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High-energy radiation generated by winds and shocks: SNRs and superbubbles

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Abstract. We discuss populations of X-ray and γ-ray sources in star-forming regions (SFR). Interacting winds of massive stars and high supernova activity in SFRs can be powerful sources of high energy emission. Models of nonthermal particle acceleration in the vicinity of active SFRs are reviewed. A class of hard emission sources where a fast wind from a massive star collides with a supernova shell is described. Stellar winds of massive stars and core collapsed supernova explosions with great energy release in the form of multiple interacting shock waves inside the superbubbles are argued as favorable sites of nonthermal particle acceleration. Young stellar objects and supernova activity in the dense environment of starforming regions produce an another potentially abundant class of hard faint X-ray sources due to interaction of fast moving knots with the dense ambient medium. The knots could have very different physical nature, e.g. supernova ejecta fragments or Herbig-Haro-like objects. We argue that the sources may have rather steep logN—logS distribution and can contribute substantially to the galactic diffuse emission including the both low-ionized 6.4 keV and He-like Fe lines.

Keywords. X-rays: ISM, acceleration of particles, ISM: bubbles, supernova remnants

1. Introduction

Energetic outflow events with fast shocks in a dense ambient medium should result in a rapid conversion of kinetic power into emission. The star-forming regions in galaxies are generically associated with molecular clouds and contain a variety of energetic outflows at different stages of massive star evolution from proto-stellar accreting objects through fast winds of massive OB or WR stars to the most energetic supernova events.

A spectacular example is an interaction of a supernova remnant (SNR) with a molecular cloud that manifests itself by a number of appearances in a wide range of wavelengths from radio to gamma-rays (e.g. Shull 1980, Wheeler *et al.* 1980). Propagation of a radiative shock wave driven by a supernova shell through a molecular cloud leads to a substantial non-thermal emission both in hard X-rays and in γ-rays. The complex structure of a molecular cloud consisting of dense massive clumps embedded into the inter-clump medium could result in localized sources of hard X-ray/γ-ray emission correlated with bright molecular emission. It has been shown that a hard X-ray and γ-ray emission region should consist of an extended shell-like structure (appearing also in radio as a shell of a relatively flat spectrum) related to the radiative shock and localized sources corresponding to shocked molecular clumps (Chevalier 1999, Bykov *et al.* 2000). The shocked clumps would have (sub)parsec scales and emit very hard X-ray continuum spectra with no strong radio counterparts.

Here we shall discuss different phenomena of SFR activity in the dense environment – a potentially abundant class of hard faint X-ray sources due to interactions of fast moving supernova ejecta fragments with dense medium and non-thermal sources powered by SNR shell interactions with a fast wind of a massive star.

2. X-ray emission of fast moving knots in SFRs

2.1. *Supernova ejecta fragments in SFRs and their X-ray emission*

Multiwavelength studies of SNRs have revealed a complex structure of metal-rich ejecta with the presence of fast moving isolated fragments of SN ejecta, interacting with the surrounding media. In the optical a few hundred fast moving knots (FMKs) were observed with *HST* outside the main shell of Cas A (e.g. Fesen *et al.* 2002; 2005) and in some other SNRs. Optical FMKs in Cas A are very abundant in O-burning and Si-group elements. They have a broad velocity distribution around 6,000 km s^{-1} and apparent sizes below 0.01 pc.

An appearance and detection probability of individual fast moving knots in the X-rays depend strongly on the ambient density. The optical knots in Cas A should have $\mathcal{L}_x < 10^{29}$ erg s^{-1} because of the low ambient density. Similar FMKs in the dense environment of the Galactic Centre (GC) region would have $\mathcal{L}_x \gg 10^{29}$ erg s^{-1} with bright IR counterparts.

In a low density medium only relatively large FMKs can be observed in X-rays individually, but since they are long-lived, their collective emission could be substantial. *Chandra* and *XMM-Newton* observations revealed a head-tail structure with a prominent Si line in the Vela shrapnel A, indicating that the object is a fast ejecta fragment of the size ∼0.3 pc, velocity about 1,000 km s^{-1} and $\mathcal{L}_x \sim 10^{31}$ erg s^{-1} (see e.g. Aschenbach 2002).

