CLUSTERED SUPERNOVAE
vs.
THE GASEOUS DISK AND HALO:
A Rematch

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ABSTRACT. Recent developments, both observational and theoretical, require a reevaluation of the effects of clustered supernovae on the two-dimensional porosity parameter Q_{2D} and the rates of mass injection into the halo $\dot{M}$ of both cold and hot gas. Clustered supernovae produce two types of bubble. Most clusters produce breakthrough bubbles, which do no more than break through the dense gas disk. But large clusters produce enough energy to make blowout bubbles, which blow gas up into the halo. We calculate area filling factors and mass injection rates into the halo for different types of galaxy. We relate our calculations to two observables, the area covered by H I 'holes' and the area covered by giant H II regions. We also reiterate the difficulty of producing the very largest supershells by clusered supernovae.

1. INTRODUCTION

In a spiral galaxy the gas and new stars are concentrated into a relatively thin disk. The stars are formed in clusters. The massive stars become supernovae and these explosions are correlated in space and time. These correlated supernovae produce one large bubble instead of many small ones. If the bubble is large enough, it becomes larger than the thickness of the disk and 'breaks through'. We made calculations on these matters in Paper I (Heiles 1987), which provided unsatisfactory agreement with observation. New theoretical and observational developments cause us to perform new calculations, which are presented in detail in Heiles (1989) and briefly summarized here.

Mac Low and McCray (1988, hereafter MM) and Mac Low, McCray, and Norman (1989, hereafter MMN) have made detailed calculations of this process and made a very important point: just because a bubble breaks through the 'classical' dense gas disk does not mean that it 'blows out' into the halo. This is because of the extensive, low-density 'Lockman' (1984) $|z|$ extension of disk gas. Communication with the halo requires that the shell break through these components and open out into the halo, which requires much more energy. We define ***'breakthrough'*** bubbles as those that break out of the dense, relatively low-scale-height part of the disk; and ***'blowout'*** bubbles as those that actually break through all disk gas and communicate with the halo. Both types of bubble can be observed as HI shells and supershells in our own Galaxy and as H I 'holes' in external galaxies.

Crucial to our calculation is knowledge of the fraction of clusters that are large enough to produce breakout or blowout. Recently, we have been blessed with a remarkable paper that allows us to calculate the fraction of clusters of each type. Kennicutt, Edgar, and Hodge (1989; KEH) have derived the frequency and spatial distribution of Hα luminosities $L(obs)$ of bright H II regions in external galaxies, as functions of galactic type. These bright H II regions are produced by precisely those clusters that produce superbubbles. We can use KEH to obtain the formation rates per unit area on the disk of clusters as a function of N.

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2.1. The relation between $L(obs)$ and N.

To use KEH's observations of $L(obs)$ to calculate the influence of supernovae on the interstellar medium, we must know the relation between $L(obs)$ and the number of supernovae N. This is not a simple matter, because it is thought that all stars more massive than 8 $M_\odot$ become supernovae. Since the initial mass function (IMF) favors less massive stars, most of the supernovae come from stars with masses just above this value. However, most of the ionizing photons that produce the H II regions come from the very massive stars. Thus, both the slope and upper mass cutoff of the assumed IMF affect the desired relation.

Fortunately, careful calculations have been done by Lequeux *et al.* (1981), Melnick, Terlevich, and Eggleton (1985), and McKee (1989), and all agree quite well in predicting about 4.8×10^{62} Ly-continuum photons per supernova. McKee (1989) has evaluated the reliability of this relation by using it to predict the overall Galactic Type II supernova rate from the measurements of Galactic thermal emission of Güsten and Mezger (1982) and comparing the result with the rate derived from pulsar statistics and from rates in other galaxies. Agreement is quite satisfactory.

However, performing the same comparison for external galaxies using the integrated Hα luminosities provides unsatisfactory agreement. The extragalactic Hα luminosities imply a much smaller ionizing flux, and thus a much smaller supernova rate, than the Galactic thermal radio emission. It is unlikely that our Galaxy has many more ionizing photons than otherwise comparable external galaxies, and we do not understand the source of discrepancy. To recover the expected supernova rates in external galaxies, we must adjust the relation between number of supernovae in a cluster and the cluster's Hα luminosity upwards by a factor of about five. Our calculations use this adjusted rate.

