X-RAY FILAMENTS IN YOUNG SUPERNOVA REMNANTS: LINKS TO COSMIC-RAY PHYSICS

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ABSTRACT

The recent observations of X-ray filaments in young supernova remnants (SNr) by the satellites Chandra and XMM-Newton have very deep implications on the physics of diffusive shock acceleration. The filaments probably result from synchrotron radiation of relativistic TeV electrons. Their typical sizes of the order of 10^{-2} parsec imply a strong amplification of the magnetic field ahead the shock by the streaming of shock accelerated cosmic rays. Magnetic fields with strengths about two order of magnitude above the standard interstellar medium values have been derived in several young SNr. In this article, it is shown that the X-ray observations can also help us to constrain the properties of the turbulence at work in collisionless shocks. In case of isotropic turbulence models, we predict maximum cosmic ray energies under the cosmic ray knee at 3 10^{15} eV. We also limit the turbulence index variations between 1 (Bohm regime) and typically 1.5 in the selected sample of SNr; the Kolmogorov-type turbulence is rejected. This work also discuss more complex and complete modelling of the turbulence spectrum in SNr as well as alternative scenarii to produce cosmic ray energies up to the cosmic ray ankle at 3 10^{18} eV.

Key words: X-rays, particle acceleration, cosmic-ray physics, supernova remnants.

1. INTRODUCTION

The high spectro-imagery resolution X-ray satellites ASCA, Chandra and XMM-Newton have recently detected non-thermal X-rays in several young supernova remnants (or SNr hereafter) like CassiopæA, Képler, Tycho, G266.2-1.2, SN1006, G347.3-0.5, G28.6-0.1, RCW86 (see as a non-exhaustive list of references Koyama et al (1995), Koyama et al (1997), Gotthelf et al (2001), Slane et al (2001), Rho et al (2002), Hwang et al (2002), Bamba et al (2003),Long et al (2003), Vink & Laming (2003), Cassam-Chenaï et al (2004), Hwang et al (2004)). These observations have a strong impact on our knowledge of the physics of supernova nucleosynthesis, on collisionless shock mechanism (see the review by J.Vink in these proceedings) as well as on the diffusive shock acceleration (DSA) process of energetic particles. The non-thermal X-ray emission originates from thin filaments associated with the SNr forward shock and is most probably related to the synchrotron emission of high energy electrons (Ballet, 2005, references therein and section 2). A series of paper (Berezhko et al (2003), Vink (2004), Berezhko & Völk (2004), Völk et al (2005), see also section 3.1), have demonstrated that the magnetic field associated with these X-ray filaments could reach amplitudes close to one hundred time above the standard interstellar medium (ISM) values (of the order of $3-6\mu$Gauss). However, the previous analyses have assumed a particular regime of particle diffusion around the forward shock; e.g. the so-called Bohm diffusion regime where the particle mean free path equals its Larmor radius around the total magnetic field $\rm R_L = E/ZeB$ (Ze is the particle charge). In this work, we do not retain any assumption on the diffusion regime and show in section 3.2 that the X-ray observations lead to important constraints on the diffusion coefficients and then on the properties of the turbulence around SNr shocks. In the case of Bohm diffusion several investigations have concluded that magnetic field amplification around the forward shock in young SNr allows to accelerate cosmic rays up to the cosmic-ray (CR) knee at $\simeq 3\times10^{15}$ eV or in the most extreme cases up to the CR ankle at $\simeq 3\times10^{18}$ eV supporting the standard galactic cosmic-ray acceleration scenario (see the recent review by Hillas (2005) and the references therein). This issue is treated and questioned in section 3.3. Before concluding in section 5, we investigate in section 4 more complex turbulence models one may expect around collisionless SNr shocks that may change the above conclusions. We will center our discussion on two effects: the anisotropy up- and downstream and the relaxation of the turbulence downstream.