In a dense cloud, fast moving knots will be bright, but short-lived. IC 443 – a SNR interacting with a molecular cloud is an obvious candidate to search for X-ray knots in a dense cloud. Some of the hard X-ray sources detected with *XMM-Newton* and *Chandra* in the "molecular" SNR IC 443 are likely to be fragments of the SN ejecta. In Fig. 1 (left panel) we present a *Chandra* image of XMMU J061804.3+222732 - an isolated source interacting with a molecular cloud border in IC 443 (Bykov, Bocchino & Pavlov 2005). The source has an extended morphology with two compact cores. The morphology is consistent with that expected for a crushed supernova ejecta fragment (see e.g. 2D simulations by Klein *et al.* 1994). The source size is below 0.1 pc and $\mathcal{L}_x \approx 10^{32}$ erg s^{-1} in the (0.5-7) KeV band (at 1.5 kpc distance). It has a very hard spectrum of a photon index $\Gamma \lesssim 1.3$ with a prominent thermal component. Further multi-wavelength high resolution observations will finally establish the nature of the source in IC 443.

2.2. *X-ray knot ensemble and the Galactic ridge emission*

The observed X-ray emission of the Galactic ridge is known to contain an extended component which can not be accounted for by the resolved X-ray point sources (e.g. Tanaka 2002, Ebisawa *et al.* (2000)). Two basic possibilities exist — unresolved faint sources or truly diffuse emission. Thus the problem of the origin of the observed large scale X-ray emission from the Galactic ridge requires a careful study of possible classes of abundant hard X-ray sources with $\mathcal{L}_x \sim 10^{29}$ erg s^{-1}.

Recently Ebisawa *et al.* (2000) analyzed deep *Chandra* observation of the Galactic plane at $(l, b) = (28.5°, 0.0°)$ with flux limit down to $\sim 3 \times 10^{-15}$ erg cm^{-2} s^{-1} in 2-10 keV band and $\sim 2 \times 10^{-16}$ erg cm^{-2} s^{-1} in 0.5-2 keV band. The number of sources detected in the hard band is consistent with the extrapolation of the extragalactic $logN - logS$ distribution of index about 1.3. They concluded that the sum of all detected point sources accounts only for 10% of the total observed flux and that the X-ray emission from the galactic plane has a truly diffuse origin. The later conclusion was drawn on the basis of the assumption that if there exists a large population of faint yet unresolved sources it should

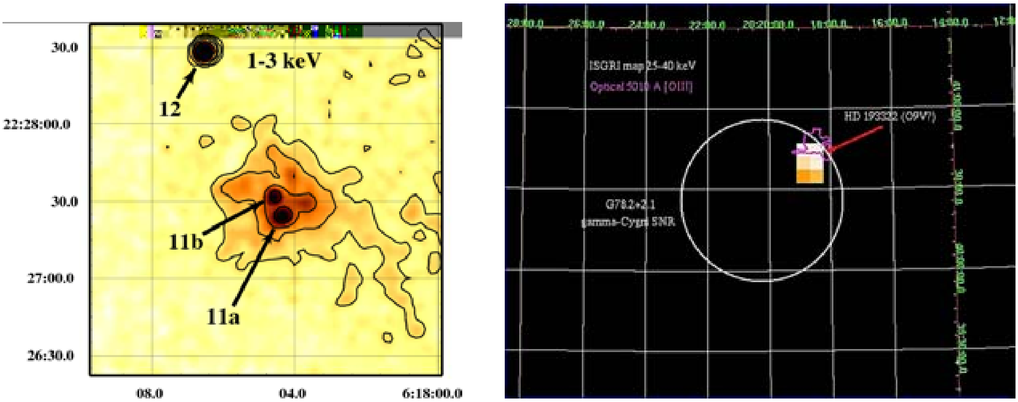

Figure 1. Left panel *Chandra* ACIS 1-3 keV image of XMMU J061804.3+222732 in the region of interaction of IC 443 SNR with a molecular cloud - a possible FMK.
Right panel *INTEGRAL ISGRI* 25-40 keV image of γ-Cygni SNR (Bykov *et al.* 2004). Optical [OIII] 5010 Å line contour (solid line) from Mavromatakis (2003). The SNR border (radio) is roughly indicated by the large solid circle. The arrow points to the position of the O9V star HD 193322 (20:18:07,+40:43:55). All maps are made for J2000. The source may originate from the SNR-O star wind interaction.

