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Cosmic-ray acceleration in supernova remnants

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Abstract.
The very strong shocks generated by supernova explosions are the most popular candidate for accelerating Galactic cosmic-rays. Supernova remnants have long been known to harbour GeV electrons (radiating radio synchrotron). More recently, X-ray synchrotron radiation was unambiguously detected, and TeV γ-ray emission has been reported. It is now becoming possible to address observationally questions which were until recently the realm of pure theory, such as the maximum energy reached by particles, the magnetic field strength and orientation, and the fraction of the explosion energy which ends up in accelerated particles.

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1. Introduction

Supernova remnants (SNRs) are the hot bubbles created in the interstellar medium by supernova explosions (a general review of SNRs may be found in Ballet (2003)). They are limited by an expanding blast wave. This review deals only with isolated SNRs, maybe half the number of supernovae. The other half arises from massive stars in clusters, which tend to explode at short intervals and generate a single superbubble.

Radio emission of SNRs was discovered in the 1950's. Its nature was rapidly understood as synchrotron emission by accelerated electrons in the local magnetic field. However, the origin of those electrons was more difficult to fathom. Shklovskii (1960) proposed that they were accelerated during the supernova explosion. However the adiabatic losses sustained during the very large expansion from supernova ($\simeq 10^{13}$ cm) to SNR ($\simeq 10^{19}$ cm) would leave only very little energy in accelerated particles. van der Laan (1962) proposed that the emission is due to the simple compression of already existing cosmic-ray electrons and magnetic field behind the blast wave. This is indeed probably a significant contribution to the radio emission of old SNRs (such as the Cygnus Loop) but it falls way short of explaining the strong radio emission of young SNRs. Gull (1973) proposed that magnetic field amplification and particle acceleration could occur at the (unstable) interface between the ejecta (matter expelled by the supernova) and the ambient medium. This is probably at work in remnants like Cas A, but cannot explain the emission just behind the blast wave.

Finally, in 1978, a number of authors (see Parizot, this volume) proposed that the particles could actually be accelerated at the shock itself, by successive diffusions on both sides of the shock (first order Fermi mechanism). This provided not only a simple explanation of the radio emission in SNRs, but a specific model to explain the acceleration of cosmic-rays. SNRs became then (and still are) the best laboratory to study diffusive acceleration at strong shocks.

In steady-state planar shocks, arbitrarily large energies could be reached, even though the acceleration time and the mean free path increase with energy. In SNRs, the shock has a finite size (the radius of the SNR), a finite duration (the age of the SNR), and its velocity decreases with time. Because of those three effects ,the maximum energy which may be reached by ions (for which cooling is negligible) is (Lagage & Cesarsky 1983)

$$E_{max} \simeq 23\,\mathrm{TeV}\,\frac{Z\,B_{\mu G}\,E_{51}^{1/2}}{n_0^{1/3}\,M_{ej}^{1/6}} \qquad (1)$$

For a typical interstellar magnetic field of 5 μG, this results in an energy of about 100 TeV for protons, whereas the cosmic-ray spectrum turns down only above 1000 TeV (see Paul, this volume).

2. The electromagnetic spectrum

2.1 Radio domain

The radio emission of SNRs is entirely due to the synchrotron emission (see Marcowith, this volume) of accelerated electrons. An electron at energy E emits synchrotron emission around frequency

$$\nu_{\rm el} \; = \; 1.65 \times 10^7 \; B_{\mu\rm G} \; E^2_{\rm GeV} \; \sin\theta \; \rm Hz \qquad (2)$$

where θ is the angle between the electron velocity and the magnetic field. In standard interstellar magnetic fields (a few μG), the radio emission around 1 GHz is due to electrons at a few GeV. At those energies, the electron distribution is close to a power law. The energy index α of the radio spectrum ($F_\nu \propto \nu^{-\alpha}$) is related to the index q of the energy distribution of the electrons by $\alpha = (q-1)/2$.

