THE STATISTICS OF SUPERBUBBLES: A MARRIAGE OF...
THE STATISTICS OF STELLAR ASSOCIATIONS
and
WIND-DRIVEN BUBBLE THEORY

Contents

1. INTRODUCTION

A sufficiently massive cluster has enough SN to produce a superbubble large enough to break through the gaseous disk and inject mass into the halo; this is a "chimney" (Norman and Ikeuchi 1989). To determine the statistics of superbubbles and chimneys, one needs to know:

(1) The statistics of stellar associations and their SN: what fraction, and how many per unit disk area, contain at least $\mathcal{N}_{*h}$ SN progenitors? And how many SN in a cluster produce a big enough superbubble to break through the gaseous disk?

(2) The assembly of SN in a large association, with its repetitive explosions, can be approximated as a steady wind. How powerful a wind—i.e., how many SN in a cluster, and consequently how large a stellar association—is required for breakthrough, or to produce a superbubble of a given size?

Here we review, first, the observational determination of the statistics of stellar associations in the Milky Way (MW); this takes up §2 → 5. Then, in §6, we review the theory of stellar winds in a stratified medium.

Several authors have discussed these issues. To my knowledge, the first is Heiles (1987, 1990), who provided basic and relatively short discussions; such are often easiest to approach for educational purposes. But, as usual, when McKee and his students set their mind on a topic they supersede everything else and produce the definitive work by employing attention to detail and proper physics and mathematics. In this instance, the relevant papers are, for the statistics of associations, McKee and Williams (1997), which we denote by MW (MW also denotes the Milky Way!); and, for the wind bubble dynamics, Koo and McKee (1992, KM). Much to my amazement, my old results are in rough agreement with their sophisticated calculations.

2. THE STATISTICS OF STELLAR ASSOCIATIONS AND THEIR UV PHOTON LUMINOSITIES: OUTLINE OF ATTACK

MW treat the Milky Way (MW) as the primary example. The goal is to determine the distribution of the number of SN per stellar association, and the birthrates of such associations, and also to do this as a function of Galactic radius. To do this, one realizes the following:

(1) Any star sufficiently massive becomes a SN. This limit is about $8M_\odot$, determined both observationally and theoretically (Kennicutt 1984); this corresponds to spectral type $\sim$B3 which have surface temperatures $\sim$ 18000 K and do not produce significant HII regions. Thus, our goal of determining the number of SN progenitors becomes equal to determining the number of stars earlier than B3.

(2) If one wants to determine the number of stars earlier than B3 using direct observational techniques, one has to take lots of stellar spectra: in particular, to categorize the stellar population of every recognizable stellar association. This is a lifetime's work: not even McKee makes his students do *this* much for a thesis! Moreover, you can't do it for distant stars in the Galaxy because of dust extinction.

(3) What is "easy" to do is to measure the Hα emission or radio luminosity for all the recognizable HII regions in a galaxy. For the MW one uses radio, because the results are unaffected by foreground extinction; for external galaxies, one uses Hα. This photon production rate tells us the number of OB stars. The radio and/or Hα luminosities can be directly converted to the UV photon production rates.

(4) Given the UV production rates, we know the total number of OB stars—if we know the distribution of stellar masses. We assume that there is a universal distribution of stellar masses. This is called the Initial Mass Function (IMF).

(5) Combining **(3)** and **(4)** provides the total number of stars formed in the cluster that powers each observed HII region galaxy and, because we know the IMF, it also provides the number of SN progenitors in each cluster.

(6) Combining the total number of stars with the lifetime for UV photon production gives us the total stellar birthrate. Because we know the IMF, a known fraction of these are SN progenitors, so it also tells us the SN rate in the each cluster. Integrate over the cluster distribution to get the total Galactic rates.

(7) Use the known radial dependence of star density to derive the radial dependence of the above.

The following three sections review MW's treatment of these matters in detail.

