Supernova Environmental Impacts
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The Supernova – ISM/Star-formation interplay

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Abstract. Supernovae are the most energetic stellar events and influence the interstellar medium by their gasdynamics and energetics. By this, both also affect the star formation positively and negatively. In this paper, we review the complexity of investigations aiming at understanding the interchange between supernova explosions with the star-forming molecular clouds. Commencing from analytical studies the paper advances to numerical models of supernova feedback from superbubble scales to galaxy structure. We also discuss parametrizations of star-formation and supernova-energy transfer efficiencies. Since evolutionary models from the interstellar medium to galaxies are numerous and are applying multiple recipes of these parameters, only a representative selection of studies can be discussed here.

Keywords. ISM: supernova remnants, ISM: kinematics and dynamics, ISM: bubbles, ISM: structure, stars: formation, galaxies: evolution, galaxies: ISM

1. Introduction

Stars form from the cool gas of the interstellar medium (ISM) and couple to their environment during their lives already by stellar mass and energy release, the latter comprising radiation and stellar wind energy. Nevertheless, the most vehement effect to the ISM and whole galaxies is contributed at their deaths when massive stars explode as supernovae type II (SNeII) and intermediate-mass stars expel planetary nebulae or die as SNeIa from binary systems. Only a minor fraction of the initial star mass is retained as remnants, almost 10–15% for the massive and 20-30% for intermediate-mass stars (Weidemann & Koester 1983) and zero in the SNIa case. The rest refuels the ISM. This cosmic matter cycle acts on intra-galactic scales and contributes not only energy but also nucleosynthesis products to the ISM (e.g. Hensler & Recchi 2010). The processes which determine this galactic ecosystem seem to be fine-tuned in a manner that e.g. galactic gas disks are mostly in energy balance in which the vertically integrated star-formation rate (SFR) $\Sigma_{\rm SFR}$ (in units of $M_\odot yr^{-1} pc^{-2}$) correlates with the gas surface density $\Sigma_{\rm g}$ over orders of magnitude, known as Kennicutt-Schmidt law (Kennicutt 1998). More precisely, this relation holds for the molecular gas $\Sigma_{\rm mol}$ (Schruba *et al.* 2011) what can be understood because the molecular gas fraction is determined by the ISM pressure and, by this, also the star-formation efficiency (SFE) $\epsilon_{\rm SF}$ (Leroy *et al.* 2008).

If the SFR is simply determined by the molecular gas reservoir and by the free-fall time $\tau_{\rm ff}$ of molecular clouds (Elmegreen 2002), it would exceed the observed one in the Milky Way by up to two orders of magnitude (e.g. Hensler 2011), energetic processes have to intervene and to stretch the star-formation (SF) timescale with respect to the dynamical timescale implying the SFE such that $\delta\rho_{\rm SF}/\tau_{\rm SF} = \epsilon_{\rm SF} \cdot [\rho_{\rm g}/\tau_{\rm ff}]$. This equilibrium on disk scales requires that heating processes balance the inherent cooling of the ISM. Besides multiple heating processes from dissipation of dynamics, as e.g. differential disk rotation, gas infall, tidal interactions, etc., the above-mentioned local and immediate feedback by formed stars themselves is the most favourable mechanism of SF regulation. Köppen, Theis, & Hensler (1995) demonstrated already that the SFR achieves a dependence on ρ_g^2, if the stellar heating is compensated by collisional-excited cooling emission (e.g. Böhringer & Hensler, 1989).

2. Supernova feedback

2.1. *Supernovae and the Matter Cycle with Star Formation*

The most efficient stellar energy power is exerted by SNe, of which those SNeII accumulate to superbubbles because of their local concentration still in the star-forming sites and their short lifetimes, while SN type Ia occur as isolated effects on long timescales (Matteucci & Recchi 2001) and are more distributed over the ISM on larger scales.

After the confirmation of the existence of a hot ISM phase as predicted by Spitzer (1956) and an observational baseline of SN remnants (SNR) over decades (Woltjer 1972), the importance to understand SNR (Chevalier (1974)) and their relevance for the energy, dynamics, and mass budget of the ISM phases (McKee & Ostriker 1977) and for the non-dynamical matter cycle as interplay of gas phases (see e.g. Habe, Ikeuchi, & Takaka (1981), Ikeuchi & Tomita (1983)) moved into the focus of ISM and galactic research in the 70's. With a toy model consisting of 6 ISM components and at least 10 interchange processes Ikeuchi, Habe, & Tanaka (1984) included SF from giant molecular clouds after their formation from cool clouds, which are swept-up and condensed in SN shells. By this, SF and SN explosions together with different gas phases form a consistent network of interaction processes. As a reasonable effect of this local consideration the SF oscillates with timescales determined by the gas density and the interaction strengths.