The radio observations are the most obvious sign that particle acceleration is indeed going on in SNRs, although the radio traces only electrons. The radio images are clearly limb-brightened (*e.g.* Reynoso et al. 1997). The limb-brightening confirms that acceleration is indeed occurring at the shock, in contrast to plerions like the Crab where the electrons are accelerated in a central pulsar.

The spectral slope α in the radio varies from 0.4 to 0.7 (corresponding to q from 1.8 to 2.4), in general agreement with the prediction of the diffusive acceleration model. Variations exist both from place to place within one remnant (*e.g.* DeLaney et al. 2002) and from one SNR to another (Green 2004).

Polarisation is detected, at a level of 5 % or so. This is much smaller than the theoretical polarisation of synchrotron emission in an ordered magnetic field (70 % or so). The discrepancy can be due partly to integration along the line of sight (although this should be a small effect if the pre-supernova field was ordered) and to differential rotation (see next paragraph) between the near and the far side of the SNR. But the most likely reason is that the field is actually largely turbulent. This is required by the acceleration mechanism anyway (Sect. 3.3).

An interesting complication (Faraday rotation) is that the polarisation plane rotates when the wave travels in an ionised gas in a magnetic field (such as the SNR itself, but also the ionised interstellar medium between the SNR and us). This is characterised by the rotation measure RM ($\rm cm^{-3}$ G pc) $= \int n_e \, B_{//} \, ds$ along the line of sight. The polarisation

angle rotates by an amount $\Delta\Phi$ (deg) $= 4.1 \times 10^3\, \lambda^2_{\rm cm}$ RM. The rotation measure can be estimated by measuring the polarisation angle at several wavelengths. It is usually dominated by the interstellar contribution. But in Kepler, Matsui et al. (1984) have shown a clear spatial correlation between the rotation measure and the X-ray emission (mostly thermal). This led them to estimate the ordered field at 15 μG and the full field at 74 μG.

The magnetic field direction estimated from polarisation varies a lot at large scale, (*e.g.* Matsui et al. 1984; DeLaney et al. 2002). In young remnants, it tends to be dominantly radial. This might be due to the magnetic stretching induced by the Rayleigh-Taylor instability at the interface with the ejecta. In older remnants, it tends to be dominantly tangential. This can naturally be explained because the tangential component of $\vec{B}$ at the shock is enhanced (by the compression factor R) whereas the radial component is conserved.

2.2 Infra-red domain

Most of the infra-red emission (at wavelengths 10 μm and beyond) is due to dust heated by the thermal electrons. This cannot teach us much about the accelerated particles. However the synchrotron emission must be present at some level below that. The easiest band for detection is the near infra-red (a few μm), and it was recently detected in Cas A for the first time (Jones et al. 2003). When the sensitivity of that method gets better, it holds the promise of measuring the curvature of the synchrotron spectrum (between the radio and the IR band) predicted by the non-linear models (Sect. 3.4).

2.3 Optical domain

Most of the optical emission is due to radiative shocks in interstellar clouds, not relevant to particle acceleration. However, Chevalier & Raymond (1978) discovered that fainter Balmer lines (characteristic of non-radiative shocks) are emitted at the blast wave itself (whatever its velocity) if the ambient medium was partly neutral (which is the general case). Then excitation of the hydrogen atoms (leading to the Balmer lines) occurs in parallel to the ionisation. The neutral atoms do not "see" the collisionless shock, so they are still cold and give rise to narrow lines. An interesting complication is that charge exchange between the neutrals and the (hot) protons also occurs, leading to a population of hot neutrals which give rise to broad lines.

The fine spectroscopy of the Balmer lines then provides two interesting observables : the width of the broad component (directly related to the proton temperature) and the ratio between the flux in the narrow

and broad component. That ratio depends on the electron temperature. This was applied to SN 1006 (Ghavamian et al. 2002) leading to $T_p \simeq 10$ keV and $T_e \simeq 0.7$ keV.

Proper motion measurements, either in the radio (DeLaney & Rudnick 2003), the optical (Winkler et al. 2003) or the X-rays (Hughes 1999), combined with the knowledge of the distance to the SNR, sometimes provide an independent estimate of the shock velocity. Putting together the electron and ion temperatures and the shock velocity, it should be possible (although I don't know of any definite application yet) to derive the fraction of the shock ram pressure which goes into thermal pressure, and deduce the fraction which goes into cosmic-rays (Sect. 3.4).