For a cluster, $L(obs)$ is equal to the total Hα energy emitted divided by the lifetime of the cluster's H II region τ_{HII}. With $\tau_{HII,7}$ being τ_{HII} in units of 10^7 yr and $L(obs)_{38}$ the Hα luminosity in units of 10^{38} erg s^{-1}, the adjusted rate is

$$N = 222\ L(obs)_{38}\ \tau_{HII,7}\ . \tag{1}$$

For τ_{HII} we adopt 20 Myr because there exists ample observational evidence for star formation occuring over a substantial time interval. In our Galaxy, individual clusters such as Orion and Scorpius/Ophiuchus have undergone sequential star formation over intervals of some 15 Myr (Blaauw 1964).

2.2. Summary of results from KEH.

KEH give the distribution in $L(obs)$ of extragalactic H II regions in the form of a power law. KEH also give the observed surface density of H II regions on the disks of external galaxies, which depend on galactic type. In our calculations, we shall require weighted averages of the form $\langle L^y \rangle \Sigma$, where Σ is the formation rate per kpc^2 on the disk of clusters having L in the range L_{Min} to L_{Max}. L_{Min} is the luminosity of the smallest cluster of interest, for example the smallest whose supernovae will produce a breakthrough bubble. L_{Max} is the upper L cutoff in KEH's observed power-law distributions, which depends on galactic type. For Sb galaxies, $L(obs)_{Max,38} \approx 3$, where L_{38} has units of 10^{38} erg s^{-1}; this corresponds to a cluster than contains about 1350 supernovae.

It is convenient to express these weighted averages in terms of Σ alone. Skipping the details, we obtain

$$\langle L(obs)_{38}^y \rangle \Sigma \approx \frac{7.8 \times 10^{-3}}{1.14 - y}\ \tau_{HII,7}^{-1} L(obs)_{Min,38}^{-(1.14-y)}\ \mathrm{kpc}^{-2}\ \mathrm{Myr}^{-1}\ . \tag{2}$$

The steepness of the $L(obs)$ distribution guarantees that the clusters with fewer supernovae, which are much more numerous, dominate the interaction with the interstellar medium.

3. ISM PARAMETERS

In Paper I we used numerical parameters for the ISM as follows: the 'intercloud' gas density $n_0 = 0.24$ cm^{-3}; the 'scale height' $h_{100} = 1.85$ (see below for definition), where the subscript indicates units of 100 pc; the pressure $P_{04} = 0.40$, where the subscript indicates units of $nT = 10^4$ cm^{-3} K; and the rms velocity $v_{rms} = 9.9$ km s^{-1}.

However, the $|z|$ structure of the ISM is not the classical, simple thin disk. Instead, there is also an extended component, the Lockman component. We follow Lockman, Hobbs, and Shull (1986; LHS) and approximate the $|z|$ distribution as

$$n(|z|) = n_c \exp(-|z|^2/z_c^2) \ + \ n_L \exp(-|z|/z_L) \ . \tag{3}$$

This equation lumps the 'classical' CNM and WNM, which have different scale heights, together into the first term; the new Lockman component is represented by the second term. We adopt $z_c \approx 190$ pc, $z_L \approx 500$ pc, $n_c = 0.316$ cm^{-2}, and $n_L = 0.107$ cm^{-2}. n_0, which we use in various equations below, is the total density at $|z| = 0$, equal to 0.422 cm^{-2}.

Below we use an artificial scale height h. In our approximate theory we assume that $n(|z|) = const.$ for $|z| < h$ and $n(|z|) = 0$ for $|z| > h$. We relate h to z_c or z_L by requiring that the column densities to $|z| = \infty$ be correct. Thus, if we are discussing the classical component, we take $h_{100} = (\sqrt{\pi}/2)z_c \approx 1.7$; if we are discussing the Lockman component, we take $h_{100} = z_L = 5.0$.

