STELLAR MASS LOSS AND HII REGION MORPHOLOGY IN MAGELLANIC IRREGULAR GALAXIES

M.A. Dopita and I.R. Wilson
Mount Stromlo and Siding Spring Observatories
The Australian National University
Canberra, Australia

ABSTRACT

The problem of the interaction of a strong stellar wind with a massive collapsing neutral hydrogen cloud has been considered and a new class of steady flow solutions found.

The detailed comparison of these models with one filamentary shell, N70 in the LMC, shows that they successfully explain all the observed properties of the HII region and enable mean mass-loss rates to be derived for the central stars.

1. INTRODUCTION

The most common form taken by large HII regions in nearby Im and outer parts of Sc galaxies is that of large filamentary loops or arcs. (Davies *et al.* 1976) Frequently, these have smaller HII 'blisters' embedded in their periphery (Icke 1979, 1980).

There are, at present, three models in the literature which attempt to explain the formation of these giant HII rings, four examples of which are shown in Fig. 1. The first of these theories suggests that they are fossil supernova remnants in the 'snowplough' phase of their evolution (Oort, 1946). The second is that they result from energetic stellar winds a theme developed by many authors (Pikel'ner and Shcheglov, 1969, Dyson and De Vries, 1972, Castor *et al.* 1975, Falle 1975, Dyson 1977, Weaver *et al.* 1977). The third possibility is that of sequential star formation in shock compressed layers (Elmegreen and Lada 1977, Elmegreen and Elmegreen 1978, Bruhweiler *et al.* 1980).

This paper investigates a fourth possibility, that the interaction of the energetic wind from a star offset from the mass centre of a massive collapsing neutral cloud, can generate quasi-steady-flow bubbles with many of the observed properties of Magellanic Cloud

C. Chiosi and R. Stalio (eds.), Effects of Mass Loss on Stellar Evolution, 523–534.

HII regions. Some credence can be attached to this point of view because many of these regions are associated with massive (10^5 -5×10^6 $M_\odot$) clouds of HI (McGee and Milton 1966). The free-fall velocity for a cloud of mass 5×10^5 $M_\odot$ and radius 75 pc is 7.6 km s^{-1}, quite sufficient for the ram pressure of infall to rival the gas pressure in the HII region.

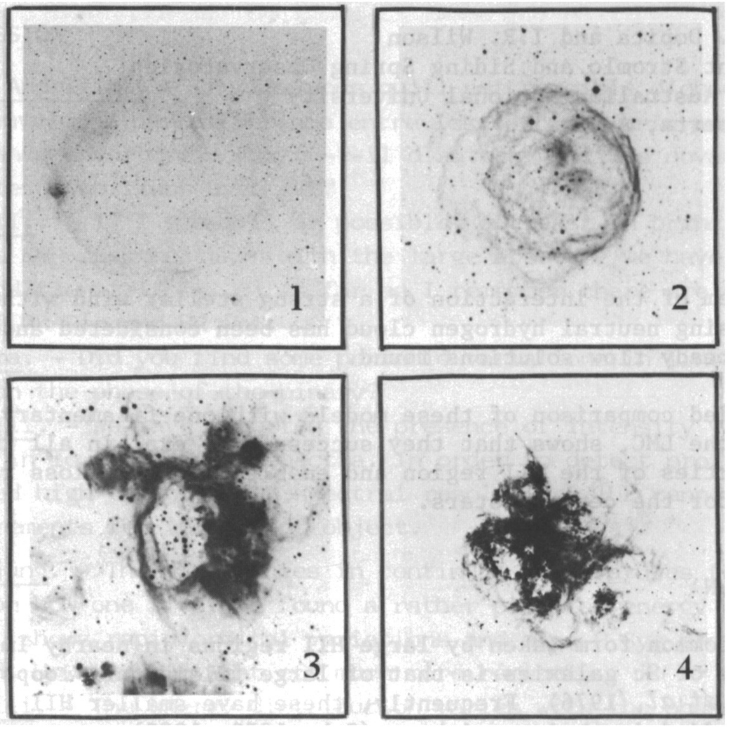

Fig. 1 Hα + [NII] photographs of giant loop HII regions in the LMC, (courtesy of UKSTU). The four regions represented are DEM45, N70, N44 and 30 Dor. The neutral hydrogen masses associated with these regions are $\lesssim 10^5$ $M_\odot$, 2×10^5 $M_\odot$, 5×10^6 $M_\odot$ and 1.4×10^7 $M_\odot$ respectively. (McGee and Milton 1966)