2.4 X-ray domain

Most of the X-ray emission is thermal, due to shock heated gas at a temperature of several million degrees. It is dominated by the atomic lines of heavy elements (from O to Fe), and is particularly strong in young SNRs, because of the metal-rich ejecta. This is not directly related to particle acceleration, but can be used to infer several important parameters, primarily the electron temperature and the gas density. It is also useful for tracing the interface between the ejecta and the ambient gas in young SNRs.

In some SNRs like SN 1006 (Koyama et al. 1995) the tail of the synchrotron emission is clearly observed in X-rays (1 keV = 2.4 10^{17} Hz). The electrons responsible for the X-ray emission must have energies near the cut-off of the electron distribution (several 10^{13} eV). The frequency at which this cut-off occurs is related (via Eq. 2) to the product $B\,E_{\rm cut}^2$. It was shown recently (Sect. 3.2) that synchrotron emission is present (at some level) in all young SNRs.

At higher energy (above 10 keV), a tail is detected in several young SNRs (*e.g.* Allen et al. 1997). This can be due either to synchrotron emission by very high energy electrons or to bremsstrahlung emission by suprathermal electrons (Sect. 3.1).

2.5 γ-ray domain

The same high energy electrons emitting synchrotron X-rays emit γ-rays by inverse Compton on the photon field. The ratio of the inverse Compton to the synchrotron emission is equal to the ratio of energy densities $U_{\rm ph}/U_B$. When the local photon field is weak (often the case, but not in Cas A), $U_{ph} \simeq U_{\rm CMB}$ is dominated by the 3 K cosmic microwave background. $U_B = B^2/(8\pi)$ (CGS) is equal to $U_{\rm CMB}$ for $B = 3.27$ μG. When the γ-ray emission is observed, as in SN 1006 (Tanimori et al. 1998), its ratio to synchrotron X-rays provides an estimate of the total magnetic field within the SNR ($\simeq 10$ μG in SN 1006). The ratio of the

inverse Compton component (on the CMB only) to the power-law part of the synchrotron component (at the same frequency) is

$$F_{\rm IC}(\nu)/F_{\rm sync}(\nu) \; = \; A(\alpha) \; (B_{\mu\rm G} \sin\theta)^{-(1+\alpha)} \qquad (3)$$

$A(\alpha)$ may be derived from the standard synchrotron and inverse Compton formulae (*e.g.* Rybicki & Lightman 1979). For a typical (for young SNRs) spectrum in $\nu^{-0.6}$, $A(0.6) = 2.75 \times 10^{-4}$.

The cosmic-ray protons may also radiate in γ-rays (above 70 MeV), by π_0 decay following nuclear interactions with the interstellar gas. The GeV range is thus the most favorable one to detect directly the accelerated protons (the rest of the non-thermal emission is due entirely to the electrons, which make up only a few % of the energy density in cosmic-rays). This process is expected to dominate over inverse Compton by electrons when the density (targets for the nuclear reactions) is larger than 1 cm^{-3} or so (Ellison et al. 2000).

2.6 Broad-band emission models

Reynolds (1998) has modelled the synchrotron emission for various assumptions about the limiting energy of electrons at the shock, within the framework of the Sedov model. He neglected cosmic-ray feedback (*i.e.* he assumed a purely gas shock with $R = 4$). He modelled the effect of magnetic orientation (assuming a uniform pre-supernova field), with a prescription predicting stronger acceleration where $\vec{B}$ is perpendicular to the shock speed (parallel to the shock surface). This results in a maximum emission in an equatorial belt and a minimum at the magnetic poles.

Sturner et al. (1997) included all non-thermal emission processes (adding inverse-Compton and π_0 decay), and accounted for the early stages of the SNRs (before the Sedov phase). They did not consider cosmic-ray feedback either, and their geometry was very simple (one zone).