4. BREAKTHROUGH: Q_{2D} FROM SUPERNOVAE

4.1. Rederivation of Q_{2D}.

The two-dimensional porosity parameter, roughly equal to the fraction of the disk area occupied by breakthrough bubbles, is denoted by Q_{2D}. Q_{2D} is given by $f\Sigma\pi R_f^2\tau_{SN}$, where Σ is the formation rate per unit disk area of clusters that produce breakthrough bubbles; R_f is the final bubble radius in the disk, somewhat larger than h, the disk thickness; τ_{SN} is the persistence time of the bubble; and f is a factor, not too far from unity, that accounts for the details of breakthrough bubble dynamics. Paper I set τ_{SN} equal to R_f/v_{rms}, the time required for the ambient gas to repenetrate the bubble with its typical random velocity v_{rms}. This is not quite conceptually correct (Koo 1989), although a conceptually correct expression provides essentially the same result.

We assume that bubble dynamics are those outlined in Paper I, namely we assume that the energetic winds and sequential explosive impulses of the N supernovae in the cluster act as a 'superwind' and produce bubble dynamics equal to that of a continuous stellar wind in the manner described by Weaver *et al.* (1977). The mechanical luminosity of the superwind, $L(wind)$, is equal to the total energy released divided by the time interval in which it is released, τ_{SN}. Paper I assumed that the energy superwind blows for 30 Myr. However, McCray and Kafatos (1987) use a better value, 50 Myr, and in this paper we will increase this to 60 Myr to account for the fact that not all the stars in a cluster are formed simultaneously. Keeping τ_{SN} as a free parameter, we have

$$L(wind)_{38} = 3.72 \times 10^{-2} \tau_{SN,7}^{-1} N. \tag{4}$$

Applying all to the theory given in Paper I, we derive

$$Q_{2D} \approx 340 \ \langle L(wind)_{38}^{1/2} \rangle \Sigma v_{rms}^{-5/2} h_{100}^2 n_0^{-1/2} \tag{5}$$

4.2. Breakthrough Dynamics.

Paper I argued that at least 12 SN are required for breakthrough. This corresponds to $L(wind)_{38} > 0.15$. MM's more recent detailed calculations show that breakthrough occurs when their parameter D (their equation [29]),

$$D \approx 940 \ L(wind)_{38} h_{100}^{-2} P_{04}^{-3/2} n_0^{1/2} \ , \tag{6}$$

exceeds a value somewhat smaller than 100. For our adopted ISM parameters (section 3), this occurs when $L(wind)_{38} > 0.12$, or $L(obs)_{38} > 0.0145\tau_{SN}/\tau_{HII}$. The near equality of this more rigorous limit with Paper I's limit is purely fortuitous.

4.3. Evaluation of Q_{2D}.

Combining equations (4) and (5) and using equation (2) together with $L(obs)_{Min,38} = 0.0145\tau_{SN}/\tau_{HII}$, we obtain $Q_{2D} = 2.6\tau_{HII,7}^{0.14}\tau_{SN,7}^{-1.14} = 0.37$. This corresponds to a an area filling factor for the hot bubbles of $Q/(1+Q) = 0.27$. Our value $Q_{2D} = 0.37$ is ~ 90 times smaller than the values derived in Paper I. This is fortunate, because the extremely large values of Paper I are not supported by observational data.

In comparing this prediction with observation, we recall that our derived area filling factor is a Galaxy-wide average because we used the average value of Σ. The average should apply roughly to the Solar neighborhood, and Q_{2D} should increase toward the interior. Our predicted area filling factor of 0.27 is about twice as large as the volume filling factor of large H I holes in the Solar neighborhood (Heiles 1980). For M31, another Sb galaxy, the observed area filling factor can be derived from Figures 21 and 22 of Brinks and Bajaja (1986). It peaks at ~ 0.09, corresponding to $Q_{2D} = 0.10$, for galactocentric radius $\sim$ 10 kpc; presumably the M31-wide average $Q_{2D} \approx 0.05$. Our calculated value should also apply roughly to M31, and it is again too large. M33 is an Sc galaxy and has an observed area filling factor < 0.4 (Deul and den Hartog 1989), corresponding to $Q_{2D} < 0.67$. KEH's data cause us to predict that Sc galaxies have 3 to 5 times higher values of Q_{2D} than do Sb's, and this again suggests that our predicted value is too high. We conclude that our predicted values of Q_{2D} are systematically too high by factors of ~ 3.