2. STEADY FLOW SOLUTIONS

An isothermal spherically-symmetric collapse (Penston 1969, Larson 1969) can be fairly well represented by its self similar form in the early part of the collapse, or later on, in the outer regions only. This has a density law $\rho = Ar^{-2}$ and constant inflow velocity. Later on, when the cloud has developed a 'core', the infalling envelope follows a $\rho = Br^{-3/2}$ law with infall velocity $v = cr^{-1/2}$. The effect of pressure support is effectively to reduce the

https://doi.org/10.1017/S0252921100095245 Published online by Cambridge University Press

gravitational constant to 2/3 of its true value.

We consider a massive mass-losing OB star or cluster to have formed away from the centre of mass of the cloud in the early collapse phase. Since the ram pressure of the stellar wind varies inversely as the square of the distance from the star, if this is not too great, there will be a stagnation point upstream from the star where the ram pressure of the star balances the ram pressure of the accretion flow. If $\dot{M}_*$, V_* are the mass flux per steradian and velocity in the stellar wind respectively and $\dot{M}_a$, V_a are the corresponding accretion flow values at the stagnation point, then;

$$\alpha = \frac{\dot{M}_* V_*}{\dot{M}_a V_a} = \left(\frac{R-R_*}{R}\right)^2 \tag{2.1}$$

is the stagnation condition, where R is the distance to the centre of the collapsing cloud and R_* the distance from the mass-loss star or cluster. For a $\rho = Ar^{-2}$ accretion flow, this stagnation point is stable, but in a $\rho = Br^{-3/2}$ it is only stable if $R_*/R < 4/5$, ($\alpha = 0.64$).

Matter escapes from the stagnation point by blowing out along an 'accretion' surface supported by the stellar wind ram-pressure. The flow generated therefore consists of:

1) A standing shock in the accretion flow
2) A compressed layer of accreted unionised matter
3) A ram pressure confined HII region
4) A mixing layer of shocked stellar wind and material from the HII region
5) The undisturbed mass loss flow, bounded by a standing shock at its outer surface.

Layers 2 to 4 may be in relative motion along the accretion surface. On the assumption, fairly easily justified, that these layers are thin in comparison with the dimensions of the flow, the equations of continuity and momentum can be solved to give the shape of the shocked shell of unionised gas. (Dopita 1980). If U,S are the velocity and surface density respectively of gas in this layer, distance Z from the stagnation point, the small angle solution is:

$$U \approx \frac{2Z\, R_*}{3R(R-R_*)}\, V_a$$

$$S = \frac{3(R-R_*)}{4RR_*}\, \frac{\dot{M}_a}{V_a} \tag{2.2}$$

Surface densities as high as those in (2.2) can be set up in a $\rho = Ar^{-2}$ accretion velocity within one free-fall timescale if

$R \lesssim 7R_*/3$. If this condition is satisfied, and if the lifetime of the mass-loss star is longer than the initial expansion timescale of the bubble or the free-fall timescale of the inflowing gas, then the bubble structure will approximate to the steady flow model.

The shapes of the computed mass-loss bubbles for the two accretion laws are shown in Figs. 2 and 3 for various values of α (defined in Eq. (2.1)).