Baring et al. (1999) and Ellison et al. (2000) improved upon Sturner et al. (1997) by including all continuous emission processes (adding bremsstrahlung) and accounting for cosmic-ray feedback.

Decourchelle et al. (2000) considered X-ray line emission after cosmic-ray feedback, in the framework of self-similar models of young SNRs. Ellison et al. (2004) included the same ingredients in a 1-D hydrodynamic code, allowing to follow what happens outside the self-similar solutions.

Another type of code (*e.g.* Berezhko et al. 2002) tries to couple hydrodynamics and particle diffusion explicitly (the ones mentioned above use a simple prescription for particle acceleration). This is more exact but also more computationally intensive.

3. Specific issues

3.1 The ejecta – ambient gas interface

In young SNRs, something specific clearly happens at the interface, as can be seen from the examples of Cas A (Gotthelf et al. 2001) and Tycho (Hwang et al. 2002). The interface, rather than the blast wave itself, is the place where the radio emission peaks. The overall X-ray emission (mostly thermal) peaks there as well (because the metal-rich ejecta dominate the line emission). A distinct correlation thus exists between the radio and X-ray (lines + continuum) images.

However, it does not mean that this correlation actually reveals a common physical origin. In particular, in most cases (but see below the specific case of Cas A), the X-ray non-thermal emission is not very strong at the interface. This probably means that the electrons have lost energy (adiabatically or through synchrotron cooling) as they were advected from the blast wave to the interface, and were not reaccelerated there. As a result the cut-off frequency is lower than the X-ray range. The origin of the bright radio emission is probably related to magnetic field amplification at the interface (in Cas A, it is estimated at 1 mG or so there), due to Rayleigh-Taylor instabilities.

In Cas A, the X-ray non-thermal emission does peak at the interface (is correlated with the line emission), as can be seen from the XMM/EPIC map above 8 keV (Bleeker et al. 2001). The reason for that (Vink & Laming 2003) is probably acceleration of low-energy (suprathermal) electrons in the weak shocks induced by the bullets of dense ejecta overtaking the interface. The radiation process is bremsstrahlung. This mechanism cannot accelerate particles to very high energies (it is not an additional source of cosmic-rays), and it does not seem to play a role in remnants without very clumpy ejecta like those of SN Ia (Tycho).

3.2 The nature of the X-ray emission behind the blast wave

It was originally thought that the X-ray emission behind the blast wave would be the thermal emission of the shocked ambient gas. But the *Chandra* results challenged that preconception. The images of the continuum emission (4 to 6 keV) in Cas A (Gotthelf et al. 2001) and Tycho (Hwang et al. 2002) show clearly that it originates in a very thin sheet just behind the blast wave. Most of the volume between the blast wave and the interface with the ejecta is actually X-ray dark. The physical width of the emission region is less than $4''$ or $\Delta r = 2 \times 10^{17}$ cm in Cas A (about 2% of the SNR radius), for a shock velocity around 5000 km/s (Vink et al. 1998) and appears to be twice lower at places. Since this is observed in projection, the scale height of the spherical layer must be even smaller.

This is inconsistent with thermal models in a uniform medium which predict emission everywhere up to the interface, with only a slight maximum at the blast wave. This region (about 10% of the SNR radius) is full of hot gas, which cannot cool down efficiently at those low densities, as the gas moves away from the shock. The sharp observed decline of the X-ray emission behind the blast wave could be due to a recent density increase of the ambient gas, but it would have to be an extraordinary coincidence that this happens exactly at the same time all around the remnant and in both remnants.

Another argument against a thermal origin is the nearly featureless nature of the spectrum. In a thermal framework, this can be explained if ionisation is far out of equilibrium (Hwang et al. 2002; Cassam-Chenaï et al. 2004), but much further than expected with the density required to explain the brightness.

The only other possible source of X-ray radiation is the accelerated particles. Non-thermal bremsstrahlung (by low-energy suprathermal electrons) has the same difficulties as thermal bremsstrahlung. The density of targets (the thermal gas) does not decline steeply behind the shock, and collisional losses are not strong enough to get rid of the particles themselves as they are advected downstream.