have rather flat $logN - logS$ distribution of index ∼1.3. We will show below, however, that some faint source populations may have much steeper distributions. Analyzing *XMM-Newton* observations covering three square degrees between $l = 19^\circ - 22^\circ$ and $b = \pm 0.6^\circ$ Hands *et al.* (2004) concluded that the integrated contribution of the detected galactic sources plus the extragalactic signal accounts for up to 20% of the observed surface brightness.

The Galactic center region was deeply studied with *Chandra* observatory (Muno *et al.* 2003, 2004; Park *et al.* 2004). With an about 600 ks *Chandra* exposure of a $17' \times 17'$ field in the GC region Muno *et al.* (2003) catalogued 2357 X-ray sources limited by the luminosity $\mathcal{L}_{\rm x} \gtrsim 10^{31}$ erg s^{-1} (2.0–8.0 keV). A substantial part of the positions of the *Chandra* sample sources is projected onto the Circum-Nuclear Disc (see e.g. Mezger *et al.* 1996) between 1.7 and 7 pc around the GC that contains $\sim 10^4 M_\odot$ of highly clumped matter. The sources have $logN - logS$ distribution of index $\alpha = -1.7 \pm 0.2$ which is substantially steeper than the indexes of the distribution at other galactic locations (c.f. Ebisawa *et al.* (2000)). A subclass of cataclismic variables - intermediate polars, was suggested by Muno *et al.* (2004) as a possible contributor of the sources in the sample, given their spectral properties. The properties of $logN - logS$ distribution of intermediate polars are not yet studied to draw the conclusion if the observed steep $logN - logS$ index can be extended down to the low luminosities ($\mathcal{L}_{\rm x} \sim 10^{29}$ erg s^{-1}) to account for the substantial diffuse component.

In this respect we discuss here a potentially numerous ensemble of X-ray point sources associated with fast moving knots. A very important distinctive feature of the X-ray emission of fast moving knots is a strong dependence of the knot luminosity $\mathcal{L}_{\rm x}$ on the ambient density. The knots can be metal-rich SN ejecta fragments (Bykov 2003) or alternatively they can result from some processes in accreting systems producing jets and ballistically moving isolated knots. An example is the Herbig-Haro flows in star formation regions. The flows may appear as parsec scale structures with the flow collimation depending on the young stellar object (YSO) mass. Most outflows from high-mass protostars are poorly collimated (e.g. Reipurth and Bally 2001).

An ensemble of unresolved knots can contribute substantially to the diffuse X-ray emission including the iron line emission observed from the Galactic Center region and the Galactic ridge.

An ensemble of hard X-ray point-like sources associated with fast moving supernova ejecta fragments is abundant and can account for the observed properties of the detected GC sources such as the hardness ratios and the logN–logS distribution.

We have simulated X-ray spectra of the FMKs of different velocities in the GC environment. In our model the hard X-ray emission of FMKs is due to both hot thermal postshock plasma and nonthermal particles accelerated at the bow shock. The particles propagate through a metal-rich clump, producing K-shell ionization line photons and hard nonthermal bremsstrahlung. It should be noted that most of continuum emission simulations made for the metal-rich supernova ejecta fragments are relevant to any kind of FMKs that do not necessarily originate from SN activity and thus have the standard composition. The knots could be ejected by compact objects like Sgr A*, YSOs or other objects. The X-ray line emission from metal-rich supernova ejecta fragments has specific features due to the substantial internal line resonant absorption effect. The efficiency of the bremsstrahlung non-thermal emission of the knot body is higher than that from the shocked ambient gas, because of high mean charge <Z> in the metal-rich knot.