5. Q_{2D}^{HII} FOR H II REGIONS

The basic theory of the Stromgren sphere (see Spitzer 1978), together with the approximate ratio of $L(obs)$ to $L(uv)$, allows us to write

$$R_{HII} < 0.12 \ L(obs)_{38}^{1/3} n_0^{-2/3} \ \text{kpc} \ . \tag{7}$$

The inequality results from clumping, which should be minimal (McKee *et al.* 1984). Q_{2D}^{HII} is equal to $\Sigma^{HII} \pi R_{HII}^2 \tau_{HII}$, or

$$Q_{2D}^{HII} < 0.45 \langle L(obs)_{38}^{2/3}\rangle \Sigma^{HII} n_0^{-4/3} \tau_{HII,7} , \quad (8)$$

where Σ^{HII} is the formation rate per Myr per unit area of disk of clusters that produce the H II regions of interest.

We assume that the only H II regions to produce observable holes are those that attain breakthrough, *i.e.* $R_{HII} > h$. For the ISM parameters values of section 3, and assuming equality in equation (7), this requires $L(obs)_{38} > 0.51$. Applying equation (2) yields $Q_{2D}^{HII} = 0.032$, about 8 times smaller than Q_{2D}. The main reason is that the H II region produced by a cluster's massive stars is smaller than the bubble produced by its supernovae.

The partial correlation of observed H I holes with OB associations and H II regions in M31 found by Brinks and Bajaja (1986) and in M33 by Deul and den Hartog (1989) may be consistent with our results. The H II regions are not easily visible on broad-band optical photographs because the emission measures are small. The emission measure of an H II region that breaks through is $2hn_0^2$, or 68 cm^{-6} pc for the ISM parameters of section 3.

6. BLOWOUT: Q_{2D} AND $\dot{M}$

Blowout requires a more stringent condition on D in equation (6), because we must use the scale height of the Lockman component (and, according to MM, the density at $z = 0$). With $h_{100} = 5$, $D > 100$ requires $L(wind)_{38} > 1.036$. This corresponds to 167 supernovae, or $L(obs)_{38} > 0.125\tau_{SN}/\tau_{HII} = 0.375$. We assume that equation (5) applies for these bubbles, but use $h_{100} = h_{c,100} = 1.7$ instead of $h_{100} = h_{L,100} = 5$ because the dynamics of the classical dense disk gas should not be affected much by the evolution of the bubble after breakthrough.

We obtain $Q_{2D} = 0.65\tau_{HII,7}^{0.14}\tau_{SN,7}^{-1.14} = 0.0931$. Thus, about 1/3 of the H I hole area is occupied by blowout bubbles. Associated with these blowout shells are two forms of mass injected into the halo, cold shell fragments and hot gas.

6.1. $\dot{M}_{cold}$: cold shell fragments.

The supernovae drive a radiative shock into the ambient ISM. The matter in this cold radiative shell moves up in $|z|$ through the negative density gradient, accelerating and undergoing Rayleigh-Taylor instability, which makes it break up into fragments of cold neutral gas (McCray and Kafatos 1987). If the supernovae are infrequent and do not approximate a continuous wind, there may perhaps be further instabilities (Tenorio-Tagle, Bodenheimer, and Różyczka 1987). If these clouds pursue ballistic trajectories beginning at $|z| = 4z_L \approx 2$ kpc with a of 100 km/s, they would rise to $|z| \approx 3.7$ kpc and fall back to $|z| = 0$ after about 80 Myr.