The only remaining option is synchrotron emission by high energy electrons. Here again, advection of the particles and the magnetic field (with only slight adiabatic losses) cannot explain the very sharp drop behind the shock. On the other hand, the particles may lose their energy radiatively fast enough as they are advected (so that their synchrotron emission is shifted below the X-ray range) to explain a very thin emission region if the magnetic field is large enough (Vink & Laming 2003). The synchrotron cooling time is

$$t_{\rm cool} = 398\ (B_{\rm G}\ \sin\theta)^{-2}\ E_{\rm TeV}^{-1}\ {\rm s} \quad (4)$$

$$t_{\rm cool} = 1.75\times10^{3}\ (B_{\rm G}\ \sin\theta)^{-3/2}\ {\rm s} \quad (5)$$

The second equality is obtained at the energy required to emit X-rays of 1 keV, say, using Eq. 2. This is the only model which is able to provide a satisfactory explanation for the geometry of the X-ray emission behind the blast wave. The radio emission starts at the same place (the shock), but decreases much more slowly behind the shock (Long et al. 2003). This is very consistent with the model, since the electrons which emit the radio emission (10^4 times less energetic) sustain negligible cooling.

This implies that the density (or the temperature) of the ambient gas must be low enough that it does not contribute to the X-ray emission. This is possible if the post-shock density is less than 0.15 cm^{-3} in Kepler (Cassam-Chenaï et al. 2004). The constraint for Tycho and Cas A is probably a little less severe.

Quantitatively, the magnetic field must be large enough to ensure that $t_{\rm cool}$ is smaller than the advection time $t_{\rm adv} = R\Delta r/v_{\rm sh}$ over the observed width of the emission region (another condition, which I ignore here, is that the diffusion length must be smaller than the width of the emission region as well). In Cas A or Tycho, this imposes B $>$ 100 μG or so.

It is a very important result because it provides observational evidence for the idea (Bell & Lucek 2001) that diffusively accelerated particles streaming ahead of the shock are able to generate a turbulent magnetic field larger than the original ordered field (which cannot be larger than a few μG in such surroundings). This is the key for pushing the Lagage & Cesarsky (1983) limit (Eq. 1) up to the 'knee' of the cosmic-ray distribution at 3 10^{15} eV.

In SN 1006 it has been long known that the X-ray emission in the bright limbs is synchrotron by high energy electrons. The downstream profile in that remnant is not everywhere as sharp as in Cas A or Tycho. But it is comparable in the filaments where the downstream width is minimum (Bamba et al. 2003). This can be easily explained if the magnetic field is large as well.

The consequence of a large magnetic field is that, for the same observed synchrotron emission, the energy density of accelerated electrons must be smaller than previously estimated, hence the inverse Compton γ-ray emission as well (Sect. 2.5). For SN 1006, this means that the TeV emission reported by Tanimori et al. (1998) would have to be π_0 decay (Berezhko et al. 2002), which requires a large fraction of the shock's energy be used to accelerate the protons.

Another interesting issue is what happens in older remnants. Ptuskin & Zirakashvili (2003) have recently studied the balance between excitation of the turbulence (by the cosmic-rays streaming ahead of the shock) and damping (by non-linear wave interactions and ion-neutral collisions). They have shown that the ratio between the two processes depends a lot on the shock velocity. As a result, damping reduces the turbulence level considerably in older SNRs (to below the ordered field level).

3.3 The shock precursor in the ambient gas

The principle of diffusive acceleration predicts that the accelerated particles and the magnetic field should also be present some distance ahead of the shock. This means that synchrotron emission should be observed at some level upstream of the blast wave. Defining the turbulent field δB, and using Eq. 2 and assuming $R = 4$ (no cosmic-ray feedback)

for the second equation, the diffusion length is

$$l_{\rm diff} = \sqrt{2\,\kappa\,\tau_{\rm acc}} \simeq \sqrt{\frac{2\,R\,(R+1)}{3\,(R-1)}}\,\frac{c\,E}{e\,\delta B\,v_{\rm sh}} \quad (6)$$

$$l_{\rm diff} \simeq \frac{9.75\times10^{10}\ {\rm cm}}{\delta B\,v_{\rm sh}}\sqrt{\frac{\nu_{\rm el}}{B}} \quad (7)$$