The lifetime of an FMK in a dense media is an important factor in the study of the knot statistics. A fast moving knot decelerates due to the interaction with the ambient gas. The drag deceleration time of a knot of velocity v, mass $\mathcal{M}$ and radius $\mathcal{R}$ can be estimated as $\tau_{\rm d} \sim \mathcal{M}/(\rho_{\rm a} v \pi \mathcal{R}^2) \approx 10^3 \cdot \mathcal{M}_{-3}/(n_{\rm a2}\, v_8\, \mathcal{R}_{-2}^2)$ years. Here $\mathcal{M}_{-3} = \mathcal{M}/10^{-3}\, M_\odot$ and $\mathcal{R}_{-2} = \mathcal{R}/(0.01\mathrm{pc})$. The number density $n_{\rm a2}$ of the ambient matter is measured in $100\ \mathrm{cm}^{-3}$ and the FMK velocity v_8 is measured in 1,000 $\mathrm{km\ s}^{-1}$. In the inner $20'$ of the GC region the average number density $n_{\rm a} \gtrsim 100\ \mathrm{cm}^{-3}$ (e.g. Mezger *et al.* 1996) and the fragment deceleration time $\tau_{\rm d} \lesssim 10^3$years.

The high pressure gas behind the strong bow shock of a fast moving ejecta fragment could drive an internal shock resulting in the knot crush and fragmentation. In the case of an adiabatic bow shock the internal shock velocity $v_{\rm is} \approx v/\chi^{1/2}$, where the density contrast $\chi = \rho_{\rm k}/\rho_{\rm a}$, and $\rho_{\rm a}$ and $\rho_{\rm k}$ are the ambient gas and the dense fragment densities, respectively. The knot crushing time scale $\tau_{\rm c} = \mathcal{R}/v_{\rm is}$. There are 2D hydrodynamical simulations showing that the fast knot fragmentation occurs on the timescale of $\sim(3-4)\tau_{\rm c}$ (e.g. Klein *et al.* 1994). For the FMKs of mass $\mathcal{M}_{-3} \sim 1$ and $\mathcal{R}_{-2} \sim 1$ the fragmentation time scale is a factor of ∼2.5 less than the drag deceleration time. However, the FMK will be a source of hard X-ray emission even at the fragmented stage if the strong forward shock is still driven by the FMK.

The hydrodynamical estimation of the inner shock velocity $v_{\rm is}$ given above assumes an efficient conversion of the bow shock ram pressure to the knot internal shock energy. The effects of nonthermal particle acceleration reduce the postshock gas pressure and the internal shock velocity, thus increasing $\tau_{\rm c}$. In that case the life time would be close to $\tau_{\rm d}$, unless the ablation processes. The effect of magnetic fields and nonthermal particles on the knot ablation is not yet studied in any details.

Massive star winds would change the circum-stellar environment, creating caverns of low density matter. The lifetime of fast fragments of a SN in the low density cavern should be longer than $R_{\rm b}/v_{\rm k}$, where $R_{\rm b}$ is a wind bubble size. Following the approach of Chevalier (1999) and accounting for the high pressure of the GC ambient matter one may estimate the typical scale $R_{\rm b}$ ∼3 pc, for WR, while $R_{\rm b}$ is ∼1 pc for O9-B0 progenitor stars. The lifetimes of FMKs are $\sim10^3$ years. The collective effect of powerful stellar winds in compact associations could blow out a more extended cavern - superbubble, providing longer lifetimes for the fragments of the SNe exploded inside the cavern. Metal rich FMKs moving through the hot superbubble cavern can provide an efficient cosmic ray injection mechanism. We will discuss superbubbles in Section 3.

The X-ray spectra of the fragments are hard. They contain thermal and power law components with possible Fe lines. Both 6.7 and 6.4 keV lines are expected, depending on the FMK ionization structure and the relative strength of the nonthermal component. The total equivalent width is about 500 - 600 eV for a Fe mass of $\sim 10^{-4}\ M_\odot$.

Two or three SNRs during the last 1,000 years could produce an ensemble of more than 1,500 FMKs in the GC region providing a normalization of the logN–logS distribution consistent with the *Chandra* data in the Galactic Centre region. The filamentary features apparent in the *Chandra* images of the region could be also relevant to the SN activity.