3. INITIAL MASS FUNCTION AND ITS UV-PHOTON OUTPUT

3.1. The concept of the truncated power law distribution

First, assume that all distributions such as the IMF are described by truncated power laws:

$$\mathcal{N}_{(x>x_*)} = \frac{\mathcal{N}_u}{\alpha} \left[\left(\frac{x_u}{x_*} \right)^{\alpha} - 1 \right] \tag{1}$$

where x_u is the upper cutoff of the power law. We expect $\alpha \sim 1$, which means that:

(1) $\mathcal{N}_u$ is approximately the number of objects between $0.5x_u \rightarrow x_u$.

(2) $\frac{\mathcal{N}_u}{\alpha}$ is the number of objects that would exist above x_u if there were no cutoff.

If $\mathcal{N}_u$ is large, then there must be some physical process that cuts the distribution off. In contrast, if $\mathcal{N}_u \sim 1$, then the cutoff arises from some other cause, such as lack of resources to form larger objects.

3.2. The Massive-Star IMF in terms of a truncated power law

Regarding the IMF, the current standard is the Scalo (1986) IMF. His is not a power law distribution, but for large masses $M \gtrsim 5M_\odot$ a power law is a good approximation. Here we use not an absolute number distribution but, rather, a fractional distribution $\mathcal{F}$, and the result is

$$\mathcal{F}_{(m>m_*)} = 4.5 \times 10^{-5} \left[\left(\frac{120}{m_*} \right)^{3/2} - 1 \right] \ , (m_* \gtrsim 5) \tag{2}$$

where all masses are in solar masses. We find that 1 out every 400 stars will become a SN. This is equivalent to 1 SN for every 196 $M_\odot$ of stars formed.

Below, when we refer to the IMF, we are referring to the above *massive-star* IMF. Because it has no lower mass limit, it does include stars with $m \lesssim 5$ even though it is not accurate for those stars.

3.3. The expected S-distribution of clusters

Let S be the production rate of ionizing photons from an assembly of $\mathcal{N}_*$ stars and s_{m_*} be the rate for a star of mass m_* *in units of* 10^{49} sec^{-1}. Published observational/literature (Vacca, Garmany, and Shull 1996) provides s_{m_*}:

$$s_{m_*} \approx 8.2 \times 10^{-4} m_*^2 \quad , (m_* = 40 \rightarrow 120) \tag{3a}$$

$$s_{m_*} \approx 5.5 \times 10^{-7} m_*^4 \quad , (m_* = 20 \rightarrow 40) \tag{3b}$$

Averaging over the Scalo IMF gives

$$\langle s \rangle = \frac{S}{\mathcal{N}_*} = 8.9 \times 10^{-4} \tag{4}$$

and this lasts for $\langle t_{ms} \rangle = 3.7$ Myr.

So you'd think that you could determine the number of stars in the cluster $\mathcal{N}_*$ by measuring the radio flux of its HII region, converting that to the UV photon production rate for the cluster (denoted S), and dividing by $\langle s \rangle$. This works fine as long as $\mathcal{N}_*$ is large enough that the average $\langle s \rangle$ is meaningful.

However, for clusters without many stars ("small clusters"), the *actual* values of both s_{m_*} and t_{ms} are highly variable because of small-number statistics: s_{m_*} can be zero if the cluster happens not to have an OB star and it can be huge if it happens to have a 100 $M_\odot$ star; t_{ms} can be large or small if its one OB star is 20 $M_\odot$ or 100 $M_\odot$. As a result, small clusters of a given total number of stars have a huge variance in $\frac{S}{\mathcal{N}_*}$, depending on what the OB star population happens to be.

MW attack this by setting up the joint probability distribution $dP(S|\mathcal{N}_*)$ that an association having $\mathcal{N}_*$ stars produces a UV photon luminosity $S \rightarrow S + dS$. This is a complicated business because not only does S depend on the stellar mass (through s_{m_*}) , but so does the time over which the star produces its photons (through t_{ms}). The derivation requires their section 3 and Appendix A; their result is presented in their Figure 3.