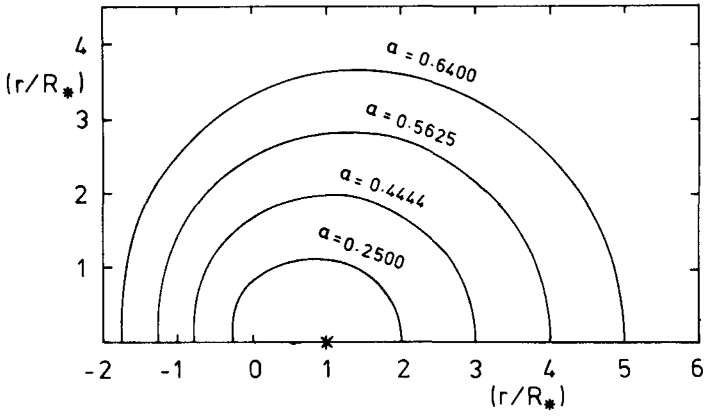

Fig. 2 Steady flow mass loss bubbles in $\rho \propto Ar^{-2}$ accretion flow. α is the ratio of momentum flux ster^{-1} in the mass loss flow to the same quantity in the accretion flow.

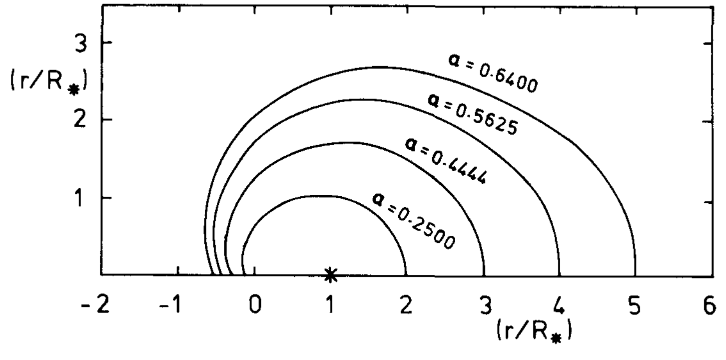

Fig. 3 As Fig. 2, but for $\rho \propto Br^{-3/2}$ accretion flow.

3. THE STRUCTURE OF THE SHOCKED LAYERS

Regions (2) to (4) are all subject to both Rayleigh-Taylor and

https://doi.org/10.1017/S0252921100095245 Published online by Cambridge University Press

Kelvin-Helmholtz instabilities. Considerable mixing may therefore occur between them.

The neutral layer is particularly interesting, since all the material being accreted is gathered into the thin accretion surface and conveyed in a converging flow towards a point on the opposite side of the mass centre than the star. Elmegreen and Elmegreen (1978) have shown that such a layer will become self-gravitationally unstable when its surface density, S, satisfies the inequality

$$S \gtrsim 0.91 \left(\frac{P}{\pi G}\right)^{\frac{1}{2}} \qquad (3.1)$$

where P is the gas pressure near the stagnation point, the inequality is not satisfied. However, for both a $\rho = Ar^{-2}$ and $\rho = Br^{-3/2}$ accretion laws, S increases faster than P as the distance r from the mass centre decreases. In the $r^{-3/2}$ law, over a wide range of α, the shocked neutral layer can become self-gravitatingly unstable in the range $0.8R_* \gtrsim r \gtrsim 0.35R_*$.

Thus, it seems most possible that secondary star formation can be induced in this layer giving rise in a natural way to 'blister' HII regions (Icke 1979, 1980).

Since the neutral shell forms a rather massive external wall to the HII region, the latter will be radiation limited and in pressure balance with the ram pressure in the radial direction.

The condition that it be thin in comparison with the radial dimension reduces to the condition that the number of H-ionising UV photons in units of 10^{49} sec^{-1} (N49) produced by the central stars of luminosity L_{39} (units of 10^{39} $erg.s^{-1}$) satisfy:

$$\left(\frac{r_{pc}}{\Delta r}\right) = 55.8\gamma^2 L_{39}^{2} N_{49}^{-1} r_{pc}^{-1} > 1.0 \qquad (3.2)$$

r_{pc} is the radius of the shell in pc and γ the ratio of momentum in the stellar wind to momentum in the radiation field. The right hand side varies in the range 0.3 to 3.5 for main-sequence stars, is perhaps a factor of two or three larger for supergiants and ranges as high as 160 to 2000 for the Wolf-Rayet Stars (Barlow *et al.* 1980).

