SHOCKS AND PARTICLE ACCELERATION IN SUPERNOVA REMNANTS: OBSERVATIONAL FEATURES

Jacco Vink *

ABSTRACT

The last ten years a number of observational advances have substantially increased our knowledge of shock phenomena in supernova remnants. This progress has mainly been made possible by the recent improvements in X-ray and γ-ray instrumentation. It has become clear that some shell-type supernova remnants, e.g. SN 1006, have X-ray emission dominated by synchrotron radiation, proving that electrons are accelerated up to 100 TeV. This is still an order of magnitude below $3 \times 10^{15}$ eV, at which energy the ion cosmic ray spectrum at earth shows a spectral break. So one of the major goals is to prove that supernova remnants are capable of accelerating ions at least up that energy.

Here I review the evidence that ions and electrons are accelerated up to energies $\sim 100$ TeV in supernova remnants, and, in addition, the recent progress that has been made in understanding the physics of collisionless shock fronts and the magnetic fields inside supernova remnants.

1. INTRODUCTION

Supernova remnant shocks are considered to be the prime source of cosmic rays for energies at least up to the “knee” at $\sim 3 \times 10^{15}$ eV and probably up to the “ankle” at $\sim 10^{18}$ eV (above which the cosmic rays are thought to be of extra-galactic origin). One of the main reasons is that supernova remnants (SNRs) are the only galactic sources that are able to provide the energy necessary to maintain the observed cosmic ray density, $10^{48}$ erg/yr, if about 10% of the average supernova kinetic energy is dumped into cosmic ray acceleration, and assuming a supernova rate of 1 every 50 - 100 yrs (e.g. Longair [1994]). Another reason is that radio synchrotron emission from SNRs have spectral indexes implying a spectral energy slope of $\sim -2.2$, consistent with the locally observed cosmic ray spectral index, which has a slightly steeper index due to propagation effects.

For a long time the observational evidence that SNRs are indeed the source of cosmic rays consisted solely of the observation of radio synchrotron emission, caused by the presence of relativistic electrons. In some cases SNRs may just light up the relativistic galactic background electrons by means of compressing the local magnetic field (van der Laan [1962]), but for the very bright, young, SNRs, the most likely explanation is that the electrons are accelerated by SNR shocks. A good example is the youngest and brightest known galactic SNR, Cassiopeia A (Cas A).

Although for these reasons it is likely that SNRs accelerate electrons to relativistic energies, at least up to several GeV, radio synchrotron emission does not prove that SNRs are capable of accelerating cosmic rays up to the “knee”, and, moreover, it only proves that electrons are being accelerated, whereas the cosmic rays observed at earth are dominated by ions. However, over the last decade evidence has been accumulating that cosmic rays are indeed being accelerated up to the “knee”. This progress has been made possible by the coming of age of X-ray astronomy, with missions like ASCA, BeppoSAX, RXTE, and, more recently Chandra and XMM-Newton. In addition, a lot has been learned from γ-ray observations with space based instruments like CGRO-EGRET and ground based Cherenkov telescopes such as Whipple HEGRA, and CANGAROO.

Although the detection of ion cosmic rays in SNRs can be considered one of the main goals of cosmic ray physics,
another important, but still poorly understood, aspect of cosmic ray physics is the injection mechanism at low energies. This process may be intimately connected to shock heating and temperature equilibration by collisionless shocks.

2. Shock Structure and Electron-Ion Temperature Equilibration

The particle collision length scales in supernova remnant shocks are much larger than the typical size of the shock structure. For instance, the young supernova remnant Cas A has a shock velocity of about 5000 km/s (Vink et al., 1998; Delaney & Rudnick, 2003) and a typical ion density of 5 cm$^{-3}$, implying that a proton entering the shock has a relative energy of $\sim 8$ keV. The deflection time scale for a proton, assuming proton proton interactions, is $\tau_{pp} \sim 800$ yr (e.g. Huba, 2002), more than the age of Cas A, which is about $\sim 320$ yr! So other, collective rather than two body, interactions, have to be at work to heat the gas behind a supernova remnant shocks. They are therefore referred to as collisionless shocks.

