation from the O stars can in principle erode and disperse the remainder of the cloud. If this happens, an overall star formation rate of $\sim 2 M_\odot$/yr in the galactic disc must be supported by a cloud formation rate of $\sim 50 M_\odot$/yr. This in turn requires that the whole interstellar medium be converted into molecular clouds every $\sim 2 \times 10^8$ yr which means essentially every spiral-arm passage.

In reality the arrangement of new stars and residual gas in a massive molecular cloud following star formation is highly chaotic. Even if the involved O stars have sufficient ionizing capacity to ionize the whole cloud on the basis of the preceding analysis, neutral condensations are likely to survive on the inner radiation-bounded side of the H II region where the density is higher than average due to the shock, and in the reaches of the cloud furthest from the ionizing stars. However, pre-existing density fluctuations in the cloud will not greatly reduce the erosion rate. Firstly, the net mass eroded M_{f} is very insensitive to the density n_0 (see (41)). Secondly, if the advance of the IF is held up by density enhancements the flow will adopt the form sketched in Fig. 3, thus concentrating erosion on the enhancement and forming a bright rim. Ionized gas coming off the IF around the enhancements ($1/R < 0$) diverges, thus letting a large flux of ionizing photons through to the IF here. Conversely, ionized gas coming off the IF between the enhancements ($1/R > 0$) converges and so lets less ionizing radiation through to the IF there. A few exceptionally dense and widely separated neutral condensations can survive as globules within the H II region, but these will not significantly reduce the overall erosion rate.

On the outer density-bounded side, where the escaping ionized gas impinges supersonically on the general interstellar medium, shocked filaments of neutral gas will accumulate. Thus, after a few million years, the stellar association will be surrounded by a chaotic and possibly very asymmetric expanding system of neutral condensations with bright

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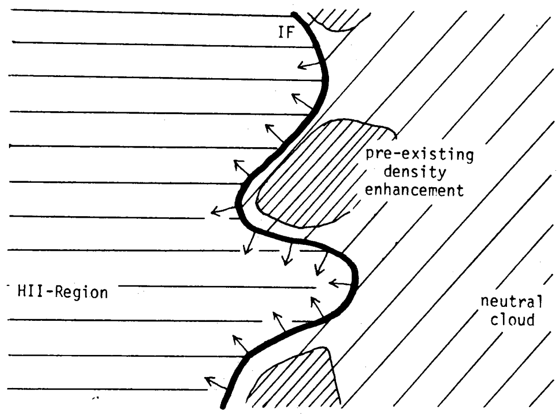

Figure 3. Flows resulting from corrugation of IF due to density fluctuations in neutral gas.

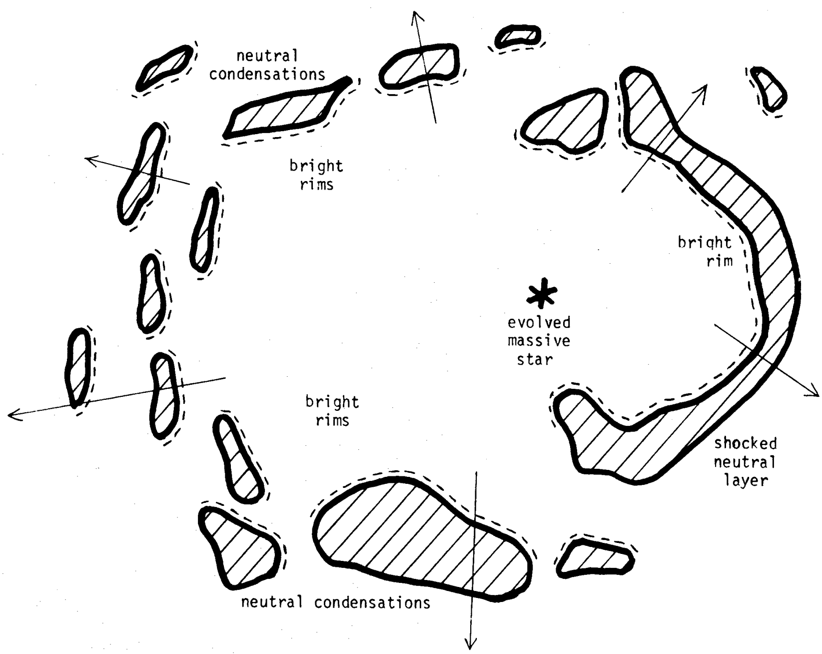

Figure 4. Aftermath of erosion of massive molecular cloud by O stars; an extended, expanding system of neutral condensations.

inner edges ~ 50 pc in extent (see Fig. 4). By this time the most massive stars will start to evolve off the main sequence.

5 Conclusions

We conclude that when star formation occurs in massive molecular clouds (say ~ $10^5 M_\odot$) it is sufficient that only a small part of the total cloud mass be converted into stars (say ~ $4 \times 10^3 M_\odot$); ionizing radiation from the O stars will then erode most of the remainder of the cloud. Thus when the O stars evolve off the main sequence they are surrounded by an extended, expanding system of neutral condensations. In order to maintain present rates of star formation in the galactic disc, virtually all interstellar matter must be converted into massive molecular clouds at each spiral-arm passage.

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