Motions in the HII layer are essentially transverse and are powered by the oblique stellar wind shock. The shocked stellar wind is expected to be rather well mixed with the HII region, because the interface between them is both Rayleigh-Taylor and Kelvin-Helmholtz unstable, and because of electron conduction, the mean temperature T_2 of the shocked gas will be dramatically lower than its post-shock value, T_s. If saturated conduction applies (Cowie and McKee 1977) then, in the absence of radiative cooling

$$T_2 = \frac{1.45\ m_e}{\mu N^2 m_H} T_s \tag{3.3}$$

Where N is the ratio of conduction surface area to stellar wind surface area. The consequence of this efficient mixing is that, in the absence of dissipative terms, the local HII velocity could be as great at $V_* \sin \xi$ where ξ is the local angle between the normal to the stellar wind shock and the stellar wind. In fact, shocks generated at the interface between the ionised and neutral medium and around neutral cloudlets serve as a viscons dissipation term, and the velocity of the ionised gas reaches a terminal velocity at which the rate of input of mechanical energy in the wind equals the rate of dissipation in the shocks. This gives rise to the filamentary, [SII] enhanced optical emission which is commonly observed and is used as supportive evidence by those who favour a supernova remnant origin of the loops.

4. APPLICATION TO N70

The nebula N70 (Henize 1956) in the LMC is a well studied almost circular filamentary shell with diameter about 110 pc associated with Lucke and Hodge (1970) OB stellar association 114. Lasker (1976) found that it was characterised by an unusually strong [SII] to Hα ratio, and also (Lasker 1977) that it had a rather large velocity dispersion. Recently Blades *et al.* (1980) and Mathewson *et al.* (1980) have studied the detailed internal dynamics by observations of the [OII] doublet at high dispersion on the Anglo-Australian Telescope.

The latter authors have also studied the radio continuum spectrum, the 21cm HI mass associated with the nebula, the surface brightness distribution in Hα, the spectrum of the nebula and the properties of the central star cluster. In this section, we draw upon these observations in order to see whether the model described earlier is applicable and whether predicted properties of the central stars are consistent with what is observed.

The most basic observation is the shape of the nebula. It is not spherical, but has axial symmetry in the NW-SE direction. We have attempted to fit this shape to our accretion modes (without rotation) in the $\rho(r) = Br^{-3/2}$ density distribution, and Fig. 4 shows that a very good fit can be obtained with $\alpha = 0.36$. Furthermore, the predicted mass loss centre is close to the exciting stars.

In fact, the star cluster is somewhat displaced from this centre towards the west, which may be ascribed to the orbital motion of the cluster, not accounted for in our model.

If N70 is, as predicted, a ionisation-limited HII shell, then the emission measure, and hence the shell surface brightness should vary inversely as the square of the distance of the exciting stars.

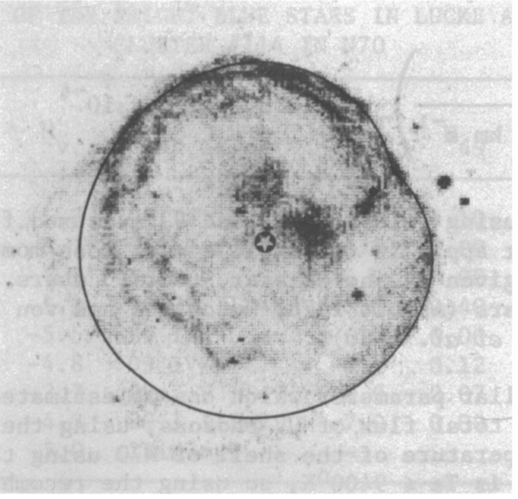

Fig. 4 The shape of N70 compared with an $\alpha = 0.36$ model (Fig. 3) without rotation. The star represents the computed centre of mass loss.

This prediction is very well confirmed by the SEC Vidicon Hα photometry.

