Revista Mexicana de
Astronomía y Astrofísica

Revista Mexicana de Astronomía y Astrofísica
Universidad Nacional Autónoma de México
rmaa@astroscu.unam.mx
ISSN (Versión impresa): 0185-1101
MÉXICO

2002
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Revista Mexicana de Astronomía y Astrofísica, volumen 012
Universidad Nacional Autónoma de México
Distrito Federal, México
pp. 50-55

RevMexAA (Serie de Conferencias), **12**, 50–55 (2002)

Ionized Gaseous Nebulae (Mexico City, 21-24 November 2000)
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SUPERBUBBLES AND THE PHYSICS OF MIXING

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RESUMEN

Se evalúa la tasa mínima de energía mecánica que un *starburst* ha de producir para causar la expulsión de su material recién procesado fuera de su galaxia anfitriona. Para ello resumimos primeramente las propiedades a esperarse de grupos de estrellas masivas así como la hidrodinámica que inducen en el medio interestelar. Nuestras estimaciones resultan de una especial atención a la presión que causa el medio intergaláctico en el que la galaxia en consideración se encuentra, así como también a la rotación de la componente gaseosa. Tomamos en consideración estos hechos así como una componente oscura que domina el potencial gravitacional y desarrollamos una solución autoconsistente para la distribución de la masa gaseosa. Nuestros resultados estan en excelente acuerdo con los obtenidos por Mac Low & Ferrara (1999) para galaxias con un medio interestelar que despliega una distribución de disco aplanado y una baja presión intergaláctica ($P_{\rm IGM}/k \leq 1$ cm^{-3} K). Sin embargo, nuestra solución requiere de una importante mayor tasa de energía cuando se consideran ya sea una mayor presión del medio intergaláctico, o la posible existencia de un halo extendido de baja rotación y baja densidad. Los pasos a seguir para llegar a la mezcla de elementos pesados con el medio interestelar así como la escala de tiempo que requieren son también sumarizados en esta contribución.

ABSTRACT

We evaluate the minimum energy input rate that starbursts require for expelling their newly processed matter from their host galaxies. To this end we first review the main facts about the power expected from correlated massive stars and the hydrodynamics that they induce in their host ISM. Our estimate of the minimum energy input rate required for mass ejection into the intergalactic medium results from special consideration of the pressure caused by the environment in which a galaxy is situated, as well as to the intrinsic rotation of the gaseous component. We account for these factors and for a massive dark matter distribution, and develop a self-consistent solution for the interstellar matter gas distribution. Our results are in excellent agreement with the results of Mac Low & Ferrara (1999) for galaxies with a flattened disk-like ISM density distribution and a low intergalactic gas pressure ($P_{\rm IGM}/k \leq 1$ cm^{-3} K). However, our solution also requires a much larger energy input rate threshold when one takes into consideration both a larger intergalactic pressure and the possible existence of a low-density, non-rotating, extended gaseous halo component. The steps towards mixing of heavy elements with the ISM and the time scales required are also here reviewed.

Key Words: **GALAXIES: ABUNDANCES — GALAXIES: EVOLUTION — GALAXIES: ISM — GALAXIES: STARBURST — HYDRODYNAMICS**

1. MOTIVATION

The observational evidence of massive starbursts in dwarf galaxies has led to the idea that, due to their rather shallow gravitational potential, supernova (SN) products and, even the whole of their interstellar medium (ISM), may easily be ejected from the host dwarf system, causing the contamination of the intergalactic medium. Several authors De Young & Gallagher (1990), De Young & Heckman (1994), Maclow & Ferrara (1999) have made serious calculations reaching similar conclusions. There is however, also in the literature, a different point of view given by Silich & Tenorio-Tagle (1998) and D'Ercolle & Brighenti (1999) who also through numerical simulations of starbursts in galaxies of different masses have shown how much more energy is required to reach the possibility of ejection into the intergalactic gas. The fact is that to define the energy input rate required to expel the newly processed matter from galaxies one has to deeply examine two different issues: The energetics from starbursts and the density distribution of the ISM. Here I shall summarize some of the results obtained in three papers (Silich, et al. 2001; Silich & Tenorio-Tagle 2001; and Tenorio-Tagle 1996) which deal with a complete study of the required minimum energy input rate that a coeval starburst ought to produce in order to expel the newly processed matter from its host galaxy, as well as with the steps

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towards the mixing of metals with the ISM.