2. X-RAY FILAMENTS IN YOUNG SNR

The non-thermal X-ray emission observed in some SNr in the above list is probably synchrotron radiation produced by relativistic electrons. The non-thermal bremsstrahlung mechanism which would require densities $\geq 3-10\,\mathrm{cm}^{-3}$ in the environmental medium is not completely ruled-out (see the discussion in Ballet (2005).) The radiation appear to come from very thin filaments associated with the forward shock (see for instance the case of Tycho SNr in Hwang et al (2002).) The typical size of the filaments is of the order of few arc-seconds (from 4" in CassiopæA to 20 " in SN1006, see again Ballet (2005).) Considering the different SNr distances, the filament physical sizes range from $5\ 10^{-2}$ to 0.2 pc. However, due to projection effects, the real size of a filament is reduced by a factor P. Considering an exponential drop of the brightness behind the forward shock, the FHWM is reduced by P = 4.6. Berezhko et al (2003) comparing the brightness in the center of the remnant to the outer edge did found a factor 7. Then, we can safely assume that the X-ray filaments have sizes close to 10^{-2} pc in the youngest SNr (CassiopæA, Tycho, and Képler.) and $\simeq 5\ 10^{-2}$ pc in older SNr (SN1006 and G347.3-0.5.)

3. DIFFUSIVE SHOCK ACCELERATION IN SNR

The previous observations do have several interests in terms of the modelling of the shock acceleration process in SNr. First, they clearly demonstrate the presence of ultra-relativistic electrons around the forward shock. The diffusive shock theory predicts that particles with the same rigidity $\mathrm{E/ZeB}$ are accelerated in the same way in shocks. Then, one may expect for instance acceleration of protons up to energies at least of a few 10^{13} eV in SNr. This argument is supported by the recent HESS telescope detection of SNr in the galactic plane, particularly, the gamma-ray radiation emitted in RXJ1713-3946 (Aharonian et al , 2004) seem to be produced through neutral pion decay itself produced by the interaction of protons (and/or heavier nuclei) with the material of a dense molecular cloud. The spatial extension of the X-ray filaments (as well as the gamma-ray radiation in RXJ1713-3946) map the spatial extension of the relativistic particles and the magnetic field (or the dense interstellar targets.) As we shall see now, the X-ray observations appear to be rather constraining for the different processes involved in shock acceleration (advection, diffusion or shock modification) and for the turbulence around the shock.

3.1. Magnetic field amplification in the shock precursor

It known for a long time that cosmic ray can produce magnetic field fluctuations through their streaming motion in the interstellar medium (Wentzel, 1969) or upstream a super-Alfvénic shock (Skilling , 1975). At low frequencies, the particles produce resonantly hydromagnetic waves (Alfvén waves, magnetosonic waves) moving in the same direction. The waves carrying a fraction of the momentum of the particles tend to reduce the streaming velocity. Ahead a shock, the matter and the preexistent magnetic field are both compressed by factor r (= 4 in strong non-relativistic shocks.), see for instance (Drury , 1983). One can thus expect, the magnetic field just downstream B_{d} to be significantly enhanced compared to the upstream magnetic field B_{u}. The drop of the magnetic field upstream explains why most of the synchrotron radiation produced by the relativistic electrons is coming from the downstream medium (Berezhko et al , 2003). Downstream the shock, the particles suffer from two different kind of transport: they are advected with the flow towards the SNr interior and they scatter off of the magnetic field fluctuations. We will assume here that the magnetic field downstream drops over a scale $\simeq R_{\mathrm{SNr}}$ and can be supposed to be constant over the scales explored by the relativistic electrons; we say that the observed outer rims are limited by the radiative losses.