3.4. Photons destroyed by dust

In Appendix B, MW consider a standard Stromgren sphere HII region and find that about 55% of the UV photons are destroyed by dust. In the envelope of an HII region, called an Extended Low Density HII region, a smaller fraction are killed by dust, only about 20%. Most of a galaxy's UV photons are produced the ELD HII region instead of standard HII regions (!), and a weighted average gives 27% of all the UV photons produced by a galaxy being killed by dust.

4. OBSERVATIONAL DETERMINATION OF UV PHOTON LUMINOSITY FOR THE ENTIRE GALAXY

4.1. The Two Major Observational Tracers of S: Classical HII Regions and ELD HII Gas

In the classical picture all the UV photons from the stars produce the local HII region. But in fact it doesn't work that way. Some are destroyed by dust. Some escape from the HII region because the stars that power HII regions tend to be located at the edge of a dense cloud ("champaign" or "blister" HII regions) so that the HII region is partly density bounded instead of being totally ionization bounded as in the classical Stromgren sphere. Lots of photons that do escape produce a low-density, large size ionized envelope (called Extended Low Density HII regions, or ELD HII regions); . And some escape completely from the galaxy.

The classical HII region is the one near to the star and characterized by the dense gas in the star-forming environment and surroundings. Regarding ELD HII regions, there are probably two types:

(1) True envelopes of classical HII regions that have the electron density decreasing monotonically away from the classical HII region's boundary. An example is W3/W4/W5 region (Grey et al 1999).

(2) Superbubbles and worms, where the ELD HII gas lies far from the stars on the walls of a supershell. For example, the Orion nebula is a discrete, classical HII region, but its UV photons travel hundreds of parsecs to ionize the gas in the walls of the surrounding superbubble. Larger-scale versions exist in the Galactic interior where giant "worms", which are probably superbubbles that have blown out of the Galactic gaseous disk, are ionized by the photons that leak out of the core HII regions (e.g. Heiles et al 1996).

In the MW, both types of ELD HII gas are traced by low-frequency radio H recombination lines, a research area dominated mainly by Anantharamaiah and his collaborators/students (e.g. Roshi and Anantharamaiah 2000).

There's no theory for determining the fraction of photons that are absorbed by the classical HII region. You have to determine this observationally by determining each part separately, as we now discuss.

4.2. Dense "classical" HII regions

First we consider ordinary HII regions, like say Orion but also bigger (much!) or smaller. The important thing is that they are characterized by their discreteness, which gives one the ability to make catalogs. Regarding the MW's classical HII regions, there are two sizes: giant/supergiant and small. The division occurs because only for sufficiently powerful ones—giant and supergiant—are the MW radio survey data complete. In this context, a giant HII region is at least 4 times bigger than Orion. Regarding the UV photon output, a giant HII region is excited by at least 3.4×10^{49} photons sec^{-1}(which, because of two corrections, one for most of the photons go into the ELD HII emission, and one for dust absorption, corresponds to the stars producing 4.5 times more, or $S = 15$).

4.2.1. The giant and supergiant radio HII regions

In external galaxies we have a birdseye view and it's easier to use Hα; in the Milky Way it's easier to use radio. You recognize classical HII regions by their discreteness. In the MW, the restriction to Giant and Supergiant HII regions occurs because only for such powerful ones are the MW radio survey data complete; in this context, a giant HII region is 4 times bigger than Orion.