Taking single SNR models into account, e.g. Chevalier (1974), Cioffi & Shull (1991) modelled the evolution and volume filling of randomly distributed and temporally exploding SNe with SNR cooling and expansion and with mutual transitions between the warm and cool gas phases. Since it is obvious that this hot SN gas dominates energeticly and kineticly the ISM, the detailed understanding of its interaction with the cool gas, its cumulative effect as superbubbles, and the dynamical structuring of galactic gas disks (comprehensively reviewed by Spitzer, 1990) is of vital importance for the evolution of galaxies. Because SN interactions happen on largely different length and time scales such studies have to cover a large variety of aspects (Chevalier 1977) reaching from the stirr-up of the ISM by turbulence (this sect.), by this, regulating the galactic SF, to the triggering of SF (sect. 2.2), and at least to the gas and element loss from galaxies (sect. 3).

First dynamical approaches to the structure evolution of the ISM and gas disks, aiming at understanding the disk-halo connection were performed by Rosen & Bregman (1995). As heating sources they took the energy of massive stellar winds only into account, but overestimated their impact on the ISM because highly resolved numerical studies reveal surprisingly low energy transfer efficiencies (Hensler 2007). Nonetheless, their models show the compression of gas filaments and the expulsion of gas vertically from the disk even under self-gravity.

The influence of SNe on the SF can be imagined by two measures: the expansion of hot gas, its deposit of turbulent energy (Mac Low & Klessen 2004), and its evaporation of embedded cool gas should, at first, lead to the suppression of SF, while vice versa the sweep-up and condensation of surrounding gas in the shells of SNRs and superbubbles could trigger SF. That hot SN gas regulates SF thermally has been demonstrated by Köppen, Theis & Hensler (1998) who analysed the equations of a multi-component system when thermal conduction accounts for gas-phase transitions (see fig. 1).

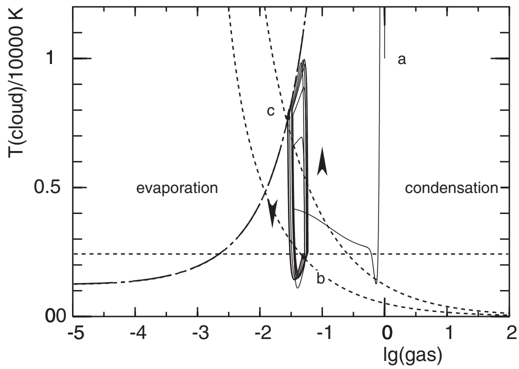

Figure 1. Evolution of the full system of cold+hot gas from the initial state ('a') until the completion of the first few oscillations (solid line). The dashed lines descending to the right are the loci where the system switches from evaporation to condensation (lower curve, at 'b') and vice versa (at 'c'). The horizontal dashed line is the locus of the evaporation funnel and the dot-dashed curve depicts the condensation funnel. *(for details see Köppen, Theis & Hensler (1998)).*

