Energetic processes and nonthermal emission of starforming complexes

A.M. Bykov

A.F.Ioffe Institute for Physics and Technology, St.Petersburg, Russia, 194021

Abstract: We discuss models of energetic particle acceleration, interactions and nonthermal emission in active starforming regions at different stages of their evolution. Powerful stellar winds and supernova explosions with intense energy release in the form of strong shock waves can convert a sizeable part of the kinetic energy release into energetic particles. The starforming regions are argued as a favorable site of energetic particle acceleration and could be efficient sources of nonthermal emission.

1 Introduction

The star-forming regions (SFRs) in galaxies are generically associated with molecular clouds and contain a variety of energetic outflows at different stages of massive star evolution from protostellar accreting objects through fast winds of massive OB or WR stars to the most energetic supernova events. Energetic outflow events with fast shocks in a dense ambient medium should result in a rapid conversion of kinetic power into emission. Here we shall discuss two different phenomena of SFR activity — a class of hard non-thermal emission sources due to supernova remnant (SNR) shell interactions with a fast wind of a massive star and a process of magnetic field generation in superbubbles related with energetic particle acceleration by shocks.

Young massive star formation occurs in massive molecular clouds. A gravitational collapse of a giant molecular cloud can result in a formation of several groups of massive O and B stars considered as an OB-association. The distance between two neighboring stars in the groups could be less than 10 pc. The compact groups are the favorable sites of some new type of high energy sources produced by shocks and winds.

A substantial amount of massive stars are binaries. Colliding winds in early type binaries were suggested (e.g. Eichler & Usov 1993) as possible strong sources of nonthermal particles and emission. Indeed, nonthermal radio emission was observed from WR type stars in binary systems (Dougherty & Williams 2000; Rauw 2004).

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. 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 a converging flow will exist between the fast stellar wind and the expanding supernova ejecta. The converging flow in a diffusive medium (particle diffusion coefficient $\kappa_{\rm i}(\gamma)$ depends on the Lorentz factor γ) is argued to be a plausible site for GeV–TeV regime lepton acceleration.

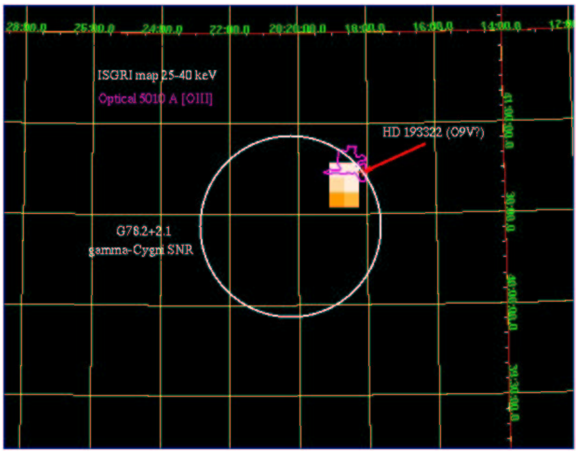

Figure 1: *INTEGRAL ISGRI* 25-40 keV image of γ-Cygni SNR (Bykov et al. 2004). Optical [OIII] 5010 Å line contour (solid line) from Mavromatakis (2003). The SNR border (radio) is roughly indicated by the large solid circle. The arrow points to the position of the O9V star HD 193322 (20:18:07,+40:43:55). All maps are made for J2000. The source may originate from the SNR-O star wind interaction.

A kinetic model without nonlinear back-reaction effect predicts efficient particle acceleration between converging flows (of velocities u_1 and u_2) with the acceleration time

$$\tau_a(\gamma) \approx \frac{3}{u_1 + u_2} \int_{\gamma_0}^{\gamma} \left(\frac{\kappa_1(\gamma)}{u_1} + \frac{\kappa_2(\gamma)}{u_2} \right) \frac{d\gamma}{\gamma} \tag{1}$$

and a hard spectrum of electrons at the TeV energy regime inside the converging flow

$$N_i(z, \gamma, t) = \frac{N_0(\gamma_0, \gamma_m)}{\gamma} \cdot H(\gamma - \gamma_0) \cdot H(t - \tau_a(\gamma)) \cdot \exp(-u_{\rm i} \cdot |z| / \kappa_{\rm i}(\gamma)), \tag{2}$$

where γ_m is the maximal Lorentz factor, and $H(x)$ is the standard Heaviside step function.