With the above statements, it is now possible to link the observed size of the X-ray filaments with the downstream magnetic field. Within a synchrotron loss timescale $\tau_{\mathrm{sync}} \propto E^{-1}B_{\mathrm{d}}^{-2}$, the radiating electrons of energy E cannot move farther than the maximum of the advective distance $\Delta R_{\mathrm{adv}} = V_{\mathrm{d}}\tau_{sync}$ and the diffusive distance $\Delta R_{\mathrm{diff}} = (D(E,B_{\mathrm{d}})\tau_{\mathrm{sync}})^{1/2}$. Here, $D(E,B_{\mathrm{d}})$ is the downstream diffusion coefficient of relativistic particles of energy E. The X-ray observations have been made at a particular synchrotron photon frequency E_{ph} leading to one to one relationship between the particle energy and the magnetic field: $E \propto B^{-1/2}E_{\mathrm{ph-obs}}^{1/2}$. The condition $\Delta R_{\mathrm{rim}} \geq \mathrm{Max}(\Delta \mathrm{R_{adv}}, \Delta \mathrm{R_{diff}})$, leads to a lower limit on the downstream magnetic field once the form of the diffusion coefficient have been specified (see Berezhko et al (2003), Vink (2004), Berezhko & Völk (2004), Völk et al (2005), Ballet (2005).) If the Bohm scaling is assumed; e.g. $D = 1/3(R_{\mathrm{L}}c) \propto EB^{-1}$, the magnetic field strength is found to be two orders of magnitude above the standard ISM values. These results are difficult to conciliate with a simple magnetic field compression. The compression factor in that case should be much larger than 10 and is difficult to explain with the shock Mach and Alfvénic Mach numbers expected in a standard interstellar medium (Bykov , 2004). Such a high magnetic field amplification in the shock precursor has recently been modelled by Bell and collaborators (see Bell & Lucek (2001), Lucek & Bell (2001)) using analytical estimates and particle-in-cell and magnetohydrodynamical simulations.

In fact, within the loss-limited rim hypothesis, it is possible to derive a self-consistent magnetic field strength through a combination of both the above defined advective and diffusive lengths. This estimate assumes that the particles loose their energy on timescales short compared to other energy transport timescales (Berezhko et al , 2003). In that case, the loss term in the diffusion-convection transport equation can be simplified and the observed rim size can be directly related to the two lengthscales. This calculation will be generalised in the next section.

3.2. On the turbulence in young SNr shocks

All the previous magnetic field estimates have been made assuming a particular law of diffusion: the Bohm scaling. It corresponds to a particle mean free path equals to its Larmor radius and is the *minimum* diffusion coefficient one may expect in an *isotropic* turbulence (if the fluctuations are equally reparted in all direction around the mean magnetic field.) Different recent modelling have suggested that the tangled character of the magnetic field implies a cosmic ray mean free path of the order of its Larmor radius. For instance Lucek & Bell (2001) in their simulations did reported evidences of particle isotropisation over a Larmor radius in a magnetic field amplified by the streaming of cosmic ray. However, the previous theoretical work suffer from various limitations: cosmic-ray streaming amplifies forward waves at the same time as it damps backward waves, and the transfer of energy between these two types of waves has not been modelled by Bell & Lucek (2001). The numerical simulations using coupled particle-in-cell and magnetohydrodynamics codes suffer from limited wave number dynamics and a crude modelling of the acceleration mechanism. This questions the value obtained for the non-linear saturation level of the magnetic field. The argument in favor of a Bohm diffusion regime is also phenomenological since no MHD theory has rigorously predicted a Bohm regime yet (see Casse et al (2002) and references therein), Finally, the non-resonant instability mechanism uncovered by Bell (2004) has not been taken into account in previous studies. We shall come back on the last point in section 4.2.

3.2.1. Constraints on isotropic turbulence models

The diffusion coefficient entering in the particle acceleration timescale $\tau_{\rm esc} \propto D/U_{\rm sh}^2$ is an essential ingredient of the theory of diffusive shock acceleration. Unfortunately, as discussed above, no theory of strong turbulence in collisionless shock does exist that allow a firm derivation of the diffusion coefficient D. The Bohm scaling appears solely as a possible conjecture. It should be stressed here that even if the Bohm scaling gives diffusive lengths downstream quite consistent with observed X-ray filament size, the law of diffusion followed by the relativistic particles around a SNr shock could be quite different and produce a diffusion coefficient close to the Bohm one at the energy of the electrons radiating the observed synchrotron photons. In the view of accounting for these uncertainties we decided to use a general form for the diffusion coefficient: $D(E) = k\, D_{\rm Bohm}(E)\, (E/E_0)^{\alpha-1}$ and to constrain the parameters k, α and E_0 using the X-ray observations. In the above formula, k is a coefficient eventually dependent on the particle energy and is related to the level of the magnetic field fluctuations, E_0 is a normalisation energy which can be related to the maximum scale of the turbulence and α is an index related to the turbulence index $\beta = 2 - \alpha$.