2. THE POWER OF STARBURSTS

Our knowledge of stellar evolution has now been assembled by several groups in order to predict the properties of stellar clusters, given an IMF and a stellar mass range. These are the so called synthesis models of starbursts (Mas-Hesse & Kunth 1991; Leitherer & Heckman 1995) which predict a variety of observable quantities, as well as the energetics that one is to expect from a stellar cluster, as a function of time. Now we know that a $10^6\ M_\odot$ coeval starbursts with a Salpeter IMF and stellar masses in the range 1–100 $M_\odot$ leads to the appearance of several thousands of O stars strongly correlated in space (within a radius smaller than 100 pc). All massive stars undergo strong stellar winds and all of them with a mass larger than 8 $M_\odot$ will end their evolution exploding as supernova. And therefore, one is to expect from our hypothetical cluster several tens of thousands of SN over a time span of some 40 Myr. During the supernova phase the stellar cluster will produce an almost constant energy input rate of the order of 10^{40} erg s^{-1}. On the other hand, the ionizing luminosity emanating from the $10^6\ M_\odot$ cluster would reach a constant value of 10^{53} UV photons s^{-1} during the first 3.5 Myr of evolution to then drastically drop (as time^{-5}) as the most massive members of the association explode as supernova. The rapid drop in the ionizing photon flux implies that after 10 Myr of evolution, the UV photon output would have fallen by more than two orders of magnitude from its initial value and the H II region that they may have originally produced would have drastically reduced its dimensions. Thus the H II region lifetime is restricted to the first 10 Myr of the evolution and is much shorter than the supernova phase. It is important to realize that only 10% of the stellar mass goes into stars with a mass larger than 10 $M_\odot$, however, it is this 10% the one that causes all the energetics from the starburst.

One of the features of the stellar synthesis models regarding the energetics of star clusters is that fortunately they scale linearly with the mass of the starburst. It is therefore simple to derive the properties of starbursts of different masses, for as long as they present the IMF, metallicity and stars in the same mass range considered by the models.

3. THE ISM DENSITY DISTRIBUTION

It is now well established that it is the dark matter (DM) what dominates the gravitational potential in galaxies. The interstellar medium, subjected also to galactic rotation and the energetics from massive stars, is at all locations in a galaxy in search of a balance between all these effects while continuously undergoing phase changes. From the theory point of view perhaps the simplest approach to the interstellar matter density distribution in a galaxy comes from ignoring the various phases of the ISM, as in the approach of Mac Low & Ferrara (1999) and Silich & Tenorio-Tagle (2001). In the latter approach, a single ISM phase is held together by the dark matter potential while being in pressure balance with the intergalactic medium. Under these conditions, different solutions regarding the fraction of the radial component of gravity balanced by centrifugal forces (ϵ^2) lead to the density distribution of the ISM with a characteristic value of its velocity dispersion. Figure 1 of Silich & Tenorio-Tagle (2001) shows as an example various possible solutions for a $10^8\ M_\odot$ ISM and an intergalactic pressure of 1 K cm^{-3} under the assumption that ($\epsilon =$) 0.8, 0.25 and 0.0 of the radial component of gravity is balanced by rotation. The ISM density distribution under these assumptions ranges from extremely flattened disks to round galaxies without rotation. Needless to say, if a massive starburst is placed at the centre of these configurations, the ejection of the newly processed metal into the intergalactic medium will be easier for flattened disk cases as the amount of material that they will have to shock and displace to reach the intergalactic space is much smaller in these cases. This is also promoted by the hydrodynamics of remnants produced by multi-supernova events which contrary to the continuous deceleration that they suffer as they evolve into a constant density medium, when in a more realistic ISM density distribution they may experience the phenomenon of breakout and blowout.