The radio images ($\nu_{\rm el} \simeq 1$ GHz) are sharp-edged, though, with no evidence of any emission beyond the blast wave. The absence of such a precursor in the radio range (an upper limit on its width) implies an upper limit on the diffusion coefficient at the energy of electrons which radiate in the radio. This is equivalent to a lower limit on the turbulent field which is hundreds of times larger than the ordinary interstellar turbulence. This argument led Achterberg et al. (1994) to conclude that accelerated particles could indeed generate the turbulent field which is required for acceleration to be a fast process.

Because the diffusion coefficient (for a given level of turbulence) increases with energy, X-ray observations (corresponding to electron energies 10^4 times larger than radio observations) provide a much more stringent constraint. In Cas A and Tycho, the radial profile of the sharp X-ray filament appears symmetric (it does not decrease more steeply outwards than inwards), so one might think that the width used in Sect. 3.2 can be used as an upper limit to the size of the precursor.

It is not so, though, because the shock compression necessarily results in compression of the magnetic field. Assuming isotropic magnetic turbulence upstream and shock compression (of the two tangential components) by a factor R, the magnetic field downstream may be larger than upstream by a factor $\sqrt{(1+2R^2)/3}$, reducing the synchrotron emission and moving it to lower frequencies by the same amount. As a result the expected X-ray emission beyond the blast wave is quite small (Berezhko et al. 2003) and the present data does not allow constraining the shape of the precursor.

In SN 1006, there is no evidence of a precursor either. Long et al. (2003) argue that this could be explained with a large compression ratio (larger than 4), predicted by non linear acceleration models. Bamba et al. (2003) argue that it can be due to a perpendicular (to the shock normal) magnetic field. But Rothenflug et al. (2004), on the basis of the overall geometry of the X-ray emission, show that this cannot be true (the bright limbs must be polar caps rather than an equatorial belt). An alternative perhaps simpler (after the results of Sect. 3.2) explanation to the very weak or narrow precursor is that the magnetic field is large as well.

3.4 The fraction of energy channeled into particles

The diffusive acceleration mechanism may extract a large fraction (up to 50%) of the kinetic energy available (Drury 1983; Blandford & Eichler 1987; Berezhko & Völk 1997). If this is indeed the case, then the accelerated particles modify the shock (and their spectrum) in the following way (*e.g.* Berezhko & Ellison 1999; Baring et al. 1999) :

- a smooth precursor appears (ahead of the gas subshock) where the gas is slowed down (in the shock frame) and progressively compressed. This precursor is due to the high energy cosmic-rays (holding a large fraction of the cosmic-ray pressure) which reach far upstream.
- the gas subshock becomes weaker than a standard strong shock (compression ratio $R < 4$). This results in less gas heating (lower temperature for the same shock speed). Another way to see that is that the energy which goes into cosmic-rays is lost to the gas.
- energy is not conserved any more (because the highest energy particles escape) increasing the overall compression ratio (possibly to more than 10).
- the low energy particles diffuse only around the gas subshock (small R), whereas the high energy ones diffuse over the whole shock structure (large R). This leads to a concave particle spectrum (flatter at higher energy).

That so-called 'non-linear' model naturally predicts a radio spectrum (due to low-energy electrons) steeper than $\nu^{-0.5}$, contrary to a pure gas shock. This is indeed what is observed in young SNRs (Reynolds & Ellison 1992). The concave particle spectrum leads to a concave photon spectrum, so the real test would be to see a flatter index in the infra-red, say, than in the radio.

Using a simplified parameterisation of the cosmic-rays' feedback on the shock (Berezhko & Ellison 1999), it is possible to solve the dynamic equations (Decourchelle et al. 2000), adding a cosmic-ray fluid (relativistic, with $\gamma = 4/3$), and assuming it follows the gas (*i.e.* diffusion is not important at the SNR scale). One may then quantify on a true SNR the two other predictions of the model : small gas temperature and larger compression (narrower shell of emission).