We now choose $E_0 = E_{\rm eMax}$, the maximum energy of the electrons. This last quantity is fixed by balancing the diffusive shock acceleration timescale with the synchrotron loss timescale and using the relation $E_{\rm eMax} \propto < B >^{-1/2}\ E_{\rm ph-cut}^{1/2}$. The magnetic field entering in the previous relation is the mean magnetic field experienced by a relativistic electrons during one Fermi cycle (moving from downstream to upstream and back) around the shock. It can easily be linked to the downstream magnetic field and the shock compression ratio through the Rankine-Hugoniot conditions at the shock front. Finally $E_{\rm ph-cut}$ is the observed cut-off frequency of the synchrotron spectrum (typically around 1 keV in the young SNr considered here.) Once, the X-ray filament size has been related to the two transport lengths at the frequency of the Chandra observations (at 5 keV), we formally have enough relations to eliminate both k (supposed to be identical up- and downstream as it should be in the isotropic turbulence hypothesis), $E_{\rm eMax}$ and to derive an expression relating α with $B_{\rm d}$, r, and the observables $E_{\rm ph-cut}$, $E_{\rm ph-obs}$, $\Delta R_{\rm rim}$, and $U_{\rm sh}$. For instance, in case of Kolmogorov-type turbulence with $\alpha = 1/3$ we obtained magnetic field strengths of the order of 300-400 μGauss in the youngest SNr (400 μGauss for Tycho) and $\simeq 100$ μGauss in the older SNr (110 μGauss in SN1006.) The magnetic field values are similar, however slightly higher, in case of Bohm diffusion ($\alpha = 1$). The coefficient k is found between 1 and 10 and the maximum electrons energies are of the order of a few tens of TeV. Our results are very similar to the previous derivations (see Berezhko et al (2003)), however we have demonstrated that the Bohm scaling is not the unique solution consistent with the X-ray observations of the SNr outer rims.

Another condition can be added that can further constrain the characteristics of the turbulence. The maximum cosmic-ray energy $E_{\rm pMax}$ can be directly derived in terms of α either by calculating an escape limit; e.g. the cosmic ray diffusion coefficient upstream $D_{\rm u}(E_{\rm pMax}) = R_{\rm sh} U_{\rm sh}$ or balancing the integrated acceleration timescale with the SNr age. It should not be forgotten at this point that we use an isotropic turbulence model, this means that the diffusion coefficient at $E_{\rm pMax}$ has to be larger than $D_{\rm Bohm}(E_{\rm pMax})$. This constraint allows us to reject low values of α (typically lower than 0.5). Figure 3.2.1 displays a sketch of the above procedure: Two different diffusion laws are presented, the first one corresponds to a Bohm diffusion regime ($\alpha = 1$) and the second one represents a diffusion regime with $\alpha < 1$. The diffusion coefficients cross each other at an energy value close to $E_{\rm obs} > E_{\rm cut}$ ($E_{\rm obs}$ and $E_{\rm cut}$ are the energies of the electrons producing synchrotron radiation at $E_{\rm ph-obs}$ and $E_{\rm ph-cut}$ respectively), this explains that the diffusion coefficient found at $E_{\rm obs}$ is close to the Bohm value. Two cases for the maximum cosmic-ray energy are also displayed: if $E_{\rm pMax} = E_{\rm pMax1}$ then the value of $\alpha < 1$ is authorised, if $E_{\rm pMax} = E_{\rm pMax2}$ then $D(E_{\rm pMax2}) < D_{\rm Bohm}(E_{\rm pMax2})$ and the corresponding α value is rejected (see also 3.3.1). All the calculations discussed above can be found in Parizot et al (2005).

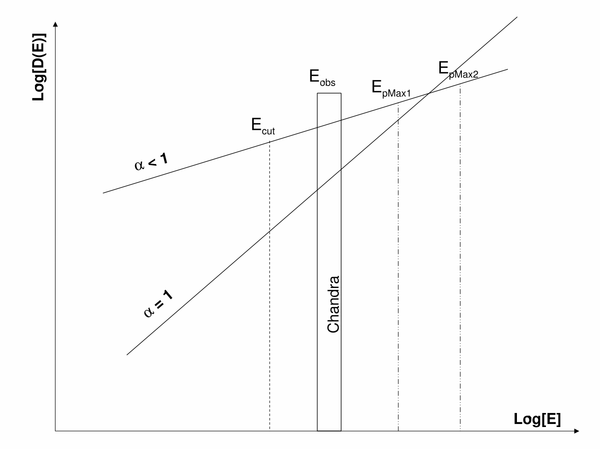

Figure 1. Sketch of the procedure presented to select the α parameter. See text for details