Although SNRs have collisionless shocks, the Hugoniot relations, which are based on the conservation of mass, momentum, and energy, are still valid. If we neglect, for the moment, the energy deposition in cosmic rays, and radiative losses, the Hugoniot relations in the limit of high Mach number shocks state (e.g. Zeldovich & Raizer, 1966; McKee & Hollenbach, 1980):

\[
\frac{\rho_{2,i}}{\rho_{1,i}} = \frac{\gamma + 1}{\gamma - 1} = 4 \tag{1}
\]

\[
kT_{2,i} = \frac{2(\gamma - 1)}{\gamma + 1)^2} \frac{m_i v_s^2}{3 \times 16 m_i v_s^2} \tag{2}
\]

where subscript 1 and 2 refer to the pre-shock and post-shock conditions for particle species $i$, with $v_s$ the shock velocity. The numerical values were obtained for $\gamma = 5/3$, the specific heat ratio for a monatomic gas. Note, however, that for a relativistic gas (i.e. the pressure is dominated by relativistic cosmic rays) $\gamma = 4/3$, giving a compression ratio of $\chi = 7$. The post-shock gas moves away from the shock front with a relative velocity of $u_2 = v_s/\chi$.

The shock jump conditions hold for each particle species $i$, and raises the question whether the, still poorly understood, mechanism for shock heating the particles will also tend to rapidly equilibrate the temperatures of the various particles involved. In addition, if a large neutral fraction exists in the pre-shock material, or the shock is moving through a medium with a high metal content (e.g. ejecta), a large fraction of the electrons behind the shock may originate from ionizations. These so-called secondary electrons have to be heated by primary electrons, resulting in an overall lower electron temperature than indicated by Eq. (2), see Itoh (1984).

The earliest indications that the electron and ion temperatures are indeed not equilibrated are the relatively low electron temperatures inside SNRs, which, according to X-ray observations, in no object seem to exceed 5 keV, whereas a typical shock velocity of 4000 km/s should give rise to a mean plasma temperature of 19 keV.

More direct evidence for only modest equilibration of electrons and ions behind SNR shocks comes from optical and UV spectroscopy. H$\alpha$ emission from non-radiative shocks in a number of SNRs is characterized spectroscopically by a narrow component and a broad component (Ghavamian et al., 2001). The narrow component is thought to come from neutral hydrogen briefly excited after being overtaken by the shock. The broad component is the result of charge exchange between neutral and ionized hydrogen. The ionized hydrogen is heated according to Eq. (2), and after charge exchange, which leaves the atom in an excited state, the thermal motion of the heated hydrogen gives rise to Doppler broadening. The width of the broad line component can be used to determine the shock velocity, if the equilibration fraction is known (see Eq. (2)). The equilibration fraction is determined from the ratio between the narrow and broad component (Ghavamian et al., 2001).

Several SNRs with broadened H$\alpha$ emission are known (e.g. Smith et al., 1991; Ghavamian et al., 2001). In particular the work by Ghavamian et al. (2001, 2002) provides clear evidence that the youngest SNRs, i.e. the ones with large shock velocities such as SN 1006 and Tycho, have a large ratio between the electron and proton temperatures ($T_e/T_p < 0.07$). Additional proof for low equilibration behind the shock front of SN 1006 comes from UV spectra
Fig. 1. Evidence for non-equilibrated oxygen and electron temperatures behind the shock front in the northwest of SN 1006 based on XMM-Newton observations (Vink et al., 2003). On the left: XMM-Newton EPIC-MOS (lower) and EPIC-PN (x5) spectra with best fit nonequilibrium ionization model. On the right: XMM-Newton RGS1 spectrum of the O VII line emission. The best fit model (solid line) has a significant thermal broadening; the best fit model without broadening is indicated by the dotted line.

obtained with the Hopkins Ultraviolet Telescope, which show broad C IV, N V and O VI lines, indicating temperature non-equilibration of these elements (Laming et al., 1996).

Very recently Vink et al. (2003) determined the amount of electron-oxygen equilibration from X-ray observations by XMM-Newton. The observation pointed at a bright, but narrow (0.4′ FWHM) knot in the northeast of SN 1006, which made it a good target for the XMM-Newton reflective grating spectrometer (RGS). The size of the knot translates into a spectral broadening of $\Delta \lambda \sim 0.05$ Å (FWHM) or a resolution power of $\lambda/\Delta \lambda \sim 430$ for the dominant O VII Heα line emission. However, SN 1006 itself is very extended (30′) and contributes to the spectrum as well. What made it, nevertheless, a good target for measuring the thermal Doppler broadening is that this knot is compact and lies at the edge of the remnant, making it very likely that Doppler broadening is due to thermal motions rather than internal bulk velocities.