4. BREAKOUT AND BLOWOUT

The expansion of multi-supernova remnants is promoted by the pressure ($P_{\rm interior}$) resultant from the thermalization of the sequential supernova. This leads to the outer shock that accelerates and collect the surrounding ISM of density (ρ) into a dense shell. The velocity of the shock is $V_{\rm S} = (P_{\rm interior}/\rho)^{0.5}$ and as the remnant evolves and its volume grows $P_{\rm interior}$ decreases as $E_{\rm total}$/volume. This fact in a constant density medium leads to a continuous deceleration of the the remnant. However, if the evolution takes place in a disk-like configuration, and the density falls off steeply in the direction perpendicular to the plane of the galaxy, much more rapidly than the fall of the pressure, then the shock will be force to accelerate in the direction of the density gradient. This is the moment of breakout (Kompaneets 1960). Upon breakout, the section of the shell following the shock will also experience a sudden acceleration, fact that will promote the development of Rayleigh-Taylor instabilities that will lead to its fragmentation. The hot gas filling the remnant interior will then be able to stream between fragments venting the high pressure of the remnant into the the extended halo of the galaxy or into the IGM in the case of flattened disk-like systems (see Tenorio-Tagle & Bodenheimer 1988 and references therein).

5. THE ENERGY REQUIREMENTS

Figure 1 shows the energy estimates resultant from the numerical integration of the hydrodynamic equations for coeval starbursts with a constant energy input rate during the first 4 $\times 10^7$ yr of the evolution, and initial density distributions that consider a range of galactic ISMs (from 10^6 to 10^9 $M_\odot$) and extreme values of ϵ ($\epsilon = 0.9$ for flattened disk-like density distributions and $\epsilon = 0$ for spherical galaxies without rotation) and also for a range of values of $P_{\rm IGM}/k$ (equal to 1 and 100 cm^{-3} K).

In Figure 1, values below each line imply total retention, while the region above each line indicates the expulsion of the hot superbubble interior gas (the new metals) out of disk-like distributions ($\epsilon = 0.9$), and of the new metals and the whole of the ISM in the spherical ($\epsilon = 0$) cases. Each line that separates the two regions marks the minimum energy input rate needed from a coeval starburst to reach the outer boundary of a given galaxy, regardless of the time that the remnant may require to do so. In the case of disk-like configurations, this energy input rate warrants breakout and the ensuing continuous acceleration. In most of these cases the ejection of the hot gas into the intergalactic medium occurs before the starburst supernova phase is over (4×10^7 yr). In galaxies with $\epsilon = 0$, however, the evolution time considered largely exceeds the starburst supernova phase. This causes the decelerating shell of interstellar swept up matter to reach the galaxy edge by means of the momentum gathered during its early evolution.

The right-hand axis in our summary Figure 1 indicates the mass of the coeval starburst able to produce the energy input rate indicated in the left-hand axis. This has been scaled from the synthesis models of Leitherer & Heckman (1995) for a 10^6 $M_\odot$ starburst under the assumption of a Salpeter IMF with a lower mass limit of 1 M$_\odot$, an upper stellar mass equal to 100 $M_\odot$, and a metallicity $Z = 0.1$. In this case, the log of the mechanical energy input rate in erg s^{-1} is 40.5, and scales linearly with the starburst total mass.

In Figure 1, we have also indicated the results of another two calculations where we assumed a gravitational potential corresponding to a $M_{\rm ISM} = 10^9$ $M_\odot$ galaxy. In these two models however, we have adopted a spherical halo with total masses of 10^8 $M_\odot$ and 10^7 $M_\odot$ and an intergalactic gas pressure equal to $P_{\rm IGM}/k = 1$ cm^{-3} K. The derived minimum energy input rate (or minimum mass of the coeval starburst required to expel the ISM) clearly indicates that it is the mass of the halo, instead of the disk component, what determines the minimum energy input rate necessary for ejection. Figure 1 shows that a halo with only 1/100 of the mass of the disk-like configuration ($M_{\rm ISM} = 10^9$ $M_\odot$) increases the value of the minimum energy input rate required for mass ejection by approximately an order of magnitude. An energy input rate nearly two orders of magnitude higher is needed if the spherical halo has a mass of 1/10 of the disk-like configuration.

6. THE ENERGY LIMIT FOR MASS EJECTION INTO THE IGM

We have described a simple, self-consistent, approach to build the ISM gas distribution of galaxies, accounting for the gravitational potential exerted by a massive DM component, as well as for rotation of the ISM and the intergalactic gas pressure. The numerical experiments and analytical estimates have then showed that the final fate of the matter ejected from a starburst region, as well as that of the shocked ISM, is highly dependent on the boundary conditions. Following a continuous transition from a fast rotating, thin, disk-like to a spherical non-rotating interstellar gas distribution, we have found that the ISM to be more robust and resistant to ejection than estimated in earlier papers.