Synchrotron emission of the TeV electrons may have a very hard spectrum with a photon index ~ 1 and a spectral break in between keV and MeV photon energies for extended SNRs. Because of that hard spectrum 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 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 sources are promising candidates for observations with H.E.S.S. and other TeV telescopes.

2 Non-thermal phenomena in superbubbles

At intermediate stages of OB association evolution (after a few million years) 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 were constructed by Bykov (2001). The models demonstrated a high efficiency of the conversion of

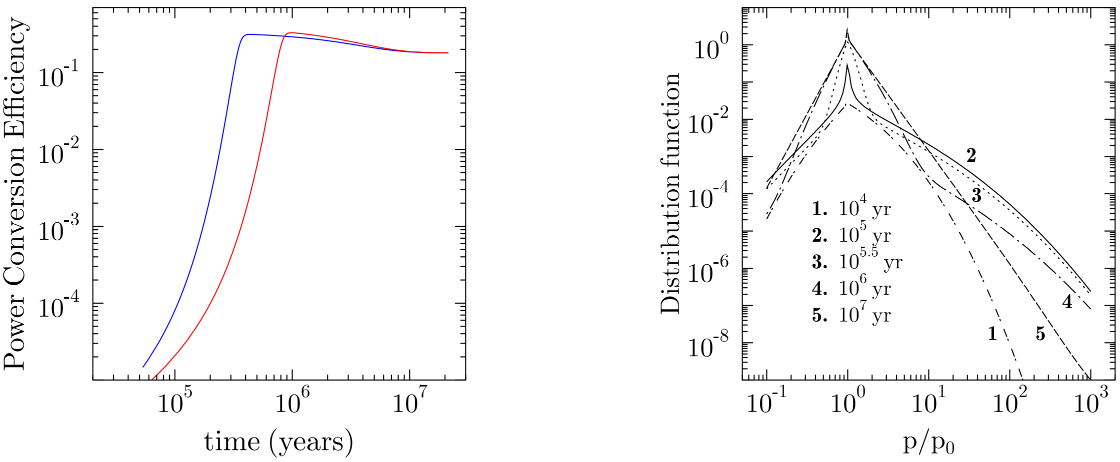

Figure 2: The evolution of nonthermal energetic particles in a superbubble, with the standard IMF. Monoenergetic injection was assumed with the injection energies 10 keV. The temporal evolution of the power conversion efficiency for two different IMF models (see Bykov 2001 for details) is presented in the left panel, while the particle distribution function is in the right panel.

the large-scale turbulence energy to energetic particles on ∼ 0.1 Myr time scale. They also showed soft-hard-soft evolution of the particle spectra in 10 Myrs. The particle spectra are power-laws of indices between 1 and 3 with the time asymptotic power-law energy spectral index below 3 (see Fig.2). 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 the 30 Dor superbubble by Bamba et al. (2004) revealed the presence of some particle acceleration processes there. Magnetic fields in the extended superbubbles are the governing parameters to determine the maximal energies of the accelerated particles. There are different possible processes of magnetic field generation in a highly turbulent compressible medium in a superbubble environment. We shall discuss here a possible new mechanism of magnetic field generation associated with the particle acceleration process.