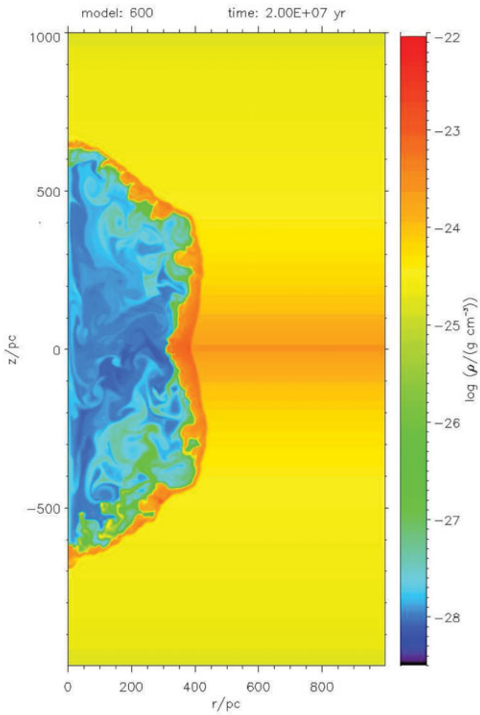

Figure 2. Density distribution of a superbubble after almost 20 Myrs. The superbubble results from 100 supernova typeII explosions of stars in the mass range between 10 and 100 $M_\odot$. The temporal sequence of explosions happens according to the lifetimes of massive stars with a Salpeter IMF. The star cluster is located at the origin of the coordinates. The galactic disk is vertically composed of the three-phase interstellar medium, cool, warm, and hot phase, respectively, with (central density ρ_0 [$in\, g\, cm^{-3}$]; temperature T [$in\, K$]; scaleheight H [$in\, pc$]) of (2×10^{-24}; 150; 100), (5×10^{-25}; 9000; 1000) (1.7×10^{-27}; 2×10^6; 4000). The density varies from almost $10^{-23}\, g\, cm^{-3}$, in the densest part of the shell to $2 \times 10^{-28}\, g\, cm^{-3}$ in the darkest bubble interiors. *(from Gudell 2002)*

In more comprehensive numerical investigations of the ISM evolution Slyz *et al.* (2005) studied the influence of SF and SN feedback on the SFR with self-gravity of gas and stars. As the main issues one can summarize that feedback enhances the ISM porosity, increases the gas velocity dispersion and the contrasts of T and ρ, so that smaller and more pronounced structures form, and, most importantly, that the SFR is by a factor of two higher than without feedback.

At the same time, de Avillez & Breitschwerdt (2004) simulated the structure evolution of the solar vicinity in a $1 \times 1 \times 10\, kpc^3$ box and identified the Local Bubble and its

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neighbouring Loop I in their models as well as the vertical matter cycle. In addition, filamentary neutral gas structures become visible where SF of low-mass star clusters (see next sect.) resulting from the production of gas shells by local SNe express the positive SN feedback. Since their ISM processes do not include SF self-regulation processes by stellar radiation and winds as well as heat conduction, they lack of negative SF feedback.

2.2. *Star-formation triggering*

SN and stellar wind-driven bubbles sweep up surrounding gas, condense it, and could, by this, trigger SF in a self-propagating manner as a positive feedback. The perception of SF trigger in SN or superbubble shells sounds reasonable from the point of view of numerical models because shock front compression as shown by Chevalier (1974) and sufficient swept-up mass from the ambient ISM (as shown in fig. 2 preferably in the gas disk itself) lead to cooling and gravitational instabilities. This mechanism, however, is not generally confirmed by observations. Shell-like distributions of young stars, are e.g. found in G54.4-0.3, called *sharky* (Junkes, Fürst, & Reich 1992), in the Orion-Monoceros region (Wilson *et al.* 2005), more promising in the Orion-Eridanus shell (Lee & Chen 2009), and in several superbubbles in the Large Magellanic Cloud, as e.g. Henize 206 (Gorjian *et al.* 2004). The SF associated with the SNR IC443 (Xu, Wang, & Miller 2011) raises e.g. the already above-mentioned question, whether SNR-triggered SF is capable to lead to massive star clusters which fill the whole stellar mass function equally, because here only about $10^4 M_\odot$ of molecular gas is involved. Also the formation of Gould's Belt as site of low-mass stellar associations in the shell of a superbubble is most probable (Moreno, Alfaro, & Franco 1999).

Such SF trigger by the condensation of swept-up gas in SN or more efficiently in superbubbles (see fig. 2) can be explored in detail by the investigation of the fragmentation timescale (see e.g. Ehlerova *et al.* 1997, Fukuda & Hanawa 2000). Ehlerova *et al.* compared a self-similar analytical solution with the results of 3D numerical simulations of superbubble expansions in homogeneous media. The amount of energy supply from the final number of young stars in an OB association, the value of the sound speed, the stratification and density of the ambient medium, the galactic differential rotation, and the vertical gravitational force in the galactic disk, all these influence the fragmentation. The typical superbubble radius, at which shells start to fragment, decreases from almost 700 pc at an ambient gas density of 1 cm^{-3} to 200 pc at 10 cm^{-3}. While in thick disks like they exist in DGs nearly the whole shell fragments, so that the SF may propagate in all directions, in thin disks it is restricted to gas layer around the galactic equator only. Since the applied thin shell approximation is reasonably only a 0th-order approach, in a recent paper Wünsch *et al.* (2010) clarify that the shell thickness and the environmental pressure influences the fragments in the sense that their sizes become smaller for higher pressure. Nevertheless, the deviations from the thin-shell approximations are not large.

Since these studies do not allow for the inhomogeneity of the ISM, another possible feedback effect by SN can be caused, when the ultra-fast SNR shock overruns a dense interstellar cloud, so that the clouds are quenched (Orlando *et al.* 2005). Stars should be formed instantaneously by such cloud crushing, and the cloud mass determines the star cluster mass.