Consider FMK ejecting events at a rate $\nu_{SN}(\vec{r}, t)$ with the total number $\mathcal{N}_\star$ of the ejected fragments per event. A simplified order-of-magnitude estimation of the summed contribution to the galactic X-ray emission from an ensemble of fast moving supernova ejecta fragments can be made using the relation $L_x \propto \mathcal{N}_\star \cdot \nu_{SN} \cdot \tau_d \times \mathcal{L}_\mathrm{x}$. The thermal component of X-ray luminosity for a knot of velocity above 1,000 km/s scales with $\mathcal{L}_\mathrm{x} \propto n_\mathrm{a}^2\, \mathcal{R}^3\, T^{1/2}$. Then the total thermal X-ray luminosity of the FMK ensemble is

$$L_{xT} \sim 10^{37} \cdot \frac{\Delta M_{ej}}{M_\odot} \cdot \frac{\nu_{SN}}{0.03\ yr^{-1}} \cdot \mathcal{R}_{-2} \cdot n_{\mathrm{a}2} \ \ \mathrm{erg\ s^{-1}}.$$

The nonthermal emission component is more sensitive to some poorly constrained parameters, as the magnetic field in the cold ejecta fragment and the magnetic fluctuation spectrum. The nonthermal luminosity can be approximated with $\mathcal{L}_\mathrm{x} \propto\ < Z > n_\mathrm{a}\, \mathcal{R}^2\, v^\zeta$. In a highly idealized case of a “thick target” where all the nonthermal electrons are stopped inside the knot we have $\zeta = 3$. That requires a relatively low particle diffusion coefficient in a dense knot of the mean atomic charge $< Z >$. Then

$$L_{xNT} \sim 2 \times 10^{37} \cdot \frac{\Delta M_{ej}}{M_\odot} \cdot \frac{\nu_{SN}}{0.03\ yr^{-1}} \cdot \frac{< Z >}{8} \cdot \left(\frac{v}{6,000\ \mathrm{km\ s^{-1}}}\right)^2 \ \ \mathrm{erg\ s^{-1}}.$$

For typical parameters of the fast oxygen knots of velocity $\sim$6,000 km s^{-1}, the mean charge $< Z >= 8$ and the total mass of the ejected knots $\Delta M_{ej} \sim 0.5 M_\odot$ we obtain $L_{xNT} \sim 10^{37}$ erg s^{-1}. If a SN ejects $\mathcal{N}_\star$ $\sim$500 FMKs of mass $10^{-3} M_\odot$ and velocity 6,000 km s^{-1}, the FMKs would carry about 15% of the SN kinetic energy. The “thick target” approximation is probably oversimplified, and $\mathcal{L}_\mathrm{x} \propto\ v^\zeta$ with $\zeta < 3$ seems to be more realistic. On the other hand it is possible to develop a general approach to simulate the logN–logS distributions for an ensemble of ballistically moving sources providing a more rigorous description of their collective X-ray emission. The approach allows to study the logN–logS distribution of FMKs of supernova origin as well as ballistically moving objects ejected by accreting processes (e.g. jets and Herbig-Haro outflows).

2.3. *The* logN–logS *distribution of FMKs*

The X-ray luminosity $\mathcal{L}_\mathrm{x}(v, M, \mathcal{R}, n_a)$ of an FMK depends on the knot velocity, mass, radius, and the ambient matter density. To simulate the logN–logS distribution of FMKs we should know the FMK velocity and size distributions. We consider here a simplified analytic model for logN–logS distributions. The differential distribution function of the FMKs velocities and radii $\mathcal{N}(\vec{r}, \vec{v}, \mathcal{R}, t)$ satisfies

$$\frac{\partial \mathcal{N}}{\partial t} + \dot{\vec{r}}\,\frac{\partial \mathcal{N}}{\partial \vec{r}} + \dot{\vec{v}}\,\frac{\partial \mathcal{N}}{\partial \vec{v}} + \dot{\mathcal{R}}\,\frac{\partial \mathcal{N}}{\partial \mathcal{R}} = q(\vec{r}, \vec{v}, \mathcal{R}, t), \tag{2.1}$$

where the source function $q(\vec{r}, \vec{v}, \mathcal{R}, t) = \nu\, \mathcal{N}_\star\, \psi(v, \mathcal{R})$. Here $\psi(v, \mathcal{R})$ is the probability distribution of the initial sizes and velocities of the FMKs. For a ballistically moving

FMK the drag deceleration in the ambient medium is $\dot{\vec{v}} \propto -\rho_a v \vec{v} \mathcal{R}^2$ (for a stretched knot $\mathcal{R}$ is the transverse radius).