We have shown (see Fig. 1) that superbubbles evolving in galaxies that have a gaseous disk-like density distribution are likely to undergo the phenomenon of breakout. This allows them to accelerate and expel all of their newly produced metals, and perhaps even a small fraction of the interstellar medium, into intergalactic space. On the other hand, much larger energy input rates, or more massive coeval starbursts (up to 3 orders of magnitude larger), are required to provoke breakout or push a shell to the galaxy outer boundary for a spherically-symmetric ISM mass distribution. Even low mass ($\sim$ 1–10% of the total ISM mass), non-rotating subsystems increase the energy requirements by more than an order of magnitude. This makes the low density haloes, rather than DM itself, the key component in the evolution of dwarf galaxies.

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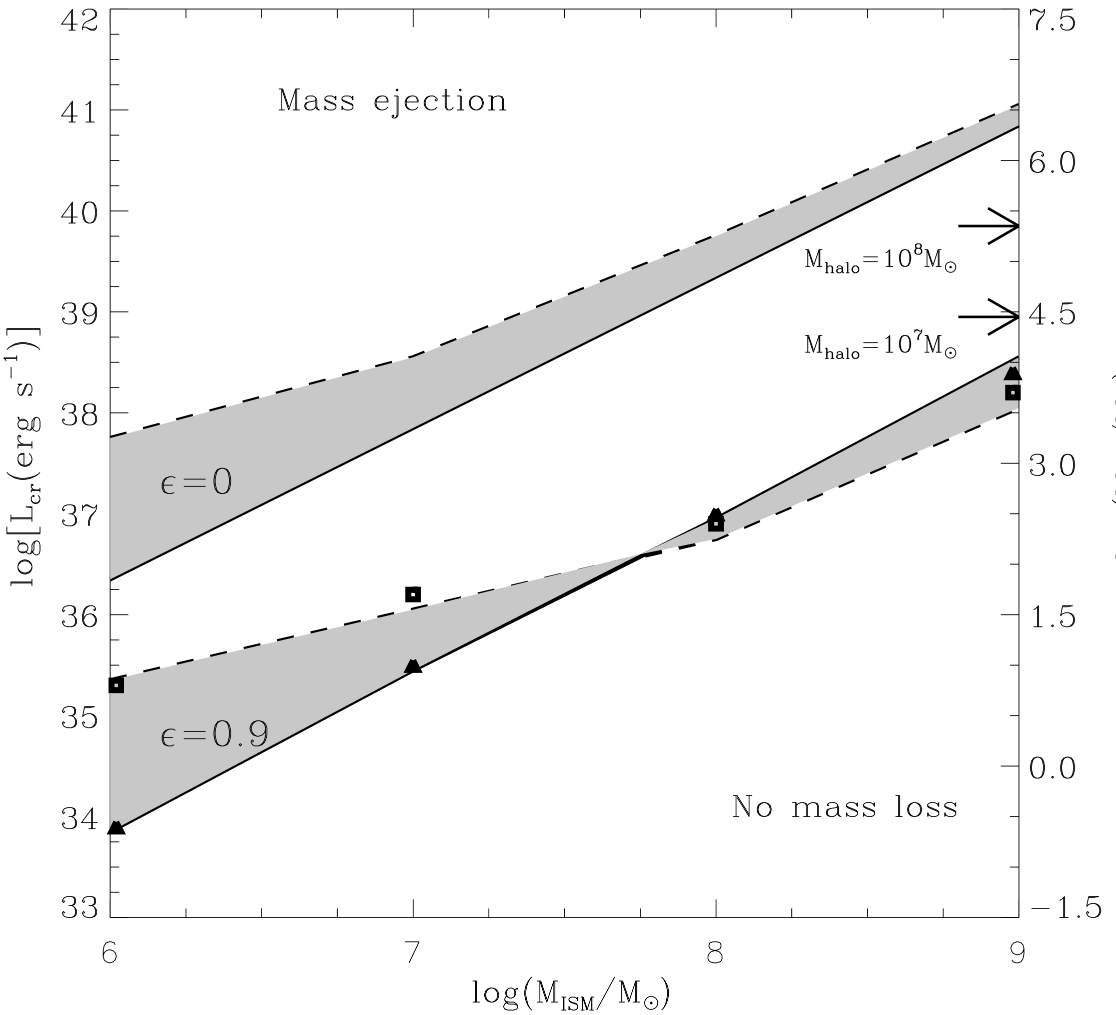