Modeling of the O VII line emission, which consists of three bright lines, revealed both a very low ionization parameter, $\log(n_e t) \simeq 9.2$ (cgs units), and a substantial line broadening with $\sigma_B = 3.4 \pm 0.5$ eV at 540 eV (Fig. 2). The detection of broadening is statistically very significant (> 6.5σ level), and corresponds to a temperature for the oxygen ions of $kT = 528 \pm 150$ keV, or, according to Eq. (2), a shock velocity of $\sim 4100$ km/s. This is comparable, but somewhat faster, than the shock velocity inferred from the Hα emission ($\sim 3000$ km/s). This is not surprising as the X-ray emission comes from further downstream the shock front, where the plasma may have been shocked earlier, when the shock velocity was higher than at present. The electron temperature of the knot has been measured with the CCD instruments of XMM-Newton, and is $T_e = 1.5 \pm 0.2$ keV. Calculations of the plasma history show that the difference between electron and oxygen temperature support only a small equilibration fraction near the shock front ($\sim 5\%$), and subsequent equilibration proceeds through Coulomb interactions. A conclusion that, at least for the case of SN 1006, is based on optical, UV and X-ray spectroscopy.

3. COSMIC RAY ACCELERATION AND X-RAY SYNCHROTRON EMISSION FROM SHELL TYPE SNRS

The most likely mechanism for cosmic ray production in SNRs is first order Fermi acceleration, according to which an energetic particle repeatedly scatters upstream and downstream due to the presence of plasma waves. For each scattering the energy of the particle in the local frame is conserved, resulting in an increase in energy after each crossing of the shock front, i.e. after each change of local frame (see e.g. Bell, 1978; Blandford & Ostriker, 1978). As
the flow in the post shock region has a tendency to sweep the particles away from the shock front with a probability of $4u_2/v_s$, i.e. independent of the particle energy, the particle distribution is an inverse power law in momentum. The predicted power law index is $\Gamma = (2u_2 - u_1)/(u_1 - u_2) = (\chi + 2)/(\chi - 1)$, which corresponds to $\Gamma = 2$ for a shock compression ratio of $\chi = 4$.

The earliest evidence that SNRs are indeed sites of cosmic ray acceleration was their non-thermal radio emission, which for the brightest remnants could only be explained by assuming recent electron cosmic ray acceleration. The SNR radio emission is the result of synchrotron radiation caused by relativistic electrons with energies in the MeV to GeV range. Most shell-type SNRs have radio spectral indexes of $\alpha \sim 0.6$ (Stephenson & Green 2002), but some remnant have steeper spectra, like Cas A, which has $\alpha = 0.77$, steeper than predicted by simple first order Fermi acceleration theory, $\alpha = (\Gamma - 1)/2 = 0.5$. This is probably the result of the back reaction of the cosmic ray pressure on the shock structure. For a substantial cosmic ray pressure the flow ahead of the shock will be slowed down, as seen from the shock frame. As a result a shock pre-cursor forms and the density jump is smoothed over larger length scales (e.g. Eichler 1979, Bell 1987). Moreover the density jump experienced by relativistic particles depends on the particle’s gyroradius, i.e. particle energy. Very energetic particles will experience the full density jump from the undisturbed medium to the fully shocked plasma, whereas less energetic particles will only experience the difference between the shock precursor and the main shock, which may be less than the canonical factor 4 (see Eq. 2). As a result, the radio spectral index should be steeper at low radio frequencies than at high frequencies. This theory has been tested and confirmed for the Tycho and Kepler SNRs by Reynolds & Ellison (1992). Very recently Jones et al. (2003) reported that infrared observations of Cas A also indicate a flattening of the synchrotron spectrum at high frequencies.

An extreme case of cosmic ray modification of the shock structure is one in which the pressure is completely dominated by cosmic rays. In that case the shock structure is smooth instead of characterized by a distinct pressure jump. Malkov (1997) has shown that this will result in a particle index $\Gamma = 1.5$. It is not clear how physical this solution of the couple gas/cosmic ray model is, but there is no observational evidence that some SNR shocks are characterized by this extreme case of cosmic ray acceleration, which should be distinguishable by a rather flat radio index of $\alpha = 0.25$ and large energy losses due to escaping high energy cosmic rays (for $\Gamma \leq 2$ the highest energy cosmic rays carry most of the energy). $\Gamma = 1.5$ is also the spectral index expected for a relativistic gas with $\chi = 7$, but Malkov (1997) has shown that for cosmic ray dominated shocks $\Gamma = 1.5$ even for $\chi > 7$. 