We apply the Eq. (2.1) to some active region assuming a constant local ejection rate ν and a locally homogeneous ambient medium (on the FMK deceleration scale). Then the asymptotic averaged distribution is

$$\mathcal{N}(v, \mathcal{R}) = \int_v^\infty \frac{\bar{q}(v, \mathcal{R})}{\dot{v}} \, dv, \tag{2.2}$$

where $\bar{q}(v, \mathcal{R}) \propto a^{-1} q(v, \mathcal{R}/a)$ and $a(\chi)$ is the knot expansion factor simulated by Klein *et al.* (1994) within an associated model of shocked cloud evolution.

It is instructive to estimate a power-law index of the flux distribution function $N(S)$. The index, defined as $\alpha = \mathrm{logN/logS}$, is constant for a relatively narrow flux band. We shall consider both thermal and non-thermal emission models for FMKs described by Bykov (2003).

We assume that $\psi(v, \mathcal{R}) \propto \mathcal{R}^{-\beta} v^{-\eta}$ in a relatively narrow range of $\mathcal{R}$. Then, integrating the distribution $\mathcal{N}(v, \mathcal{R})$ over velocity (above the threshold $v_0 \propto \mathcal{R}^{-1/2}$) and using $\mathcal{L}_\mathrm{x} \propto n_\mathrm{a}^2 \mathcal{R}^3 T^{1/2}$, we obtain the local index estimation for *the thermal emission* $\alpha = -4/3 + \eta/6 - \beta/3$. The index is consistent with $\alpha = -1.7 \pm 0.2$ obtained by Muno *et al.* (2003) for the *Chandra* GC sample, if the initial distributions $\psi(v, \mathcal{R})$ satisfy $-3.4 < \eta - 2\beta < -1.0$. The value of $\eta \lesssim 1$ agrees with the velocity distribution of FMKs simulated by Kifonidis *et al.* (2003). The nonthermal flux distributions depend on the diffusion regime of the accelerated particles inside FMKs. The magnetic fluctuation spectrum inside an FMK and the dependence of the diffusion coefficients on the FMK size and velocity are yet poorly known. However, FMK thermal emission models and some simplified non-thermal models allow steep logN–logS distribution of $\alpha \lesssim -1.7$ with a large population of low luminosity objects. Their emission spectra contain hard power-law component of typical photon index Γ below 1.5. It remains to be checked if a numerous faint sources population can contribute seriously to the ridge diffuse emission component discussed above as it is proved to be the case in the soft γ-ray domain (see Lebrun *et al.* 2004).

3. Hard emission from SNR-wind interactions and superbubbles

Young massive star formation occurs in massive molecular clouds. A gravitational collapse of a giant molecular cloud of 10 to 30 pc size usually results in a birth of a group of several tens massive O and B stars, called an OB-association. As the O and B stars have short lifetimes (e.g. Maeder and Meynet 2000), the dispersion velocities within such a group are small, not exceeding 4-6 km s^{-1}, and the association remains compact, though it is not gravitationally bound. It is estimated that more than 60 percent of all the OB stars in the Galaxy belong to one of the OB-associations (Garmany, 1994). A typical size of such an association is about 35 pc. Thus, in an evenly distributed association containing 100 stars the distance between two neighbour stars is about 12 pc. Most of the OB-associations consist of substructures named OB-subgroups where the density is several times higher. For example, the R136 subgroup of the 30 Doradus association consists of 9 O stars within 3.4 pc (Walborn *et al.*, 1999). One of the most massive young open stellar cluster in the Galaxy is Westerlund 1 that contains more than 200 massive stars with a very rich WR star population (e.g., Clark *et al.* 2005). Another rich cluster, the Arches cluster, is situated at a projected distance of 30 pc from the Galactic centre. The age of the Arches cluster is estimated as 2-2.5 Myr. The compact groups are the favorable sites of some new type of high energy sources produced by shocks and winds.