3.3. Maximum cosmic ray energies

Maximum cosmic-ray energies derived using the procedure described in the previous section for different diffusive transport laws are displayed in the figure 3.3.1. The circles shows the maximum cosmic-ray energies expected in isotropic turbulence models. The dashed lines show the rejected α values as they produce diffusion coefficients at the highest cosmic ray energies lower than the Bohm diffusion coefficient. For all SNr considered, one can see that the maximum cosmic ray energies are under the cosmic ray knee at $3\ 10^{15}$ eV. In fact, the four observables mentionned above have some uncertainties, and in the most optimistic cases the maximum cosmic ray energies can get closer (within a factor 2) to the cosmic-ray knee, but in any cases beyond.

3.3.1. The CR ankle: alternative scenarii

Acknowledging for the previous results, it seems reasonable to explain the production of cosmic rays close to the knee in the forward shock of young SNr with enhanced magnetic fields produced by the streaming instability. However, it also seems still difficult even with such an huge magnetic field amplification to reach the cosmic ray ankle three order of magnitude in energy above the knee (see the discussion in (Drury et al , 2001) and references therein). Actually, two alternatives can be pushed forward to circumvent this difficulty and to save the standard galactic cosmic-ray scenario. The first one considers the acceleration of very high energy particles during the very early stages of a core-collapsed supernova, when the forward shock propagates in the wind of the massive star. The shock velocity can reach values of the order of 0.1c leading to faster acceleration and a fast waves growth through the non-resonant streaming instability (see Ptuskin & Zirakashvili (2003), Ptuskin & Zirakashvili (2005) and Bell (2004) respectively). The second one considers that most of the supernova explode

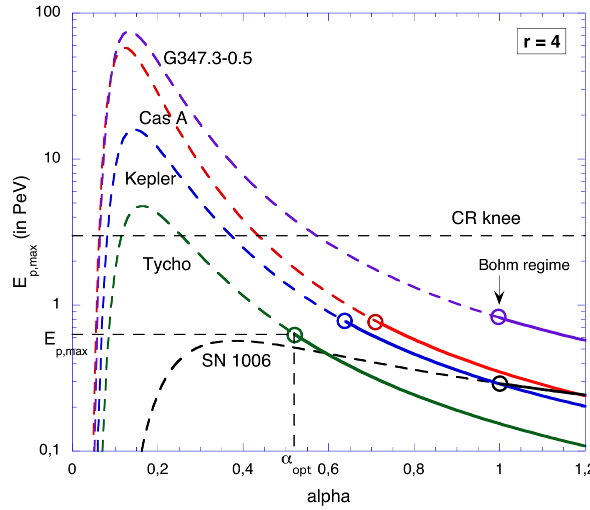

Figure 2. Maximum cosmic-ray energies in Pev (=10^{15} eV) versus the index of the diffusion coefficient α (see text for details, and Parizot et al (2005))

in localised regions of the interstellar medium; the so-called OB association. These associations blow hot and low density cavities in the interstellar medium known as superbubbles (SB). The interaction of the supersonic stellar winds each other or with dense clumps in the SB interior, the interaction of strong SN shocks with both winds and clumps must transfer a substantial fraction of their kinetic energies into thermal and turbulent energies (see the case of Doradus 30 in the LMC discussed in Cooper et al (2004), see also Nakajima these proceeding for other investigations.) Magnetic field amplification through turbulent dynamo can be as well expected in these media. A higher magnetic field, and a larger size of the acceleration regions (a few hundred parsec) can help to produce very high energy cosmic rays (see Bykov (2001), Parizot et al (2004) and references therein).

4. MORE COMPLEX AND COMPLETE MODELLING

The procedure to derive the magnetic field in young SNr from the X-ray filament observations presented in section 3.1 relies essentially on two assumptions: The magnetic field downstream does have a relaxation scale $\sim R_{\rm sh}$ and the turbulence up- and downstream is isotropic. Let us now discuss these two points in more details.