MW use the catalog of Smith, Biermann, and Mezger (1978; SBM) for the MW's giant and supergiant HII regions. These are not small clusters, so the number of OB stars is large enough that small-number statistics are not a problem and one can directly translate the observed distribution of *radio* luminosity into a distribution of UV photon *radio-HII* luminosities *for the associations that power the HII regions.* These are both characterized by truncated power laws. We italicize *radio* here because it is not the power law for the *total* UV output of the clusters; rather, it is that for what's required to produce the *radio output alone.* There is a correction factor of 4.5 to recover the total, which we discuss below. For the radio-HII region photons alone, MW derive their equation (12) for the distribution for the photon flux S_R of the powering associations as

$$\mathcal{N}_{a,(S_R > S'_R)} = 6.1 \left(\frac{108}{S'_R} - 1 \right) \tag{5}$$

We emphasize that this comes directly from MW's corrected version of SBM's catalog of radio (i.e, giant and supergiant) HII regions.

Integrate the above distribution between the relevant limits. The use a lower limit $S'_R = 4.2$; I would have thought the proper limit should be 3.4, the lower end of the giant HII regions. The difference is small; the result is the total UV photon luminosity for giant/supergiant HII regions in the whole Galaxy (subscript G stands for "Giant")

$$S'_{GT} = 2460 \tag{6}$$

Recall that all our UV luminosities are in units 10^{49} photons sec^{-1}.

4.2.2. The Small HII regions

MW use their S-distribution, discussed above in §3.3, to derive the ratio of S from small to giant/supergiant HII regions. So they use the above result to obtain the extrapolated value, not based directly on observations:

$$S'_{ST} = 3200 \tag{7}$$

4.2.3. The totality of classical HII regions

For *all* HII regions, it's the sum:

$$S'_{RT} = S'_{GT} + S'_{RT} = 5660 \tag{8}$$

Note that the small HII regions contribute more total flux than the giant/supergiant ones. It's like the human population: mediocrity wins.

4.3. The ELD HII region gas

Here one determines the Hα or radio luminosity of the ELD HII gas *exclusive* of the contribution from discrete HII regions. The result depends on integrating the diffusely-distributed Galactic thermal emission. The MW also produces diffusely distributed *nonthermal* emission (synchrotron radiation); the two are separated using broadband spectral behavior. Again MW use SBM, who discuss this issue, and make some corrections. In external galaxies the job has been done (by others; see MW) with the diffusely-distributed Hα emission. For the MW, MW apply some sophisticated corrections and obtain

$$S'_{ELD} = 15900 \tag{9}$$

One (or at least I) suspects them of finagling with these corrections so as to obtain a value that is in better accord with the other method, which is. . .

4.4. The total Galactic emission from NII FS emission lines

One can also determine the total UV luminosity for the MW using the NII fine structure lines at 122 and 205 μm. The ionization potential of NI is 14.53 ev, just above that of HI, so that it can be ionized only in HII regions; its emission line intensities are directly proportional to the

UV photon production rate as long as the lines don't become collisionally saturated. The critical densities are $n_e \sim 10\ \mathrm{cm}^{-3}$(?) and because classical HII regions have higher densities than this the correction is nontrivial—but rely on MW to make a valiant, and probably reasonably accurate, correction. Dust extinction is negligible at these IR wavelengths. COBE accurately measured the total fluxes in these lines. MW infer

$$S'_{NII} = 19200 \tag{10}$$

which is amazingly close to the radio determination above.

4.5. Reconciliation of it all: the Grand Total

One should have $S'_{RT} + S'_{ELD} = S'_{NII}$, which is very close to being realized. (We haven't mentioned a small contribution from the Galactic center, which MW included). Taking the average of radio and NII numbers, MW obtain for the whole MW:

$$S'_T = 19000 \tag{11}$$

The prime indicates that dust absorption of UV photons has not been accounted for; removing the prime multiplies this number by 1.37.

Note that only 30% of the ionizing photons are used in producing classical HII regions. *Most of the UV photons produce ELD HII gas!!*

4.6. Correction for photons that escape the Galaxy

The above distribution is based on observations of gas that has actually been ionized by stellar photons, and does not include

(1) those photons that are absorbed by dust. A weighted average of HII regions and ELD HII gas requires the stars to produce 1.37 times more UV photons than the observed number.

