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High-energy phenomena in massive star-forming regions and localized acceleration of cosmic rays

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Abstract. In massive star-forming regions, the evolution of massive stars ($M_\star > 20 M_\odot$) forming "OB associations" is so rapid that they explode as supernovae close to their birth-places, the molecular clouds. Before reaching this final stage, they lose a significant fraction of their mass via dense stellar winds. The result is a feedback effect, in the form of vast hot plasma bubbles filling the star-forming region. If supernovae explode in the pre-existing wind cavities, cosmic rays may be inefficiently accelerated or convected away by the hot gas. When supernovae collide with molecular clouds, there is observational evidence that they are powerful cosmic-ray accelerators : at high energies, they induce GeV-TeV gamma-ray emission; at low energies, they induce enhanced ionization and peculiar chemistry, as recently demonstrated using mm telescopes. As a result, the high-energy life of an OB associations is made up of successive phases of long (Myr) quiescent, wind-dominated phases, interrupted by temporary (< 0.1 Myr) episodes of supernova-dominated phases, possibly characterized, under certain conditions, by an intense, localized acceleration of cosmic rays and visible in GeV-TeV γ-rays.

Key words. Massive stars – stellar winds – supernova remnants – γ-ray sources – cosmic rays

1. Introduction

The association between high-energy γ-ray sources and supernova remnants interacting with molecular clouds has been known since the early days of γ-ray astronomy (e.g., $COS - B$ survey of the galactic plane, Montmerle 1979). The γ-ray emission mechanism is π^o-decay, following, on smaller spatial scales, the dominant γ-ray emission mechanism in the Galaxy resulting from collisions of galactic cosmic rays (hadrons) with interstellar matter, mainly molecular (and also atomic) hydrogen. This indicates that such γ-ray sources hold the potential to study in situ cosmic-ray acceleration by supernova shocks.

New data from GeV-sensitive satellites (*Compton*-GRO and more recently *Fermi*), and also from ground-based TeV sensitive Čerenkov telescopes have confirmed that massive star-forming regions (and their associated molecular clouds) housing a supernova remnant are indeed a class of GeV-TeV γ-ray sources. At the same time, because massive stars react on the surrounding medium by way of their strong stellar winds, massive star-forming regions are filled with a hot, X-ray emitting plasma, in which supernovae explode,

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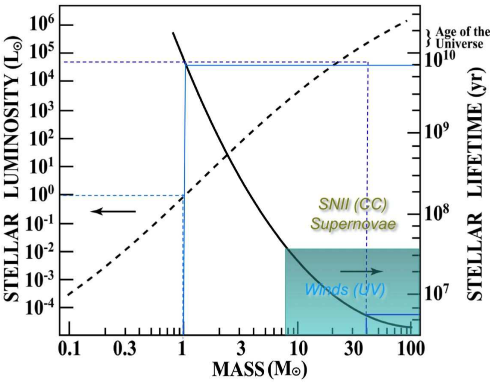

Fig. 1. Stellar luminosities (left scale) and lifetimes (right scale) as a function of mass. Stars with masses $M_\star \gtrsim 8M_\odot$ undergo strong winds before exploding as "core-collapse" supernovae. Stars more massive than $\gtrsim 30M_\odot$ live less than 5 Myr.

creating specific conditions for shock propagation, hence for cosmic-ray acceleration.

In this paper, we will briefly review the main features of massive star evolution, the related feedback effects on the ambient medium, and finally some aspects of the interaction of supernova remnants with molecular clouds (as birthplaces of massive stars), especially at low energies.

2. The evolution of a massive star-forming region in a nutshell

In the present context, we define a "massive star" as a star ending its evolution in a supernova explosion, i.e., more massive than $\sim 8M_\odot$. The lifetime of massive stars depends strongly on their mass: as illustrated in Fig. 1, an $\sim 8M_\odot$ star lives ~ 50 Myr, but stars more massive than $\sim 30M_\odot$ live less than 5 Myr, i.e., explode before the massive star-forming region (SFR) in which they are born is dispersed (e.g., Maeder & Meynet 2010). Also, before the final explosion takes place, i.e., during several Myr, the strong UV radiation resulting from the high effective temperatures ($T_{\rm eff} > 100$ kK) accelerates intense stellar winds (velocities up to several 1000 km s^{-1}, mass-loss rates up to several $10^{-6} M_\odot$ yr^{-1}; see, e.g., Kudritzki & Puls 2000; Puls, this volume).