The ratio of the shell surface brightness at the centre compared with the rim suggests that its thickness is 0.08 of its radius. Using this value, we find a mean atomic density of 5.3 cm^{-3}. This implies a gas pressure of 2.4 x 10^{-12} dynes. cm^{-2} at 50 pc from the exciting stars. In our model, this gas pressure should be equal to the ram pressure of the accreting neutral material or the ram pressure of the stellar wind. The former can be estimated directly, since we know the HI mass. Using the Parkes Radio Telescope at 21cm, we found a double component structure to the HI line in this region of the LMC. The strongest, associated with N70, was at V_{LSR} = 290 km s^{-1} and the weaker was at V_{LSR} = 311 km s^{-1}. The excess signal recorded at the position of N70 corresponds to 155000 $M_{\odot}$ of neutral hydrogen. The actual cloud mass may be higher if there is an appreciable fraction of molecular hydrogen. Nevertheless, if we assume that this mass is enclosed within 50 pc (the radius at which the shell of N70 seems to 'blow out'), then at this radius the infall velocity is 5.3 km s^{-1} (4.3 km s^{-1} if infall is gas-pressure resisted) and the gas density is 1.08 x 10^{-23} gm.cm^{-3}. This corresponds to a ram pressure in the range 2 - 3 x 10^{-12} dynes cm^{-2}, which is in excellent agreement with the pressure in the HII region, a further vindication of the model.

https://doi.org/10.1017/S0252921100095245 Published online by Cambridge University Press

The stellar mass-loss can now be estimated by setting this pressure equal to the pressure in the stellar wind, at R = 50 pc. We find:

$$\left(\frac{\dot{M}_*}{M_\odot \ yr^{-1}}\right)\left(\frac{V_*}{1000 \ km.s^{-1}}\right) = (0.8 - 1.1) \times 10^{-4} \qquad (4.1)$$

This implies, using values of $\dot{M}_*$ and V_* measured for galactic stars (which may not apply in the LMC), a mass loss momentum flux equivalent to that given by one WR star, four O I stars or about forty main sequence OB stars (Abbott 1978, Hutchings and von Rudloff 1980, Chiosi 1980, Barlow *et al.* 1980).

The second stellar parameter which can be estimated from these observations is the total flux of UV photons, using the Strömgren condition. The temperature of the shell of N70 using the [OIII] $\lambda4363/\lambda5007$ Å ratio is $T_e \lesssim 9400°K$, so using the recombination coefficient appropriate to this temperature we obtain the flux of Lyman continuum photons:

$$f_* = 3.1 \times 10^{49} \ sec^{-1} .$$

Intermediate dispersion spectra have been obtained of most of the brightest blue stars in N70. (Mathewson *et al.* 1980) These spectra, in conjunction with the photometry of Lucke (1972) enable us to classify these stars, and so derive cluster properties. These are summarised in Table 1. The UV flux, N_{49} is taken from the table of Panagia 1973.

The ionising flux of the cluster;

$$f_* = 3.7 \times 10^{49} \ sec^{-1}$$

is in excellent agreement with that derived above. The fact that the most luminous dwarf seen is of type 09-09.5 suggests that the turnoff mass is about 15 $M_\odot$, or the cluster age is about 10^7 years. This is comparable with the collapse timescale of the cloud of neutral hydrogen hydrogen, $\tau = (4GM/3)^{-1/2}R^{3/2}$ (if the pressure resists collapse). This is 1.1×10^7 years for N70.

Using the observation that the thickness of the HII region is eight percent of its radius, and applying the results of Table 1 to condition (3.2) we can find the value of γ, the ratio of stellar wind momentum to momentum in the radiation field. This gives:

$$0.87 \lesssim \gamma \lesssim 1.2$$

the lower limit is obtained using the whole cluster, but the upper limit is probably more realistic since only stars 1 and 2 have been taken into account, and these will certainly dominate the cluster mass loss.

https://doi.org/10.1017/S0252921100095245 Published online by Cambridge University Press

TABLE 1

PROPERTIES OF THE BRIGHT BLUE STARS IN LUCKE AND HODGE CLUSTER #114 IN N70

Lucke * No	M_V	MK Class	M_{BOL}	N_{49}	L39
1	-5.8	06((f)) III	-9.4	2.10	1.91
2	-6.7	08 II f pec	-9.9	1.00	2.80
3	-4.3	B0-2 V	-6.9	0.00	0.17
4	-5.3	06-09 III-V	-8.8	0.40	1.00
7	-5.5	B9 Iab	-6.8	0.00	0.16
8	-4.8	09 IV-V	-8.1	0.12	0.53
9	-3.7	09.5 V	-6.9	0.07	0.17
10	-4.3	B0-3 III-V	-7.0	0.00	0.18
11	-5.0	?Binary?	-	-	-