2.3. *Supernova energy impact*

Although numerical simulations have been performed to understand the heating (or energy transfer) efficiency $\epsilon_{\rm SN}$ of SNe (Thornton *et al.* 1998), superbubbles (e.g. Strickland *et al.* 2004), and starbursts (Melioli & de Gouveia Dal Pino 2004), they are yet too simplistic and mostly spatially poorly resolved to account for quantitative results. Thornton *et al.* derived an efficiency $\epsilon_{\rm SN}$ of 0.1 from 1D SN simulations as already applied by chemo-dynamical galaxy models (Samland, Hensler & Theis 1997), while unity is also used in some galaxy models (see sect. 3), but seems far too large.

3. Supernovae and Galaxy Evolution

3.1. *Supernova parametrization in numerical models*

Because of their high power in various forms, massive stars are usually taken into account as the only heating sources for the ISM in galaxy evolution models and here mostly only the energy deposit of SNII explosions alone. Recently, Stinson *et al.* (2013) envoked indeed the necessity of short-term SF feedback which is naturely implied by massive stellar radiation and winds but was already included in the chemo-dynamical prescription (see e.g. Samland, Hensler & Theis 1997). It must be explored, however, how effectively this energy is transferred into the ISM as turbulent and finally as thermal energy. Although it is generally agreed that the explosive energy E_{SN} of an individual SN lies around 10^{51} ergs with significant uncertainties of probably one order of magnitude, the energy deposit is still more than unclear, but is one of the most important ingredients for galaxy formation and evolution (e.g. Efstathiou 2000, Silk 2003). Massive stars do not disperse from their SF site and thus explode within the stellar associations, by this, contributing significantly to the ISM structure formation e.g. by cavities and holes in the HI gas and chimneys of hot gas. On large scales SNeII trigger the matter cycle via galactic outflows from a gaseous disk. By this, also the chemical evolution is affected thru the loss of metal-enriched gas from a galaxy (for observations see e.g. Martin, Kobulnicki & Heckman (2002), for models e.g. Recchi & Hensler (2006b)).

Although numerical experiments of superbubbles and galactic winds are performed, yet they only demonstrate the destructive effect on the surrounding ISM but lack of self-consistency and a complex treatment. Simulations of the chemical evolution of starburst DGs by Recchi *et al.* (2002, 2006a), that are denoted to reproduce the peculiar abundance patterns in these galaxies by different SF episodes, found, that $\epsilon_{\rm SN}$ can vary widely: it starts with 10% drops and increases successively but not above 18% (Hensler 2011). For the subsequent SNIa explosions, always single events, $\epsilon_{\rm SN}$ is much smaller, i.e. below 1%. Moreover, if a closely following SF episode (might be another burst) drives its SNII explosions into an already existing chimney of a predecessor superbubble, the hot gas can more easily escape without any hindrance and thus affects the ISM energy budget much less. Recchi & Hensler (2006a) found that depending on the galactic HI density the chimneys do not close before a few hundred Myrs.

Since $\epsilon_{\rm SF}$ must inherently depend on the local conditions so that it is high in bursting SF modes, but of percentage level in the self-regulated SF mode, numerical simulations often try to derive the "realistic" SFE by comparing models of largely different $\epsilon_{\rm SF}$ with observations, as e.g. to reproduce gas structures in galaxy disks and galactic winds (e.g. undertaken by Tasker & Bryan (2006, 2008) with $\epsilon_{\rm SF} = 0.05$ and 0.5). In addition, specific SN energy deposit $\epsilon_{\rm SN} \times E_{SN}/M_*$ by them is fixed to 10^{51} erg per 55 $M_\odot$ of formed stars (1.8×10^{49} erg $M_\odot^{-1}$ by Dalla Vecchia & Schaye (2008)), but their results cannot ye tbe treated quantitatively, since they also mismatch with the Kennicutt relation. Stinson *et al.* (2006) performed a comprehensive study about the influence of $\epsilon_{\rm SN}$ over a large scale of values and also of the dependence on the mass resolution of their SPH scheme GASOLINE of galaxy evolution. Although their results demonstrate the already expected trends, more realistic treatments must adapt $\epsilon_{\rm SN}$ self-consistently to the local state of