On the other hand, massive stars are generally found in clusters, called "OB associations" (from the most luminous, hence most massive, spectral stellar types) of several members up to several thousand members. The stellar masses range from very low mass stars ($M_\star \sim 0.1M_\odot$ or less: brown dwarfs) to a maximum mass M_{max}, following (above $M_\star \sim 1M_\odot$) a power-law: this is the so-called "IMF" (for "Initial Mass Function"). Several studies, starting from the pioneering work of Salpeter (1955), give the number of stars $N(M_\star)$ having a given mass $M_\star$ in the logarithmic form $dN/d(\log M_\star) \propto M_\star^\alpha$, with $\alpha \sim -2.35$: the larger M_{max}, the more numerous the OB association (e.g., Kroupa 2007). The largest possible stellar mass is still debated, although (for our purpose at least) it is generally considered that no star of mass larger than $\sim 120M_\odot$ can be stable, owing to the very large radiation pressure and the ensuing very high mass loss and "evaporation" of the star.

The population synthesis of an OB association with $M_{max} = 120M_\odot$ and a standard IMF, as a function of time, have recently been studied by Voss et al. (2009). Of interest here is the energetics (mainly their Fig. 6): one clearly sees, during the first 3-4 Myr, a "stellar wind-dominated" ("SW" for short) phase, until the first supernova explosion occurs (corresponding to the most massive star). Then follows a "supernova-dominated" phase ("SN" for short), since the wind power declines as the massive stars disappear (until about 10 Myr). Interestingly, the total kinetic energy output (winds + supernovae) remains approximately the same throughout (at a level of $\sim 10^{36}$ erg s^{-1} in this example). In the Voss et al. study, the supernova energy output is continuous (because the IMF is continuous), but in reality supernova explosions occur in a discrete fashion, both in space (in the association) and in time (say every Myr on average); in this type of environment, supernova remnants (SNR) live only $\sim 10^5$ yrs. By contrast, although decreasing with time, stellar winds are always present, also both in space (following the distribution of massive stars), and in time (until ~ 10 Myr).

For our purpose here, from the point of view of the putative cosmic rays accelerated by supernova shocks and interacting with molecular clouds, we can therefore distinguish three phases and two "modes" of evolution of an OB association (or equivalently, of a massive star-forming region: MSFR) :

(*i*) very young MSFR (age $\lesssim$ 3 Myr; the actual number depends on M_{max}): *SW phase*;

(*ii*) young MSFR (age between $\sim$ 3 and $\sim$ 10 Myr): *alternating SN and SW phases*; roughly, we take their duration to be: $t_{SN} \approx 10^5$ yrs, and $t_{SW} \approx 10^6$ yrs;

(*iii*) evolved MSFR (age $\gtrsim$ 10 Myr): stellar winds have essentially disappeared, as have most molecular clouds: supernova-molecular cloud interactions are less likely to occur at this late stage.

In other words, in this (obviously) simplified scheme, on average, young OB association spend 90% of the time in a SW phase, and 10% of the time in a SN (or "SNOB", Montmerle 1979) phase. As a result, very roughly, observing OB associations in the Galaxy, one has a $\approx$ 1/10 chance to find a SNR associated with it, or, said otherwise, at any time in the Galaxy, $\approx$ 10% of OB associations (or MSFR) are hosting a SNR. Therefore, if cosmic rays are accelerated *in situ* by SNR in MSFR, resulting in γ-ray emission by π^o -decay (see below), then we expect $\approx$ 10% of OB associations to be γ-ray sources ! (Of course, depending on intrinsic CR intensity, cloud mass, and distance to OB associations, not all such γ-ray sources will be detectable.)