(2) those photons that escape the Galaxy without producing any ionization. MW argue that this is a small fraction, no larger than 10%.

5. The distributions of star cluster

5.1. Required S

Equation 5 gave the galaxywide distribution of UV photon luminosity for clusters required to produce the giant/supergiant radio HII region catalog. We must multiply that up by a factor 3.3, which accounts for the small HII regions and the ELD HII emission, and another factor 1.37, which accounts for photons absorbed by dust. This gives the *total* Galactic UV photon luminosity distribution from stellar associations

$$\mathcal{N}_{a,(S>S')} = 6.1 \left(\frac{490}{S'_{49}} - 1 \right) \tag{12}$$

MW compare this with the data of Heiles et al (1996), who measured ELD HII emission[1] and compared that with the associated classical HII regions to produce a short list of star cluster properties including UV photon luminosities. MW find good agreement, after correcting for observational incompleteness and selection effects.

Recall the meanings of these coefficients: $\mathcal{N}_{a,(S>S')}$ is a truncated power law distribution of the UV photon flux S for stellar associations, truncated at the upper end with $S_{49} = 490$, and in the whole MW there are 6.1 clusters with that maximum number. Recall, also, that an O5 star has $s_{49} \approx 5$ and that the IMF is rather steep. This distribution will imply that the most massive clusters have a huge number of massive stars, and a huge number of SN progenitors!

5.2. Required cluster birthrate

The above distribution of S translates directly into a distribution of number of stars $\mathcal{N}_{a(\mathcal{N}>\mathcal{N}_*)}$ using equation 4:

$$\mathcal{N}_{a(\mathcal{N}>\mathcal{N}_*)} = 6.1 \left(\frac{5.5 \times 10^5}{\mathcal{N}_*} - 1 \right) \ \mathrm{Myr}^{-1} \ . \tag{13}$$

These stars have a certain lifetime; for the standard IMF and a large cluster, this lifetime is $\langle t_{ms} \rangle = 3.7$ Myr. Dividing the above by $\langle t_{ms} \rangle$ gives the rate of formation of clusters with number of stars exceeding $\mathcal{N}_*$:

$$\dot{\mathcal{N}}_{a(\mathcal{N}>\mathcal{N}_*)} = 1.65 \left(\frac{5.5 \times 10^5}{\mathcal{N}_*} - 1 \right) \ \mathrm{Myr}^{-1} \ . \tag{14}$$

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[1] A very difficult project requiring huge amounts of telescope time. It is no longer possible: the Hat Creek 85-foot telescope blew down in a windstorm in 1993.

where $\mathcal{N}$ is the number of stars in the cluster. (Dividing by 400 turns this into the SN formation rate). If we assume that *all* Galactic stars are made in associations described by this power law, then we can integrate this equation to obtain the total star formation rate: the result is $\dot{\mathcal{N}}_T = 7.8$ stars yr^{-1}. This is not too far from other estimates, as summarized by MW.

The above equation describes the result of a snapshot in time—namely, the currently observed giant/supergiant radio HII regions in the MW. There is one more aspect, however...

5.3. Stellar Generations

In stellar associations, stars don't all form at once; they form over a fairly long time interval ~ 20 Myr. There is some evidence, especially from Orion, that the star formation is episodic. Thus we arrive at the concept of stellar *generations*. In Orion, Blaauw (1964, 1991) has identified 3 or 4 distinct generations. So MW allow a star cluster to form stars for 18.5 Myr, doing so in five generations ($5\langle t_{ms}\rangle \sim 18.5$ Myr). Thus the above equation applies to a *single generation.*

5.4. The SN rate

Kennicutt (1984) derives the SN progenitor mass limit from observations (a comparison of Hα luminosity and SN rates in external galaxies, which also relies on assuming the IMF) and obtains ~ 8 M$_\odot$. With the Scalo IMF about 1 out every 400 stars becomes a SN. This is equivalent to 1 SN for every 196 M$_\odot$ of stars formed.