2.1 Magnetic fields in superbubbles

Supernova shocks in OB associations are sweeping out the matter destroying the honeycomb-like structure created by stellar winds. The matter inside the superbubble at that stage is very intermittent with patchy H_α emission structure indicating the presence of partially-ionized matter. It is known that incomplete ionization would result in ion-neutral damping of MHD waves and limit the maximal energies of accelerated particles. The effect has an important implication for nonthermal emission of supernova remnants interacting with clouds (Bykov et al. 2000). However, apart from the wave damping the presence of a neutral component is long-known to change the relation between local electromagnetic fields and the thermal plasma current — the generalized Ohm's law. The Ohm's law can be changed drastically even by a relatively small amount of neutral atoms provided the plasma is highly magnetized. The effect of MHD fluctuation growth due to CR current in the upstream of MHD shock propagating along magnetic field in a partially ionized plasma with some (small) mass fraction of neutrals F was studied by Bykov & Toptygin (2005). Their analysis is valid for fluctuations of wavelength λ above the ion-neutral collision length and provides the magnetic fluctuation growth in the wavenumber ($k = 2\pi/\lambda$) range below the cosmic ray precursor length. The magnetic fluctuation growth in a collisionless shock may convert some fraction of the supersonic flow into magnetic fields of a parsec scale.

The ion-neutral collision length in the pre-shock gas can be estimated as $\lambda_{\rm in} \lesssim 2 \times 10^{16} \cdot (F \cdot n_{-2})^{-1}$ cm (for $T \leq 10^5$K). The fluctuation growth rate Γ depends on the fraction of energetic particles N_0/n_i. The value can be expressed through the ratio η of the CR energy density to the kinetic energy density in the upstream flow. For relatively strong shocks $N_0/n_i \approx \eta/2 \cdot (1-F) \cdot (u_{\rm sh}/c)^2/\ln\gamma_m$. The magnetic field growth rate can be presented as

$$\frac{\Gamma}{ku} \approx 10^2 \times \eta \cdot \frac{F \cdot (1-F) \cdot u_8^2 \cdot B_{-6}}{n_{-2} \cdot \ln\gamma_m \cdot T_4^{0.4}} \,, \tag{3}$$

where u_8 is the shock velocity measured in 1,000 km s^{-1}, and number density n_{-2} in 10^{-2} cm^{-3}. In case of a moderate efficiency of ion acceleration with $\eta \sim 0.1$ and extended energy spectrum of accelerated ions with $\ln(\gamma_m) \sim 10$, the condition in the shock upstream $F \cdot (1-F) \cdot u_8^2 \cdot B_{-6} \cdot n_{-2}^{-1} \gtrsim 1$ must be satisfied for the fluctuations to grow.

The maximal upstream field amplitude calculation requires non-linear analysis of the instability. We can estimate the amplitude on the energetic ground as $B_m \sim (0.5 \cdot \eta \cdot n\ m_p\ u_8^2)^{1/2}$ providing $B_m \gtrsim$ 10 μG. The upstream field will be further compressed by the shock providing a few times higher downstream field, depending on the shock geometry. The resulting magnetic fields of $B \gtrsim 30\mu$G would allow cosmic ray acceleration up to the "ankle" energy region.

Acknowledgements

I would like to acknowledge my collaborators for fruitful cooperation. Support from the meeting organizers is gratefully acknowledged. The work was partially supported by RBRF grants 03-02-17433 and 04-02-16595.

References

Bamba A., Ueno M., Nakajima H., Koyama K., 2004, ApJ, 602, 257
Bykov A.M., 2001, Space Science Reviews, 99, 317
Bykov A.M., Chevalier R.A., Ellison D.C., Uvarov Yu.A., 2000, ApJ, 538, 203
Bykov A.M., Krassilchtchikov A.M., Uvarov Yu.A., et al., 2004, A&A, 427, L31
Bykov A.M., Toptygin I.N., 2005, Astron. Lett., 31, 748
Dougherty S.M., Williams P.M., 2000, MNRAS, 319, 1005
Eichler D., Usov V., 1993, ApJ, 402, 271
Mavromatakis F., 2003, A&A, 408, 237
Parizot E., Marcowith A., van der Swaluw E., et al., 2004, A&A, 424, 747
Rauw G., in *Cosmic Gamma-Ray Sources*, Eds. K. Cheng, G. Romero, p.105, Kluwer, 2004
Velázques P., Koenigsberger G., Raga A.C., 2003, ApJ, 584, 284