3. Feedback from massive stars: hot plasmas

Whether in the SW or SN phases, the ambient ISM of OB associations is dominated by high-speed ($\times 100$ to $\times 1000$ km s^{-1}) shocks: standing shocks for the outflowing material of stellar winds, and moving shocks of supernova remnants. The most visible outcome of such a feedback from stars on the ambient ISM is to generate large volumes of hot, low-density, X-ray emitting plasmas ("plasma bubbles" for short) (e.g., Montmerle 2011). As a result, while some SNR may interact with molecular clouds (i.e., a cold, high-density ISM), others will propagate in a hot, low-density ISM.

The observational evidence for the existence of such hot bubbles in MSFR is comparatively recent. Indeed, while the theoretical existence of hot bubbles due to stellar winds has been predicted long ago (Castor et al. 1975), in MSFR the observational difficulty of interpreting extended X-ray emission was to distinguish between truly diffuse emission and unresolved emission from hundreds or thousand of low-mass stars ("T Tauri" stars, having $M \lesssim 2M_{\odot}$, included in the IMF), emitting X-rays as a result of solar-like magnetic activity (e.g., Feigelson & Montmerle 1999). The evidence was found at last with the *Chandra* X-ray satellite, which, owing to the superb spatial resolution of its $17' \times 17'$ images (down to 0.17" along the axis), could distinguish -hence, allow to suppress- stellar from diffuse emission. The first MSFR which revealed wind-powered hot bubbles were young ($\lesssim$ 3 Myr) nebulae, without SNR: M17 and the Rosette nebula (Townsley et al. 2003). The $XMM-Newton$ satellite could also reveal the diffuse X-ray emission of the famous, nearby Orion nebula (Güdel et al. 2008). Other young MSFR are also known to be diffuse X-ray emitters (e.g., Townsley 2011a).

In these regions, the X-ray emission is well explained by wind-shock heated material. Because the wind velocities are high (> 1000 km s^{-1}), the X-ray temperatures are relatively high ($T_X \sim 1$ keV). The plasma densities are low ($n_e < 1$ cm^{-3}, and the X-ray luminosities are of order $L_X \sim 10^{-4} L_W$, where L_W is the total wind kinetic power. Note that, if O stars are grouped in tight sub-clusters, wind-wind collisions also contribute, but at higher X-ray temperatures (as is the case for M17, for instance).

Since the plasma temperatures and densities are measured, it is easy to determine the bubble pressure: it is found to be comparable, within a factor of 2 or so, to that of the ambient dense medium (ionized, photodissociation regions, or molecular clouds). This confirms what the X-ray images suggest, i.e., that the X-ray plasma is confined by the dense material, leaving the MSFR without exerting any significant pressure, but flowing out into the ambient hot ISM (like the Extended Orion Nebula, shown in Fig. 2, flow-

Fig. 2. An X-ray bubble in the Extended Orion Nebula. The hot gas, mapped with XMM-Newton (unpublished update of Güdel et al. 2008) is colored in blue, while the Orion cavity is clearly visible in this ~ $40' \times 40'$ Hα image. Stellar X-ray sources have been removed. The glowing ionized gas in the Trapezium region (upper left) is seen to absorb the X-rays, implying that it is actually located *in front* of the bubble, as is the "Orion Bar": the X-ray emission yields a 3D view of the cavity. Evidence for outflowing gas comes from X-ray "lips" in front of the lower edge of the cavity.

ing into "Eridanus Superbubble", as discussed by Güdel et al. 2008).

Because of this ubiquitous contribution of stellar winds in MSFR, SNRs may be difficult to detect in X-rays, and even to detect at all. One reason is that the physical parameters (T_X, n_e, etc.) of a wind plasma are very comparable to those of an SNR plasma. A case in point is the Carina Nebula, which has been surveyed in a mosaic of 22 contiguous *Chandra* fields, covering ~ 1.4 sq. deg. (Townsley et al. 2011b). The nebula is home to a mixture of several sub-clusters of massive stars of various ages (Feigelson et al. 2011), and the origin of the large-scale diffuse X-ray emission is not completely clear. While winds are likely the dominant contributor in some areas, the discovery of a neutron star not far from the central regions of the nebula (Hamaguchi et al. 2009) indicates that at least one supernova has already exploded, perhaps 1 Myr ago. Another indication for this supernova (or another) comes from a Fe enhancement in the central region (Townsley et al. 2011b). No other indication, at any wavelength, exists in the Carina Nebula, which shows that supernovae may have exploded in MSFR, but leaving no or a hardly visible remnant today. Interestingly, there is no evidence that the Carina Nebula is a γ-ray source, suggesting that no CR are accelerated in such an environment, or at least, that no CR interact with the dense material confining the X-ray plasma.