For the particular models treated numerically by MMN, about 0.075 of the total mass of ambient ISM in the cylinder of height h and radius R_f was injected into the halo as cold clouds. If this applies generally, then the rate of injected mass of cold cloud fragments is

$$\dot{M}_{cold} = 5.0 \times 10^5 \langle L(wind)_{38}^{1/3}\rangle \Sigma h_{100}^{7/3} n_0^{2/3} v_{rms}^{-1} \ \mathrm{M_\odot\ kpc^{-2}\ Myr^{-1}} . \quad (9)$$

For the Galactic parameters in section 3, this is $10300\tau_{HII,7}^{0.14}\tau_{SN,7}^{-1.14}$ $M_\odot$ kpc^{-2} Myr^{-1}. If this occurs uniformly over a disk of radius 10 kpc, it becomes $\dot{M}_{cold} = 0.46$ M$_\odot$ yr^{-1}. This is split equally between the 'northern' and 'southern' halo hemispheres. If clouds remain well-defined and follow ballistic trajectories, the amount of gas resident in the halo in the form of these clouds is $\dot{M}_{cold}$ multiplied by the residence time for a ballistic trajectory, or about 3.7×10^7 M$_\odot$.

6.2. $\dot{M}_{hot}$: hot, diffuse gas.

Hot gas is produced by evaporation of gas from clouds and the inside of the cold shell. This gas is important for the halo, because it is injected at high temperature, can travel to high $|z|$, and can spread out into a large volume. Using equations (5) and (6) from Paper I and equation (4) above, we obtain

$$\dot{M}_{hot} = 9.9 \times 10^3 \ \langle L(wind)_{38}^{8/21} \rangle \Sigma n_0^{1/3} h_{100}^{41/21} + 1.65 \times 10^4 \ \langle L(wind)_{38}^{5/7} \rangle \Sigma h_{100}^{2/7} \tau_{SN,7} \ \mathrm{M_\odot \ kpc^{-2} \ Myr^{-1}}. \quad (10)$$

For h we use $h_{c,100} = 1.7$, because after the bubble breaks through the thin dense disk the interior hot gas expands very rapidly, so evaporation becomes nearly as ineffective as it would be if the bubble had blown out (see Figure 8 of Mac Low and McCray 1988).

With our adopted parameters, we obtain $\dot{M}_{hot} = 3650 \ \mathrm{M_\odot \ kpc^{-2} \ Myr^{-1}}$. If this occurs uniformly over a disk of radius 10 kpc, it becomes $\dot{M}_{hot} = 1.15 \ \mathrm{M_\odot \ yr^{-1}}$. Again, this is split equally between the 'northern' and 'southern' halo hemispheres.

What is the fate of the diffuse hot gas that is injected into the halo? It is injected at a high temperature, and is heated further by the Type I supernovae. In Paper I we took the scale height of Type I supernovae, h_{SNI}, to be 325 pc, larger than the scale height of the gas, h. Thus the Type I supernovae were very effective in heating the diffuse halo gas. However, Lockman's disk component has $h_L = 500$ pc, which is larger than h_{SNI}. If all of the Type I supernova energy is absorbed by Lockman's gas, then the Type I supernovae will not be an effective agent for the diffuse halo gas.

The question is very important. Paper I showed that, for negligible radiative cooling and $\dot{M}_{hot} \lesssim 2.1 \ \mathrm{M_\odot \ yr^{-1}}$, the energy input from the Type I supernovae would heat the gas so much that it would exit as a wind. With $h_{SNI} < h_L$, a smaller fraction of the Type I supernova energy will heat the halo gas, and the gas might survive without leaving as a wind. A significant fraction of $\dot{M}_{hot}$ might exit the Galaxy as a wind, depending on several details. If the gas exits as a wind it should do so with a velocity of order 200 km/s, which would make its residence time of order 50 Myr. If the gas does not exit as a wind, it will fall to the Galactic plane after it cools. The cooling time should be smaller than this value. Thus the amount of hot gas in the halo, which is equal to $\dot{M}_{hot}$ multiplied by the residence time, should be $\lesssim 6 \times 10^7 \ \mathrm{M_\odot}$.

7. THE LARGEST SHELLS

Detailed properties of Galactic shells were given by Heiles (1979). There were errors for two shells in Table 2 of that paper. For GS123+07–127 and GS139–03–69, the values of $\log R_{sh}$ should be 3.0 and 1.9, smaller by factors of 1.6 and 2.5 than the values given; listed values for $\log n_0$, $\log M$, and $\log E_k$ are also erroneous.