---

**Fig. 2.** XMM-Newton (EPIC instruments) image of SN 1006. RGB color coded according to energy: 0.50-0.61 keV (red), 0.75 - 1.6 keV (green), and 2.0-7 keV (blue). Regions that show up bluish are dominated by synchrotron emission, whereas red regions have substantial O VII line emission. The image is based on mosaics of several observations; the exposure of the southwestern part was shorter, and is therefore noisier.
Although SNRs have the available energy to mark them as the primary sites of cosmic ray acceleration, one long standing questions is if they are capable to accelerate cosmic rays at least up to the observed break in the cosmic ray spectrum at $3 \times 10^{15}$ eV (Lagage & Cesarsky, 1983). A partial answer has been provided by the recent discovery that some shell-type SNRs, which usually are dominated by thermal X-ray emission, in fact also emit X-ray synchrotron radiation. This was first discovered in SN 1006.

For a long time the featureless X-ray spectrum of SN 1006 was difficult to explain by thermal radiation, as thermal radiation produces line emission. An interpretation invoking carbon rich, hot plasma, which suppresses line emission above 0.5 keV (Hamilton et al., 1986), became untenable after ASCA observations showed that SN 1006 does display line emission typical for hot plasma, but that the overall X-ray emission is dominated by continuum emission coming from the northeastern and southwestern rims of the remnant (Koyama et al., 1995). Fig. 2 illustrates this with XMM-Newton observations. This strongly suggested that synchrotron radiation is the dominant source of X-ray emission. The spectral index of $\sim 3$ (Vink et al., 2000; Allen et al., 2001; Dyer et al., 2001) is steeper than expected from Fermi shock acceleration, indicating that the photons were emitted by electrons with energies close to the maximum electron cosmic ray energy.

The spectral index of $\sim 3$ is steeper than expected from Fermi shock acceleration, indicating that the photons were emitted by electrons with energies close to the maximum electron cosmic ray energy.

The energy cut-off itself depends on the magnetic field strength and is approximately, for a photon cut-off energy of 1 keV,

$$E_e = 230 / \sqrt{B_{\mu}} \text{ TeV},$$

(3)

where $B_{\mu}$ is the magnetic field strength in $\mu$G. As the interstellar magnetic field strength is $\sim 6 \mu$G, and a shock compression factor of 4 may enhance it up to 20 $\mu$G, the implied electron cosmic ray cut-off energy is around 50 TeV. However, there is some dispute about the actual magnetic field strengths in SNRs, as will be addressed in the next section.

After SN 1006 X-ray synchrotron emission has been identified in a few other supernova remnants, notably Cas A (Allen et al., 1997), RXJ 1713.7-3946 (Koyama et al., 1997), RCW 86 (Borkowski et al., 2001; Bamba et al., 2000), and G266.2-1.2 (Slane et al., 2001). I will return to some of those objects below. Some of them have X-ray emission dominated by synchrotron radiation. However, the X-ray emission from Cas A is dominated by line emission, but a non-thermal tail of emission is seen at hard X-rays, which has been attributed to either synchrotron radiation or non-thermal bremsstrahlung (Allen et al., 1997; Favata et al., 1997; Bleeker et al., 2001; Vink & Laming, 2003).

4. COSMIC RAY ACCELERATION AND MAGNETIC FIELDS IN SNRS

The detection of synchrotron radiation in SN 1006 and other remnants has important consequences. On the one hand it is further proof that SNRs accelerate electrons, as the high electron cut-off indicates that the electrons can only have been accelerated recently. On the other hand, $\sim 100$ TeV seems to be the maximum attainable electron energy (Reynolds & Keohane, 1999), which is one order of magnitude lower than the energy at the “knee” of the cosmic ray spectrum.

The severity of the problem depends, however, on the nature of the cut-off of the electron cosmic ray spectrum. The ion and electron acceleration process is identical, apart from the initial cosmic ray injection, which means that if the energy cut-off is determined by the acceleration efficiency alone (i.e. the spectrum is age limited), the maximum electron energy is similar to the maximum ion energy. The electron energy cut-off is much less of a problem, if the magnetic fields in SNRs are greatly enhanced, and the spectra are loss limited, as losses affect predominantly the electron cosmic ray spectra. The relative importance of loss limitations to age limitations depends on the mean magnetic field strength of the medium through which the electrons move.