The fact that γ is somewhat greater than unity suggests that stars 1 and/or 2 have unusually energetic stellar winds. This is confirmed spectroscopically for star 2 at both the visual and far UV wavelengths. All the lines in the visible have blue shifted emission, displaced by -800 km s^{-1} from the rest wavelength.

An IUE spectrum of this star in the 1200-2000 Å range reveals very wide but normal P-Cygni profiles in the resonance lines (Benvenuti *et al.* 1980). The blueward shift of the CIV absorption edge suggests that the terminal velocity of the stellar wind is *at least* 3800 km s^{-1}. Thus, in order for it *alone* to supply the mechanical energy to inflate N70, its mass loss (from Eq. (4.1)) must lie in the range:

$$2 \times 10^{-5} \lesssim \frac{\dot{M}_*}{M_\odot yr^{-1}} \lesssim 3 \times 10^{-5}$$

Since most of the mass-loss is coming from this star, this will determine the dynamics in the HII region. However, it is displaced from the centre of the shell, so that the detailed velocity structure cannot easily be computed. However, since the terminal velocity is greatest where the stellar wind shock is most oblique this will occur on the side of the shell nearest the star, (which is also the brightest), the westerly part. Because motions are tangential, not radial, this translates to a large line splitting in the west, decreasing towards the centre of the nebula, and increasing again, but to a lesser extent in the east. This general pattern of the velocity field is quite different from the velocity ellipsoid obtained with an expanding shell, but corresponds much closer to what is observed (Blades *et al.* 1980, Mathewson *et al.* 1980).

The mechanical energy input $\dot{Q}_*$ by the stellar wind is dissipated by shocks in the HII region. Using the values derived above:

$$\dot{Q}_* = 1.3 \times 10^{38} \ \langle \sin^2\xi \rangle \text{ ergs sec}^{-1} .$$

The mean square obliquity $\langle \sin^2\xi \rangle$ is, to order of magnitude, 0.04 so about 5×10^{36} ergs s^{-1} are radiated by shocks. The filling factor f of shock-excited gas in the HII region needed to dissipate the input energy can be shown to be given by

$$f = 10^{14}\dot{Q}_* \left(R^2 \Delta R \ n_H^2 \ Z \ V_{100}^3\right)^{-1} \tag{4.2}$$

Where Z is the heavy element abundance with respect to solar values, R the radius of the HII region (cm), ΔR its thickness, n_H its density (cm^{-3}) and V_{100} is the mean shock velocity measured in units of 100 km s^{-1}. Substituting R = 50 pc, ΔR = 4 pc, n_H = 4 cm^{-3}, Z = 0.3 V_{100} = 0.3 (from the observed velocity dispersion) gives f $\approx 1.5 \times 10^{-3}$, quite a small filling factor. However, these shocks contribute a considerable fraction of the emission measure. Since they are approximately isothermal, the density within them is enhanced by M^2 where M is the mach number, approximately three. The contribution of the shocks to the total emission measure is therefore of order 12%. ($M^4 f$). Since these shocks will have strong [SII], both the enhancement of this forbidden line and the filamentary structure of N70 are explained by their presence.

To conclude, in all its observed properties, the structure of N70 is consistent with it being a non-pressure confined mass-loss bubble in a gravitationally collapsing massive neutral cloud. However, the most important mass-loss star, Lucke 2, in the central OB cluster must be undergoing a phase of rather rapid mass-loss, with a rate of 2-3 x 10^{-5} $M_\odot$ yr^{-1} at a terminal velocity approaching 4000 km s^{-1}. The fact that the flux of momentum in the stellar wind can be determined by observations of the HII region alone is an important advance. Our success rate at recognising stars with strong mass-loss for further observation with IUE using their position within, and the morphology of, the surrounding HII region has reached about 70% in the LMC. Observations are underway to compare our model with other, similar, HII regions in the LMC.