Shell radii in the Galaxy range up to 1300 pc, if we include only those shells with maximum confidence. Can such large shells be produced by the largest clusters? As originally emphasized by Tenorio-Tagle(1981) it is difficult for clustered supernovae to produce a shell radius very much larger than h, because once blowout occurs most of the additional wind energy is dissipated into the halo and does not produce much extra expansion in the disk. In addition there are other observational reasons for suspecting a different mechanism might operate (Mirabel 1982, and his paper presented at this meeting).

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We must appeal to other possibilities. One is that there are fluctuations in h; a large cluster, located in a region where h happens to be large (perhaps because of a previous cluster's supernovae), will be 'lucky' and make a bigger splash than usual. We might have 'clusters of clusters': the effects of multiple large clusters, located nearby in space and time, can be additive, not only in terms of $L(wind)$ but also, probably more importantly, in terms of the earlier clusters modifying the ambient ISM for later ones, for example by increasing the local value of h. Occasionally, several strategically located clusters might create neighboring holes that look like one large hole.

Apart from such effects, the most likely mechanism is completely different. Tenorio-Tagle(1981)and Tenorio-Tagle *et al.* (1987) have suggested that infalling high-velocity clouds can impart large energies to the disk ISM and cause the very largest supershells; they have also suggested ways by which this process can be observationally distinguished from clustered supernovae. There is direct observational evidence for this in our own Galaxy, as discussed by Mirabel at this meeting, and in external galaxies (Brinks 1989). In our Galaxy, some large shells are morphologically associated with high-velocity gas. The only external galaxies that exhibit very large holes have been observed are those with high-velocity gas. These include our Galaxy (Heiles 1984) and M101 (van der Hulst and Sancisi 1988). M31 contains no very large holes, and high-velocity gas at the level seen in our Galaxy is absent in M31 (Brinks 1989).

8. Discussion

Comparison of our predictions with observational data yield significant discrepencies, although they are much smaller than in Paper I and not unreasonable given the uncertainties and approximations in the approach. Different types of galaxy have different rates of clustered supernovae: rates increase in later-type galaxies, so that Sb, Sc, and Irregular galaxies have progressively higher rates.

There is observational evidence in support of our fundamental approach. The evidence is the H I supershells observed in our Galaxy (Heiles 1984) and H I holes observed in M31 (Brinks and Bajaja 1986) and M33 (Deul and den Hartog 1989). Further, in external galaxies the beautiful Hα photographs of M33 by Courtès *et al.* (1987) and of the LMC by Meaburn (1980) exhibit many large ringlike H II regions. The large rings can hardly be anything else but evolved shells produced by the superwinds of the central clusters. It takes about 5 Myr for shells to expand to the typical size of these rings, and because stars in a cluster form over a longer period of time a fraction of the shells should be ionized.

Central to our ideas is the fact that an observationally-derived quantity, Q_{2D}, and a desired but observationally elusive quantity, $\dot{M}$ (the mass injection rate into the halo), are inextricably related, although the quantitative details depend on the ISM parameters. Mass cannot be injected into the halo unless there is a corresponding Q_{2D}. Q_{2D} can be observationally derived, either relatively directly by observing the H I holes, or much less directly (and with more uncertainty) by observing the large H II regions and applying equations (5) and (8).

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Discussion:

FRANCO: Your presentation stressed the multiple SN scenario to create large structures and at the end you just gave a hint that cloud-galaxy collisions may also be operative to provide the large scale structures. The HVC-galaxy model has been worked out in some detail and there are predictions that may help to differentiate (i.e. X-ray emission in the case of the multi-supernova model) the origin of the energetic superstructures.

HEILES: Forgive me for neglecting to properly acknowlege your contribution. The paper by Tenorio-Tagle et al.(A.A. 179, 219, 1987) presents calculations of the HVC-galaxy collisions, and certainly must apply for many of the largest supershells. I was simply trying to point out that it is conceivable that multiple supernovae might produce a (probably small) portion of the very largest supershells.