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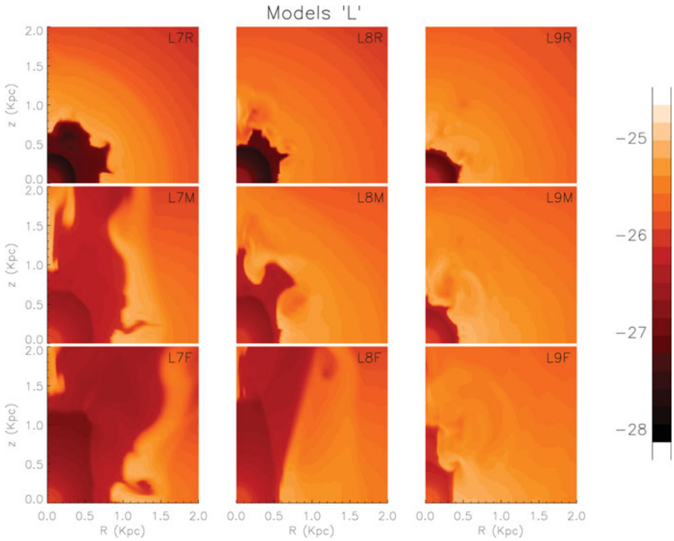

Figure 3. Gas density distribution for the 9 models of the of 60%-initial gas fraction (L) after 200 Myr of evolution. The first column represents models with $10^7 M_\odot$ of initial baryonic mass; the middle column shows the gas distribution of $10^8 M_\odot$ models, and the right column the $10^9 M_\odot$ models. The top row models are characterized by a roundish initial gas distribution (R; with b/a = 5), the middle row by b/a = 1 (M), and finally the bottom row represents flat disks with b/a = 0.2 (F). At the top-right corner of each panel the model designation is also indicated. The right-hand strip shows the (logarithmic) density scale (in g cm^{-3}). *(from Recchi & Hensler 2013)*

the ISM what requires much larger numerical capacity for more intensive high-resolution numerical simulations.

Theoretical studies by Elmegreen & Efremov (1997) achieved a dependence of $\epsilon_{\rm SF}$ on the external pressure, while Köppen, Theis, & Hensler (1995) explored a temperature dependence of the SFR both effects affecting the SFR. Furthermore, most galaxy evolutionary models at present lack of the appropriate representation of the different ISM phases allowing for their dynamics and their direct interactions by heat conduction, dynamical drag, and dynamical instabilities thru forming interfaces, not to mention resolving the turbulence cascade.

3.2. *Superbubbles and galactic winds*

A superbubble expanding from a stellar association embedded in a HI disk has, at first, to act against the surrounding medium, by this, is cooling due to its pressure work and radiation, but compresses the swept-up shell material and implies turbulent energy to the ISM. How much the superbubble expansion is efficiently hampered depends on the surrounding gas density and pressure, the HI disk shape (Recchi & Hensler 2013), and the energy loss by radiative cooling. From fig. 3 it is discernible that only flat gas disks of preferably low-mass galaxies allow a hot wind to escape from the galaxy. Consequences for the chemical evolution are in the focus of those models (Recchi & Hensler 2013). And finally, observed superbubbles also reveal a mismatch of their spatial extent and the energy content required to drive the expansion with the observed X-ray luminosity (Hensler *et al.* 1998). This fact can be only explained by a significant energy loss.

4. Conclusions

The dominating influence of SN explosions on structure, dynamics, and energy budget of the ISM are obvious and agreed. Signs and strengths of these feedback effects are, however, widely uncertain. Whether the feedback is positive (trigger) or negative (suppression) can be understood analyticly from first principles, but because of the non-linearity and the complexity level of the acting physical plasma processes clear results cannot be quantified reliably. In addition, the temporal behaviour varies by orders of magnitude because of the changing conditions. In summary, the energy transfer efficiency of SN energy to the ISM energy modes is much below unity and must not be overestimated, but also depends on the temporal and local conditions.

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Discussion

Cesarsky: Cosmic Ray and magnetic fields potentially play a big role in some of the process you were discussing, fragmentation, bubble formation and especially galactic winds. Were they considered in some of the models you discussed?

Hensler: Not yet. The actually treated complexity of the ISM processes of multi phases, SF, and star-gas interactions is already challenging the high-performance computing capacity.

Zhou, P.: Is there any clear observational evidence to prove that star formation could be triggered by SNR? How to distinguish the SNR impacts from progenitor wind impact?

Hensler: This observational evidence seems to exist, but obviously not in general. This means that local conditions determine the possibility of SF triggering. From models of wind-blown and radiation-driven HII regions the stellar wind impact seems not to sweep-up and compress the surrounding gas sufficiently; see e.g. Freyer, Hensler, & Yorke, 2003, *ApJ*, 594, 888 and 2006, *ApJ*, 638, 262.

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