4.1. Turbulently limited rims

Downstream the shock, the magnetic field fluctuations can drop towards ISM values over a scale $\ell_{\rm r}({\rm E})$ (see Pohl et al (2005)) due to various non-linear (wave-wave interactions) turbulent transfer processes. The diffusion coefficient downstream may then be written as: $\rm D_d$ =

$\mathrm{D_d}(\ell_\mathrm{r} \to \infty) \times \exp((\alpha \mathrm{x}/2\ell_\mathrm{r}))$, with $\mathrm{D_d}(\ell_\mathrm{r} \to \infty)$ being the diffusion coefficient for a relaxation scale $\simeq R_\mathrm{sh}$. Relaxation scales $\ell_\mathrm{r} \ll \mathrm{R_{sh}}$ have an average effect of increasing the particle residence timescale downstream and then the acceleration timescale. It is expected that acceleration through a relaxed turbulence is less efficient in producing high energy particles compared to the loss limited case. The typical magnetic field downstream can be expected to be higher. A detailed investigation of this effect however requires numerical simulations (as the relaxation may depends on the particle energy) and will be treated in a future work (Marcowith & Casse (2006) in preparation.)

4.2. Anisotropic turbulence modelling

Anisotropy does not appear to be an exceptional feature of the turbulence in the interstellar medium. Recent theoretical and numerical developments of magneto-hydrodynamical turbulence demonstrated that the energy cascade proceeds mostly in the perpendicular direction to the mean magnetic field due to kinematics of Alfvén waves interaction (see Galtier et al (2000) and references therein.) This non-linear transfer tends to fix the spectrum in the perpendicular direction, whereas the streaming instability builds the spectrum in the parallel direction to the magnetic field, either due to the reaction to the cosmic ray current in the case the non-resonant regime (small wavelengths) or due to the resonant interaction between cosmic rays and Alfvén waves in the resonant regime at large wavelengths (see Bell (2004) and Pelletier et al (2005).) Thus, one may expect substantial anisotropy to be produced in the shock precursor. Downstream, the magnetic field is compressed in the direction parallel to the shock front. This produces a compression of the modes parallel to the magnetic field leading to a differentiation of the maximum scale of the turbulence in the parallel direction and in the perpendicular direction (the shock is assumed to be quasi-parallel here.) Basically, we can conclude that two different anisotropic effects shape the turbulence around collisionless shocks and then modify in a sizable way the diffusion coefficients up- and downstream in regards to the isotropic case. These effects have been treated in details in Pelletier et al (2005), Marcowith et al (2005a) and Marcowith et al (2005b).

5. CONCLUSION

X-ray detection of very thin filaments in several young SNr are efficient tools to constrain the physics involved in the diffusive shock acceleration process. If interpreted as synchrotron radiation of relativistic electrons, the X-ray radiation can only been produced in magnetic fields with strengths about two orders of magnitude above the standard interstellar medium values. It seems that a strong amplification by the different regimes of the streaming instability is the most viable mechanism to explain such high magnetic fields. Considering isotropic turbulence, and accounting for the estimated cut-off frequency of the synchrotron spectrum, we have shown that the maximum cosmic ray energies are in all the SNr selected, under (but close) the cosmic-ray knee at 3 10^{15} eV. We were able to define values of the energy dependence index α in the range 1/2-1 leading to maximal possible cosmic ray energies. In order to explain the cosmic-ray knee and ankle three orders of magnitude in energy above, the standard galactic cosmic-ray model has to be improved. We have discussed two different possible scenarii. The first one locates the production of the highest energy cosmic rays either during the very early stages of a core-collapsed supernova explosion or in OB association and Superbubbles. However, one should pay attention to various subtle effects that may change the above conclusions. We think that the relaxation of the magnetic field downstream the shock through non-linear effects and an anisotropic turbulent spectrum are two important issues to investigate in greater details. Furthermore, the detection of non-thermal X-ray radiation at very early SN expansion phases, other observations at other wavelengths of the forward shock and detailed investigations of the high energy emission produced in massive star forming regions in our Galaxy or in the Magellanic clouds could distinguish between the above issues and questions.

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