Fig. 1. Numerical energy estimates. The log of the critical mechanical luminosity (left axis), and of the starburst mass (right-hand side axis), required to eject matter from galaxies with a $M_{\rm ISM}$ in the range 10^6–10^9 $M_\odot$. The lower limit estimates are shown for galaxies with extreme values of ϵ (0 and 0.9) and for two values of the intergalactic pressure $P_{\rm IGM}/k = 1$ cm^{-3} K (solid lines) and $P_{\rm IGM}/k = 100$ cm^{-3} K (dashed lines). The resolution of our numerical search is $\Delta \log L_{\rm cr} = 0.1$. Each line should be considered separately as they divide the parameter space into two distinct regions: a region of no mass loss that is found below the line and a region in which blowout and mass ejection occur that is found above the line. Also indicated on the right-hand axis are the energy input rates required for a remnant to reach the outer boundary of a halo with mass 10^8 $M_\odot$ and one with mass 10^7 $M_\odot$, for the case of a gravitational potential provided by $M_{\rm DM} = 9.1 \times 10^9$ $M_\odot$ that can hold an $M_{\rm ISM} = 10^9$ $M_\odot$. The filled squares and triangles correspond to analytical estimates. Figure adapted from Silich & Tenorio-Tagle (2001).

Clearly the energy input rates derived by Silich & Tenorio-Tagle (2001) are lower limits to the amounts required for expelling matter from a galaxy. Particularly because only one component of the ISM was considered and because the central densities adopted are well below the values expected for the star forming cloud where the starburst originated. Our estimates thus neglect the effect of the starburst plowing into the parental cloud material. These are lower limits also because we adopted a constant energy input rate (see Strickland & Stevens 2000) and because our approach neglects the presence of a magnetic

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field which could also inhibit expansion (Tomisaka 1998).

The indisputable presence of metals (in whatever abundance) in galaxies implies that the supernova products cannot be lost in all cases. Note in particular that many well known disk galaxies have a high metal abundance and a large number of centers of star formation. Most of these exciting star clusters are more massive than the $10^4 M_\odot$ lower limit established by Mac Low & Ferrara (1999) and Silich & Tenorio-Tagle (2001) as the minimum starburst mass required to cause mass ejection in the case of disk-like systems. This lower limit for disk-like galaxies with $M_{\rm ISM} \leq 10^9 M_\odot$ (see Figure 1) implies that starbursts even smaller than the Orion cluster would break through the galaxy outer boundary and eject their supernova products into the intergalactic medium. Nevertheless, disk-like galaxies can avoid losing all their freshly produced metals by having a halo component, neglected in former studies, that acts as the barrier to the loss of the new metals.

Thus the answer, the true limit for mass ejection from galaxies, must lie between the two extreme cases that we have investigated here. Note however, that in the presence of a halo, it is the mass of the halo that sets the limiting energy input rate required for mass ejection, and not the mass of the disk-like component. This argument applies to all galaxies whether spirals, amorphous irregulars or dwarfs.

The extended gaseous haloes, despite acting as the barrier to the loss of the new metal, have rather low densities ($\langle n \rangle \leq 10^{-3}$ cm^{-3}) and thus have a long recombination time ($t_{\rm rec} = 1/[\alpha n_{\rm halo}]$); where α is the recombination coefficient) that can easily exceed the life time of the H II region ($t_{\rm HII} = 10^7$ yr) produced by the starburst. In such a case, the haloes may remain undetected at radio and optical frequencies (see Tenorio-Tagle et al. 1999), until large volumes are collected into the expanding supershells. Note that the continuous Ω shape that supershells present in a number of galaxies, while remaining attached to the central starburst, and their small expansion velocity (comparable or smaller than the escape velocity of their host galaxy) imply that the mechanical energy of the star cluster is plowing into a continuous as yet undetected medium. The metals are thus here to stay.