Therefore, it may well be that, for SNRs to be visible (hence, simply to exist) and accelerate CR, the SN explosions have to take place at the *edge* of the plasma bubbles, in order to generate visible shock waves and interact with the molecular clouds that confine the hot plasma. If so, this clearly restricts the number of cases in which the SN phase may have observable consequences like γ-ray emission.

4. Supernova remnant-molecular cloud interactions

When an SNR shock wave penetrates into a molecular cloud, the physical conditions of the shock and its consequences are quite different than in the low-density ISM.

First, once the shock propagates in a dense medium ($n_H \sim 10^4 \mathrm{cm}^{-3}$ for a typical molecular cloud), radiative losses become important and the shock slows down, from a few 1000 km s^{-1}, say, to ~ 100-200 km s^{-1}. This is also why the lifetime of these SNRs is shortened, from a typical ~ 10^6 yrs in the low-density ISM, to less than ~ 10^5 yrs. At these relatively low velocities, the OH molecule is the seat of a characteristic, maser emission observable in the radio-cm band, at 1720 MHz.

Second, particle acceleration (hadrons and leptons, via diffusive shock acceleration or similar mechanisms), gives rise to two different interaction regimes. (*i*) At relativistic energies, hadrons (mainly protons) collide with cold molecules (mainly H_2) and generate γ-rays (by π^o decay), as do high-energy electrons, either by bremsstrahlung or by the Inverse Compton (IC) effect (which may be important in the case of OB associations be-

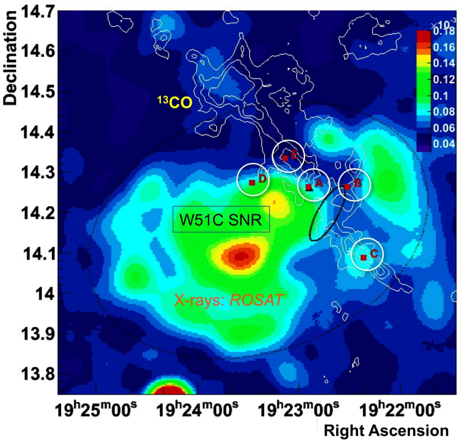

Fig. 3. The W51C SNR (bright X-ray emission, detected by ROSAT), interacting with molecular clouds (^{13}CO contours). The lines of sight observed by Ceccarelli et al. (2011) to search for enhanced ionization in the cloud are indicated (letters A to E). An enhancement factor of ~ 120 was found at position E. (Fig. courtesy A. Fiasson; see text for details.)

cause of the intense stellar radiation field). (*ii*) Since the particles are accelerated all the way from low energies up to relativistic energies, the low-energy component (mainly protons and electrons) is also important: it *ionizes* the molecular material, inducing a chemical reaction network involving many radicals.