Also, the number of SN in the current stellar generation that blow up in an association, denoted by $\mathcal{N}_{*h}$, is directly related to its UV luminosity:

$$\mathcal{N}_{*h} = 2.9 S_{49} \tag{15}$$

Being the result of a snapshot, this applies to the *current generation only.*

Applying this to the entire MW, whose total $S_{49} = 1.37 \times 19000 = 26000$, there currently exist $26000 \times 2.9 = 75400$ SN progenitors in the MW. Their birthrate, and their explosion rate, is $\frac{75400}{\langle t_{ms}\rangle}$, which amounts to 1 SN every 50 years (Type II only).

Applying this to Orion, the stars in Orion produce $S_{49} \sim 3.8$ (this is their total output, not just the radio portion); this corresponds to 11 SN. We can observe Orion's stars directly, and presumably this is close to being correct.

5.5. The number of SN that accumulate over generations in an association

Let $\mathcal{N}_{a,(\mathcal{N}_{SN}>\mathcal{N}_{*a})}$ be the total number of SN progenitors that cumulatively form over the 5 generations of star formation (which last 18.5 Myr). Over 5 generations, the upper limit of the truncated distribution of total number of stars in equation 13 gets multiplied by 5; we divide by the number of stars per SN, 400, to obtain the number of associations that accumulate at least $\mathcal{N}_{*h}$ SNR:

$$\mathcal{N}_{a,(\mathcal{N}_{SN}>\mathcal{N}_{*a})} = 6.1 \left(\frac{7200}{\mathcal{N}_{*h}} - 1 \right) \tag{16}$$

(I get 6900; I have no idea how they get 7200). Our multiplication by 5 gives us the total number of supernovae in the cluster over its entire life. To obtain the birthrate of such clusters, divide by the time each sequence of 5 generations lasts, which is $5\langle t_{ms} \rangle = 18.5$ Myr.

5.6. The distribution with Galactocentric radius

The star formation rate increases towards the Galactic interior. Normally one thinks of an exponential disk, which rises monotonically inwards; MW use the radio HII region data, and other data, to settle on a scale length of $R_H = 3.5$ kpc. However, the MW has a "hole" in the central 3 kpc, so this exponential disk must be truncated inwards of that. They also truncate it at 11 kpc. This gives a total effective area of the disk $A_{eff} = \int e^{-R/H_R} 2\pi R dR = 47$ kpc^2.

At the Solar circle, the exponential distribution gives a stellar birthrate of

$$\frac{d\dot{\mathrm{M}}_\odot}{dA} = 7.5 \ \mathrm{M}_\odot \ \mathrm{pc}^{-2} \ \mathrm{Gyr}^{-1} \tag{17}$$

and, using the 196 $\mathrm{M}_\odot$ per SN, the Type II SN birthrate near the sun is

$$\frac{d\dot{\mathcal{N}}_{*h}}{dA} = 3.8 \times 10^{-5} \ \mathrm{kpc}^{-2} \ \mathrm{yr}^{-1} \tag{18}$$

6. INTERACTION OF STEADY WINDS WITH A GALACTIC DISK

6.1. A spherically symmetric case: how far does the shell travel?

First take KM's solution for a steady wind in the spherically symmetric, constant density (i.e., independent of radius) case, for times after the ISM shocked gas is radiative, which is

$$R_s = 66 \left(\frac{L_{(w,38)}}{n_0} \right)^{1/5} t_6^{3/5} \quad \text{pc} \tag{19a}$$

$$V_s = 39.6 \left(\frac{L_{(w,38)}}{n_0} \right)^{1/5} t_6^{-2/5} \quad \text{km s}^{-1} \tag{19b}$$