The relatively hard X-ray spectrum of young SNRs, and in particular the strong Fe K line, indicates that diffusive acceleration is not very efficient at the reverse shock (Decourchelle et al. 2000). This could be because the magnetic field is very low there.

Separating the shocked ambient gas from the ejecta requires a very high spatial resolution and could not be done before *Chandra*. The spectrum of the shocked ambient gas in 1E0102.2-7219 (in the Small Ma-

gellanic Cloud) is so soft (compared to the shock speed inferred from expansion since *Einstein*) that it supports the idea that a large fraction of the energy does not end up in the thermal gas, but is diverted into something else like cosmic-rays (Hughes et al. 2000).

The shocked region is observed to be quite narrow in Tycho (Hwang et al. 2002) and Kepler (Cassam-Chenaï et al. 2004) (as predicted by models with efficient cosmic-ray acceleration), but not in Cas A (Gotthelf et al. 2001) nor in 1E0102.2-7219 (Gaetz et al. 2000). Future observations should help resolve the discrepancy. It could be because Cas A and 1E0102.2-7219 develop in the wind of their progenitor (r^{-2} density profile).

3.5 The geometry of the acceleration

A long standing issue is whether particle acceleration works better in a parallel (*e.g.* Berezhko et al. 2002) or perpendicular (*e.g.* Reynolds 1998) magnetic field ('parallel' or 'perpendicular' mean with respect to the shock speed). Many radio SNRs appear as two crescents of emission (like SN 1006, the prototype of that class). The most likely origin of that asymmetry is the initial orientation of the magnetic field. Fulbright & Reynolds (1990) interpreted those SNRs as being 'barrel-shaped', meaning that the crescents were the limb-brightened part of a fully axisymmetric emission maximum at the equator. This implied that acceleration works better in a perpendicular field.

Rothenflug et al. (2004) analysed the X-ray emission of SN 1006 in detail, and showed that this could not be true, because the X-ray emission toward the center of the SNR is so weak that it is incompatible with the equatorial maximum seen face on. This implies that the crescents are polar caps, and that acceleration works better in a parallel field, as expected from considerations on injection (Ellison et al. 1995). The spectral analysis actually shows that not only is the amount of accelerated particles larger at the poles, but the cut-off energy of the electrons is also quite low at the equator, even though synchrotron losses are probably not an issue there (no amplified magnetic field). This indicates that the acceleration rate in a perpendicular field is probably not as large as estimated by Jokipii (1987), who found that the acceleration should be very fast at perpendicular shocks even if the turbulence level is low.

Note that the results detailed in Sect. 3.2 show that the field is mostly turbulent. This is not contradictory with the geometry discussed here. What it means is that acceleration may start going only where the field was initially parallel. After some time the feedback of the cosmic-rays lead to a situation where the field is mostly turbulent. But this does not happen where the field was initially perpendicular. There the energy

density in cosmic-rays probably never reaches the point where they can make the field turbulent enough to facilitate acceleration.

4. Conclusions

The above considerations may be summarised as follows :

- There are strong indications that the (turbulent) magnetic field is amplified up to 100 μG at the blast wave in young SNRs. Electrons are limited by radiative losses, whereas protons may be accelerated up to 10^{15} eV.
- There are some indications (from the X-ray spectrum and the width of the emission region) that cosmic-ray acceleration is energetically important (takes away a sizable fraction of the energy) in those young SNRs.
- The X-ray geometry of SN 1006 favors acceleration where $\vec{B}$ was originally parallel to the shock speed (polar caps).
- The amplification of the magnetic field (and particle acceleration in Cas A) seen at the interface between the ejecta and the shocked ambient gas is probably due to a different mechanism (Rayleigh-Taylor instabilities and secondary shocks) which has nothing to do with diffusive shock acceleration, nor with the general problem of Galactic cosmic-rays.
- Shock acceleration does not seem to be as energetically important at the reverse shock into the ejected supernova material.

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