Therefore, molecular clouds and/or star-forming regions associated with bright γ-ray sources can probe enhanced high-energy cosmic-ray (CR) densities, although the dominant mechanism (π^0-decay or IC) is often not easy to pin down. The advent of ground-based Čerenkov telescope arrays (HESS, MAGIC, VERITAS, etc.), and of the *Fermi* satellite, with their improved sensitivity and spatial resolution in the GeV–TeV energy interval, have relaunched the hunt for γ-ray sources associated with SNRs interacting with or close to molecular clouds (e.g., Montmerle 2010), with the hope to identify localized sites of CR acceleration, and thus to test theoretical predictions (acceleration efficiency, spectrum, diffusion coefficient, etc.). However, as mentioned above, the main difficulty remains to distinguish between protons and electrons on the basis of γ-ray spectral information. Even in such well-documented cases as the IC443 (Albert et al. 2007) and W28 (Aharonian et al. 2008) SNRs, the GeV-TeV emission mechanism remains unclear. In more favorable cases (in particular for W51C; Abdo et al. 2009; Feinstein et al. 2009: Méhault, this volume) the π^0-decay appears to be the dominant γ-ray emission mechanism. In these cases, the derived relativistic proton fluxes are very high, typically one to two orders of magnitude higher than the average galactic proton flux, strongly suggesting an efficient high-energy CR shock acceleration by the associated SNR, or re-acceleration (eg Uchiyama et al. 2010) of pre-existing CRs .

5. Cosmic-ray induced molecular cloud ionization

Such high CR flux densities should also have visible effects at lower energies ($\lesssim$ 1 GeV), in the regime where CR ionize molecular clouds (e.g., Gabici et al. 2009, Fatuzzo et al. 2010). Ceccarelli et al. (2011) have proposed a new method to demonstrate the *physical interaction* between SNR-accelerated low-energy particles and molecular gas, where an association is suggested at high energies by the presence of a π^0-decay TeV source. The method is based on the determination of the ionization degree of the molecular cloud, which in turn gives a measure of the CR ionization rate ζ (to be compared with the "standard" value $\zeta_0 \sim 10^{-17}$ s^{-1} for dense clouds; Glassgold & Langer 1974).

In dense gas, the ionization is usually obtained by measurements of the DCO$^+$/HCO$^+$ abundance ratio, which can be shown to be an almost direct measure of the ionization degree ($x_e = n_e/n_H$) (e.g. Guélin et al. 1977; Ceccarelli, this volume). The method has been extensively applied in molecular clouds and dense cores. The measured values of x_e range between 1×10^{-8} and 1×10^{-6}, depending on the gas density, leading to estimates of ζ between 10^{-18} and 10^{-16} s^{-1} (Caselli et al. 1998). Also, Indriolo et al. (2010) recently reported line absorption observations of H_3^+, a measure of the ionization in *diffuse gas*, in the outer parts of the molecular cloud associated with

IC443. Their measurements indicate values of ζ only five times larger than for average diffuse clouds.

In contrast, using the W51C SNR and its interaction with a molecular cloud (see above), Ceccarelli et al. (2011) have reported observations of the DCO$^+$/HCO$^+$ ratio towards the *dense gas* of this cloud, near the location where the SNR penetrates the cloud (as indicated in Fig. 3), as testified by OH maser emission. They readily found that the "overionization" derived by this simple analytic method is very large ($\zeta \gg 100 \times \zeta_0$). In this case, however, the chemistry becomes more complex as new channels open, and a more sophisticated approach, using a complex network of chemical reactions (Le Bourlot et al. 1993, Le Petit et al. 2006), has to be used. As a result, a chemically more reliable value of $\zeta \simeq 120\zeta_0$ was found at position E (see Fig.3). This is consistent with a strongly enhanced high-energy CR density implied by the γ-ray source (Feinstein et al. 2009), and unequivocally demonstrates that the SNR does accelerate (low-energy) CR in the vicinity of the shock.

6. Conclusions

The association between γ-ray sources and supernova remnants interacting with molecular clouds is now well established, at least for a few, well-known objects. Whereas it is still not absolutely proven that relativistic hadrons are efficiently accelerated by their shocks (see, e.g., Gallant, this volume), the evidence for enhanced molecular cloud ionization in such an environment is certainly a big step towards the proof –at least for low-energy particles. However, such an environment represents only a fraction ($\approx$ 10 %) of the lifetime of an OB association. This fraction may even be smaller for π^0-decay γ-ray source emission, if topological conditions, such as the necessity for SN explosions to take place near the edge of the hot cavities to accelerate and inject CR into the surrounding dense material, must be met. This makes such γ-ray sources all the more valuable as laboratories to study CR acceleration, and also to probe unusual, ionization-dominated cloud chemistry.

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