REFERENCES

Abbott, D.C.: 1978, Astrophys. J. 225, 893.
Barlow, M.J., Smith, L.J. and Willis, A.J.: 1980, Monthly Notices Roy. Astron. Soc. (in press)

Benvenuti, P., D'Odorico, S., Macchetto, F., Chiosi, C., Wilson, I.R. and Dopita, M.A.: 1980, (in preparation).
Blades, J.C., Elliott, K.H. and Meaburn, J.: 1980, Monthly Notices Roy Astron. Soc. 192, 101.
Bruhweiler, F.C., Gull, T.R., Kafatos, M. and Sofia, S.: 1980, Astrophys. J. (Letters) 238, L27.
Castor, J., McCray, R. and Weaver, R.: 1975, Astrophys. J. (Letters) 200, L107.
Chiosi, C.: 1980, Astron. Astrophys. (in press)
Cowie, L.L. and McKee, C.F. 1977, Astrophys. J. 211, 135.
Davies, R.D., Elliott, K.H. and Meaburn, J.: 1976, Mem. Roy. Astron. Soc. 81, 89.
Dopita, M.A.: 1980 (in preparation)
Dyson, J.E.: 1977, Astron. Astrophys. 59, 161.
Dyson, J.E. and de Vries, J.: 1972, Astron. Astrophys. 20, 223.
Elmegreen, B.G. and Elmegreen, D.M.: 1978, Astrophys. J. 220, 1051.
Elmegreen, B.G. and Lada, C.J.: 1977, Astrophys. J. 214, 725.
Falle, S.A.E.G.: 1975, Astron. Astrophys. 43, 323.
Henize, K.G.: 1956, Astrophys. J. Suppl. 2, 315.
Hutchings, J.B. and von Rudloff, I.R.: 1980, Astrophys. J. (in press)
Icke, V.: 1979, Astron. Astrophys. 78, 352.
Icke, V.: 1980, Astrophys. J. (in press)
Larson, R.B.: 1969, Monthly Notices Roy. Astron. Soc. 145, 271.
Lasker, B.M.: 1976, "The Galaxy and Local Group" Royal Greenwich Observatory Bull. No. 182, p. 185, eds. Dickens, R.J. and Perry, J.E.
Lasker, B.M.: 1977, Astrophys. J. 212, 390.
Lucke, P.B.: 1972, Univ. of Washington Ph.D. Thesis.
Lucke, P.B. and Hodge, P.W.: 1970, Astron. J. 75, 171.
McGee, R.X. and Milton, J.A.: 1966, Aust. J. Phys. 19, 343.
Mathewson, D.S., Dopita, M.A., Ford, V., Wilson, I.R. and McGregor, P.: 1980, (in preparation)
Oort, J.H.: 1946, Monthly Notices Roy. Astron. Soc. 106, 159.
Panagia, N.: 1973, Astron. J. 78, 929.
Penston, M.V.: 1969, Monthly Notices Roy. Astron. Soc. 145, 457.
Pikel'ner, S.B. and Shcheglov, P.V.: 1969, Sov. Ast. A. J. 12, 757.
Weaver, R., McCray, R., Castor, J., Shapiro, P. and Moore, R.: 1977, Astrophys. J. 218, 377.

DISCUSSION

BASU: I wonder if you could give an idea of the amount of kinetic energy that would be imparted by the ejected mass to an average H II cloud. In particular, I would like to know whether it could be as important as the kinetic energy imparted by the UV radiation from the imbedded hot stars, assuming the conversion efficiency $\sim$ 1% .

DOPITA: The rate of kinetic energy input to tangential motions in the H II layer is about 10^{37} erg s^{-1} per Of or WR star in this model. The terminal velocity of the H II layer is limited by the point at which shock dissipation matches this energy input. This is (observationally) achieved at 3 - 4 times the speed of sound. The energy carried by the UV radiation field is of the order 10^{39} erg s^{-1} by comparison.