where ρ_0 is the ambient density. Find the time t_P, or equivalently the radius R_P, at which the shell velocity V_s is equal to the sound velocity in the ambient medium $c_{s(0,6)}$ (subscripts mean units are 10 km/s), by setting $V_s = c_{s(0,6)}$:

$$t_P = 29 \left(\frac{L_{(w,38)}}{n_0 c_{s(0,6)}^5} \right)^{1/2} \quad \text{Myr} \tag{20a}$$

$$R_P = 500 \left(\frac{L_{(w,38)}}{n_0} \right)^{1/2} c_{s(0,6)}^{-3/2} \quad \text{pc} \tag{20b}$$

Assume that the shell stalls at this point.

6.2. How high does the disk extend?

Heiles (1987, 1990) determined breakthrough by assuming that the Galactic disk layer had constant density up to some height. Koo and McKee (1992) take an arbitrary density function with height and define the effective scale height H_{eff} as

$$H_{eff} = \frac{1}{\rho_0} \int_0^\infty \rho(z) dz \tag{21}$$

where ρ_0 is the density at $z = 0$. Note this is the same ρ_0 as appears in the above equation 20.

Now determine the minimum wind luminosity (equal to 10^{51} erg times the SN birthrate) for breakthrough calculated with the naive criterion that $R_P \geq H_{eff}$ by setting the above two equal:

$$\mathcal{L}_P = 17.9 \rho_0 H_{eff}^2 c_{s0}^3 \approx 2.4 \times 10^{36} P_{04} H_{(eff,2)}^2 c_{(s0,6)} \quad \text{erg s}^{-1} \tag{22}$$

where the numerical subscripts indicate the normalization, as usual; specifically, $P_{04} = \frac{P}{10^4 k}$ cm^{-3} K, $H_{(eff,2)} = \frac{H_{eff}}{100 \text{ pc}}$, $c_{(s0,6)}$ is the ambient isothermal sound velocity in units of 10 km sec^{-1}. All these factors are of order unity.

We are not quite finished, because the above result was obtained with the *naive* criterion $R_P \geq H_{eff}$. We have to apply a fudge factor to convert naivete to reality. This fudge factor comes from numerical modeling by MacLow and McCray (1988, and subsequent works as well). KM argue that this factor is equal to 3. Thus, KM define the breakout criterion as

$$L_w > 3\mathcal{L}_P \tag{23}$$

7. HOW MUCH GALACTIC DISK AREA OCCUPIED BY CHIMNEYS?

After a superbubble breaks out of the disk, how does it expand radially *within* the disk? We imagine that the inside hot gas explodes out of the disk into the halo, leaving the inside with zero pressure. In the gaseous disk at $z = 0$, the shell expands as in the classical snowplow solution (the one in which total momentum is conserved because there is no pressure driving force). This is a 2-d snowplow and leads to $R_{(s,z=0)} \propto t^{1/3}$. If it expands until the shell velocity equals the ambient sound velocity, then the radius becomes (KM equation 5.5)

$$R_{(s,z=0)} = 1.35 H_{eff} \left(\frac{L_{(w,38)}}{P_{04} H_{eff}^2 c_{(s0,6)}} \right)^{1/6} \tag{24}$$

After stalling, the surrounding ambient medium encroaches on the carved-out volume with velocity $\sim c_{s0}$. So the chimney persists for a total time that is a suitably-weighted sum of its formation time and its destruction time; this concept of persistence time is necessarily a bit crude.

8. HOW MANY CHIMNEYS?

Above we have written:

(1) The distribution of clusters having more than $\mathcal{N}_{*h}$ SN (equation 16).

(2) The number of SN (or, more properly, the SN rate energy injection rate $\mathcal{L}_{\mathcal{P}}$) for an individual cluster required for its supershell to break out of the Galactic gaseous disk.

(3) A rough estimate of the persistence time of a chimney (§7).

It is left as an exercise for the student to calculate the number of chimneys in the Galaxy.

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