7. THE PHYSICS OF MIXING

Given the extreme violence of the ejection process, either through supernova explosions or strong stellar winds, the presence of strong reverse shocks assures that upon the thermalization the ejected matter would reach temperatures ($T \sim 10^7$–10^8 K) that would strongly inhibit recombination and thus the detection of the newly processed material at optical frequencies. Furthermore, it is now well understood that it is this hot high pressure gas the one that fills the interior of superbubbles and that drives the outer shock that sweeps and accelerates the surrounding ISM. It has then become clear in recent years that the metallicity detected in blue compact dwarfs, the same as in all other galaxies, results from their previous history of star formation and has nothing to do with the metals presently ejected by their powerful starbursts. The continuous energy input rate that in the coeval starburst model lasts until the last 8 $M_\odot$ star explodes as supernova ($t \sim 4 \times 10^7$ yr) or it extends until the star formation phase is over in the continuous star formation model, reassures that the high temperature of the ejected matter is maintained above the recombination limit ($T \sim 10^6$ K) allowing superbubbles to reach dimensions in excess of 1 kpc. During this phase the first step towards mixing takes place. About 10% of the interstellar matter swept up and stored in the expanding supershell, becomes thermally evaporated and thus injected into the superbubble interior during the evolution. As the swept up matter becomes evaporated, it streams into the superbubble and acquires a similar temperature to that of the supernova ejected gas. Under such conditions mixing is expected to become a rapid process. This is because the large temperatures favor diffusion, and also because the large sound speed ensures an efficient stirring between the two gases. Mixing of the evaporated ISM with the ejected metals lowers the metallicity of the superbubble interior. Silich etal (2001) have predicted the values to be expected from X-ray observations during this phase if one uses either iron or oxygen as tracers. There is however, no diffusion of the highly metal enriched superbubble gas over the matter either in the expanding shell or its immediate surroundings (see Tenorio-Tagle 1996).

After the last supernova explosion, the hot gas has nothing else to do but to cool down by radiation. And thus slightly denser regions within the superbubble interior will cool faster than their immediate surroundings. In such a case the process of cooling will lead to a series of repressurizing shocks causing the cooling gas to become even denser and thus able to cool even faster (cooling $\sim \Lambda n^2$; where Λ is the cooling rate and n is the density of the cooling fluid). The process will continue until pressure equilibrium is reestablished between the strongly compressed cold denser regions and their still hotter surroundings. Upon cooling, the highly metallic con-

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densations will begin to fall towards the disk under the gravitational potential of the host galaxy. The falling condensations are then likely to break, via Rayleigh-Taylor instabilities, into even smaller droplets as they ram through the lighter, but hotter gas, that attempts to decelerate their fall.

Note that the newly processed heavy elements have been generated within a region of about 100 pc (the size of the starburst) while upon cooling of the superbubble interior and their fall back towards the galaxy, the heavy elements are disseminated over a region of several kpc in size. After such a large-scale dispersal, it is diffusion what leads to a thorough mixing of the heavy elements with the host galaxy ISM, enhancing its metallicity.

Note also that during the H II region phase (the first 10 Myr of evolution) only a small fraction ($\leq$ 5%) of the total amount of heavy elements expected from a starburst, would have been ejected from the stellar sources. One would then have to wait to the end of the supernova phase ($\geq$ 40 Myr) for the full ejection of all heavy elements synthesized by the massive stars. At this stage almost 50% of the starburst mass would have been returned to the ISM and heavy elements such as oxygen would have reach its expected yield value. Other heavy elements, like Fe for example, expected from type I supernova will not reach their full yield value until much later in the evolution of the starburst. Once all heavy elements from massive stars are injected into the superbubble interior and radiative cooling begins to operate, several 10^8 yr ($t_\Lambda \sim kT/(\Lambda n)$) would have to elapse before the metals are dispersed to large distances within the host galaxy disk.

The next step towards mixing with the ISM is promoted by diffusion. Diffusion is largely enhanced in high temperature gases and thus if a new major centre of star formation develops and causes the formation of an H II region, the heavy elements will rapidly mix to show a uniform abundance. In the absence of star formation however, the heavy element droplets will also diffuse but over larger time scales.

Altogether the process of mixing takes several (4–6) $\times$ 10^8 yr to promote an enhanced almost uniform abundance in the ISM. All of these findings are strongly opposed to the common view of an instantaneous mixing of heavy elements with the ISM. In particular, we have referred to the products violently ejected during type II supernovae which at the same time acquire the large pressure that separates them from the ISM, preventing its immediate mixing.

Financial support for this research has been provided by CONACyT, México (project number 211290-5-28501E).

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