Colliding winds in early type binaries were suggested by Eichler and Usov (1993) as a possible strong sources of nonthermal particles and emission.

A region where an expanding shell of a SNR interacts with a fast powerful wind of a young massive star (or a star cluster) contains a converging MHD flow. Axisymmetric hydrodynamic simulations of SNR-wind collisions carried out by Velázques, Koenigsberger, Raga (2003) illustrate the basic properties of the multi-shock flow during the collision. Even before a direct collision the converging flow will exist between the fast star wind and the expanding supernova ejecta. The converging flow is argued to be a plausible site for GeV–TeV regime lepton acceleration. The kinetic models presented predict efficient particle acceleration with a hard spectrum of electrons at the TeV energy regime. Synchrotron emission of the TeV electrons may have a very hard spectrum with a photon index $\sim$1 and a spectral break in between keV and MeV photon energies for extended SNRs. Because of that hard spectra of accelerated electrons the mechanism provides a high efficiency of conversion of SNR shell-fast wind kinetic luminosity into hard X-rays and γ-rays. The efficiency of synchrotron emission in hard X-rays is high. The X-ray luminosity may exceed 0.001 of the kinetic power of the shocks. In Fig.1 (right panel) we show a hard X-ray emission clump detected with *INTEGRAL-ISGRI* in a region containing γ-Cyg SNR and the stellar wind of the O9V star HD 193322. The hard X-ray source can be explained in this scenario. The new type of hard X-ray sources may be rather common in star forming regions. The Galactic center region could contain such kind of objects. The X-ray ridge seen by *Chandra* in the $15''$ vicinity of Sgr $A^\star$ was suggested to be produced by interaction of Sgr A East SNR with collective wind from massive stars of the central cluster (Rockefeller *et al.* 2005). Recent hard X-ray observations with *INTEGRAL-ISGRI* of the Galactic Center region by Bélanger *et al.* (2005) revealed a number of hard X-ray sources in the close vicinity of Sgr $A^\star$ some of which may have the same nature as that due to SNR-stellar wind interaction discovered in γ-Cyg SNR. The hard X-ray emission of synchrotron origin was suggested by Neronov *et al.* (2005) to be a source of hard diffuse emission in the Galactic Center region. The sources are promising candidates for observations with H.E.S.S. and other TeV telescopes.

At the later stages of the OB association evolution the kinetic energy release within the bubble created by a stellar association may reach a few times 10^{38} erg s^{-1} due to intense stellar winds and multiple SN explosions. The process is accompanied by formation of shocks, large scale flows and broad spectra of MHD fluctuations in a tenuous plasma with frozen-in magnetic fields. Vortex electric fields generated by the large scale motions of highly conductive plasma with shocks result in a non-equilibrial distribution of the charged nuclei. Non-linear models of temporal evolution of particle distribution function accounting for the feedback effect of the accelerated particles on the shock turbulence inside the superbubble demonstrated a high efficiency of the conversion of the large-scale turbulence energy to energetic particles on $\sim$0.1 Myr time scale and soft-hard-soft evolution of the particle spectra in 10 Myrs with asymptotic power-law index below 3. The superbubbles should be very plausible sites of cosmic ray particle acceleration (e.g. Bykov 2001, Parizot *et al.* 2004).Thermal and non-thermal X-ray emission observed recently with *Chandra* in 30 Dor superbubble by Bamba *et al.* (2004) revealed the presence of particle acceleration processes there.

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References

Aschenbach, B. 2002, In: Neutron Stars, Pulsars and Supernova Remnants. Proc 270 WE-Heraeus seminar, eds. W.Becker *et al.*, MPE, p. 13

Bamba, A., Ueno, M., Nakajima, H. & Koyama, K. 2004, *ApJ* 602, 257

Bélanger, G., Goldwurm, A., Renaud, M. *et al.* 2005, *ApJ (in press), astro-ph/0508128*

Bykov, A.M. 2001, *Space Science Reviews* 99, 317

Bykov, A.M. 2003, *Astron. Astrophys.* 410, L5

Bykov, A.M., Chevalier, R.A., Ellison, D.C., Uvarov, Yu.A. 2000, *ApJ* 538, 203

Bykov, A.M., A. Krassilchtchikov, M. Yu. Uvarov, A. *et al.* 2004, *Astron. Astrophys.* 427, L31