PECKER: I presume that each individual injection of matter in the halo, from SN explosions in a cluster, would enrich the halo in "processed" matter. This would certanly affect the chemical composition of the young halo stars: this is certanly something that can be tested. Does it confirm or deny your figures about the rate of mass injection in the halo?

HEILES: I don't now. I haven't estimated what fraction of mass injected into the halo comes directly from the exploding supernovae.

KHAN: Have you allowed for radiative heat loss from the gas at large heights?

HEILES: No. I've set $T = \text{const}\ \dot{E}/\dot{M}$, where $\dot{E}$ comes from the supernovae that exploded at high Z and thus might heat the halo gas directly. If one wants to do better, one must include not only cooling, but other heating processes.

DANLY: I am wondering about the observational effects of the strong gradients with galactocentric radius in the SN rate and SN correlation which you alluded to. Do you also therefore expect a variation with galactocentric radius in the characteristics, such as ionization, of galactic halo gas? Savage & Massa looked for such variations in their survey toward the galactic center and found none. Do you feel their observations do not constrain your model?

NORMAN & HEILES: Pressure should be higher and ionizing photon flux should be higher. Not clear how this will affect observed UV lines. However, total recombination rate should be larger, so $H\alpha$ emission (Reynolds type) should be brighter.

BLADES: Is it meaningful to derive a scale-height for the material that is blown out into the halo? Ultraviolet-optical observations seem to indicate that considerable gas is situated between 0.5 and 1 kpc, and the high ions (C IV, SiIV) seem to appear at about $Z = 1$kpc.

HEILES: In this ballistic-type model you would not expect to find an exponential-like scale height. However, I would expect to see this material concentrated at Z-distances of 2-3kpc.

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TENORIO-TAGLE: I do not understand how a model of sequential cluster formation could lead to a supershell. By definition (see Heiles 1979, 1984) a supershell presents a large amount of kinetic energy E $>10^{53}$ erg. You have shown here how easy it is to exceed the dimensions of the disk and how energy from further explosions leaks out into the halo and does not provide the remaining shell with further energy. This clearly will also be the situation in the sequencial cluster scenario. Once the edge of the disk is reached, all or most of the further deposited energy will go into the halo. The remaining remnant in the galactic disk will be large but it will not present the energy of a supershell. The above point is also related to the question of Prof. Pecker most of the mass ejected into the halo is in fact supernova matter and not original cold disk material. Could you comment on this point?

HEILES: First, point 1. I was only saying that, occassionally, you might have a shell of radius that could be produced by clusters of multiple supernova. But I agree that most are produced by infalling HVC's, as your theoretical models have shown. Point 2: This is a good idea! I will be intented in making an estimate.

TERLEVICH, R. (Comment): The models you have used to compute the number of SN per unit Hα luminosity are for ZAMS stars and do not include mass loss. These two effects, reduce the total Hα luminosity per unit mass of a cluster. The HII region population of a spiral or irregular galaxy disk, samples young clusters with a distribution of ages between zero and 4/5 Myr whith a median of perhaps 3 Myr. Thus the integrated Hα flux will on average correspond to a cluster of such age and will be about a factor of 2 lower than at ZAMS. Another important ingredient is stellar winds. Massive star evolution is dominated by the effects of stellar winds. The presence of the wind reduces the U.V. flux by as much as a factor of 2. Finally, the slope of the IMF you have used ($\alpha = 2.5$) seems to be a bit flatter than the present best value for massive stars (i.e., $8<M<100\ M_{\odot}$). Massive stars IMF slope in the solar neighbourhood is more likely between 2.7 and 3.0. Changing to this value will further reduce the Hα flux per unit cluster mass by another factor of 2. All in all I believe that your estimates may be off by something between a factor of 3 to 10. Also I will suggest to use the models by Melnick, Terlevich and Eggleton (1985). They estimate many others parameters: the Hβ flux per unit mass for young clusters of stars with a range of IMFs, mass loss rates and abundances, using a self-consistent set of interior and atmosphere theoretical models.

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