Bykov, A. M., Bocchino, F. & Pavlov, G.G. 2005, *ApJ* (Letters) 624, L41

Chevalier, R.A. 1999, *ApJ* 511, 798

Clark, J. S., Negueruela, I., Crowther, P. A., Goodwin, S. P. 2005, *Astron. Astrophys.* 434, 949

Ebisawa, K., Tsujimoto, M., Paizis, A., *et al.* 2005, *ApJ (in press), astro-ph/0507185*

Eichler, D. & Usov, V. 1993, *ApJ* 402, 271

Fesen R.A., Morse, J.A., Chevalier, R.A. *et al.* 2002, *AJ*, 122, 2644

Fesen R.A., Hammell, M.C., Morse, J.A., *et al.* 2005, *ApJ (in press) astro-ph/0509067*

Garmany, D. 1994 *PASP, 106, 25*

Hands, A.D.P., Warwick, R.S., Watson, M.G. & Helfand, D.J. 2004, *MNRAS*, 351, 31

Kifonidis, K., Plewa, T., Janka, H.-Th. & Müller, E. 2003 *Astron. Astrophys.* 408, 621

Klein, R.I., McKee, C.F., & Colella, P. 1994, *ApJ*, 420, 213

Lebrun, F., Terrier, R., Bazzano, A., *et al.*, 2004, *Nature* 428, 293

Maeder, A. & Meynet, G. 2000, *Ann. Rev. Astron. Astrophys.* 38, 143

Mavromatakis, F. 2003, *A*stron. Astroph., 408, 237

Mezger, P.G., Duschl, W.J. & Zylka, R. 1996, *A*stron. Astroph. Rev., 7, 289

Muno, M.P., Baganoff, F.K., Bautz, M.W., Brandt, W.N., *et al.* 2003, *ApJ*, 589, 225

Muno, M.P., Arabadjis, J.S., Baganoff, F.K., Bautz, M.W., *et al.* 2004, *ApJ*, 613, 326

Neronov, A., Chernyakova,M., Courvoisier,T.J.-L. & Walter.R. 2005, *astro-ph/0506437*

Parizot, E., Marcowith, A., van der Swaluw, E. *et al.* 2004, *Astron. Astrophys.* 424, 747

Park, S.P., Muno, M.P., Baganoff, F.K., Maeda, Y., *et al.* 2004, *ApJ*, 603, 548

Reipurth, B. & Bally, J. 2001, *Ann. Rev. Astron. Astrophys.* 39, 403

Rockefeller, G., *et al.* 2005, *ApJ (in press) astro-ph/05006244*

Shull, J.M. 1980, *ApJ* 237, 769

Tanaka, Y. 2002, *Astron. Astrophys.* 382, 1052

Velázques, P.,Koenigsberger & G. Raga, A.C. 2003, *ApJ* 584, 284

Walborn, N.R., Barba, R.H., Brandner, W., Rubio, M., *et al.* 1999, *AJ* 117, 225

Wheeler, J.C., Mazurek,T.J. & Sivaramakrishnan, A. 1980, *ApJ* 237, 781

Discussion

Courvoisier: What is the efficiency of the energetic particle acceleration in your superbubble modeling?

Bykov: The particle acceleration mechanism by multiple weak shock in the non-linear regime considered here provides efficient creation of a nonthermal nuclei population with a hard low-energy spectrum, containing a substantial part (about 30%) of the kinetic energy released by the winds of young massive stars and supernovae.

Courvoisier: You just said that “a substantial fraction” of the energy dissipated in superbubbles comes out as non-thermal particles. This would mean that shocks deliver more non-thermal than thermal energy. Can you confirm and let us know how likely this is to be?

Bykov: Yes, indeed the efficiency of non-thermal particle generation in a superbubble could be about 20-30% in the nonlinear model I mentioned. The relative efficiency of particle acceleration as compared with thermal heating is high enough in the case of weak shocks in magnetized plasma. In a weak MHD shock the entropy production (heating) is proportional to the cube of the density contrast, while the acceleration rate is proportional to the square of the amplitude.