An additional effect of higher magnetic fields is that the acceleration is more efficient and age limitations of the ion cosmic ray spectrum can result in maximum energies beyond the “knee” energy. For that reason Biermann & Cassinelli (1993) proposed that most of the cosmic rays around the “knee” are produced in SNRs moving through the stellar winds of their progenitors, which may have enhanced the local magnetic field with respect to the average galactic magnetic field. An alternative idea is that the plasma waves generated by the cosmic rays result in non-linear behav-
ior, enhancing the background magnetic field (Bell & Lucek, 2001). In other words, once cosmic rays are present they may significantly enhance further cosmic ray acceleration. Vink & Laming (2003) proposed a way of measuring the magnetic field strength near the shock front of Cas A. Independently Bamba et al. (2003) proposed the same method for SN 1006. As an example I will concentrate on Cas A.

The main idea is that the narrow rim of X-ray continuum emission surrounding Cas A is indeed X-ray synchrotron emission (Gotthelf et al., 2001). Near the shock front, electrons are continuously being accelerated, but as soon as electrons move away from the shock front, radiative losses make that the electron population cuts off at progressively lower energies, until it no longer produce X-ray emission. The plasma moves downstream of the shock front with a velocity of $v_s$. So the timescale, $\tau$, for radiative losses is coupled to a length scale by $\Delta r = \frac{1}{4} v_s \tau$.

The shock velocity of Cas A has been measured to be $\sim 5000$ km/s (Vink et al., 1998; Delaney & Rudnick, 2003), whereas the width of the rim, i.e. the length scale $\Delta r$, is between $1.5''$ to $4''$. For a distance of Cas A of 3.4 kpc (Reed et al., 1995), this corresponds to loss times of 18 yr to 50 yr. The loss times are inversely proportional to $B^2 E_e$, whereas the photon energy corresponding to the electron energy ($E_e$) scales as $B E_e^2$. Combining the measured loss times and the fact that X-ray synchrotron radiation is observed around 5 keV allows the determination of the typical magnetic field strength near the shock front, which is about $10^{-4}$ G (Fig. 3), more than an order of magnitude higher than the average galactic field strength. Note that this approach assumes that the electrons at those high energies are still coupled to the plasma, i.e. the mean free particle path, $\lambda_{mfp}$, should be smaller than the rim width. In other words, the diffusion coefficient needs to be small. As this is a prerequisite for acceleration at those energies, this seems a reasonable assumption. In order to be self-consistent the mean free path in a radial direction should be larger than the gyroradius, $r_g$ for the derived magnetic. The mean free path is often parameterized as $\lambda_{mfp} = \eta r_g$, with $\eta \geq 1$ (c.f. Reynolds, 1998). The width of the rim implies $\lambda_{mfp} < 10^{17}$ cm$^2$, or $\eta < 100$ for $B = 0.1$ mG and $E \sim 50$ TeV.

The relatively high magnetic field in Cas A and SN 1006 suggests that rapid cosmic ray acceleration of electrons and ions is possible, and, as the electron population is loss limited, the ion cosmic rays can in principle be accelerated up to, or beyond the “knee”. In fact, close to the shock front even electrons may obtain high energies, as the electron...
energy indicated by Fig. 3 applies to the energy of the population downstream of the shock. 

Vink & Laming (2003) also used another method for estimating the average magnetic field strength inside Cas A, which consisted in comparing an upper limit on the non-thermal bremsstrahlung above 100 keV, assuming it is caused by the low energy part of the electron cosmic ray spectrum, and the overall radio flux (c.f. Cowsik & Sarkar, 1980; Atoyan et al., 2000).

The bremsstrahlung normalization scales with $n_e \Sigma_i n_i Z_i^2$, whereas the radio synchrotron emission scales with $n_e B^{(\Gamma+1)/2}$. As $\Sigma_i n_i Z_i^2$ is approximately known, the average relativistic electron density and magnetic field strength can be inferred. The measurements imply $B > 0.5$ mG, higher than the magnetic field strength near the shock. The reason is presumably magnetic field enhancements due to turbulence associated with the contact discontinuity of shocked ejecta and swept up circumstellar matter. This may explain why the brightest radio structure in Cas A is a shell coinciding with the ejecta shell, instead of with the outer rim.

The high overall magnetic field makes it unlikely that X-ray synchrotron radiation is coming from the bright radio and X-ray shell of Cas A; inside the bright shell the synchrotron loss time for the X-ray emitting electrons is only of the order of 10 yr, much less than the age of Cas A. As some hard X-ray emission seems to be associated with that bright shell (Bleeker et al., 2001), it is likely that another emission mechanism is contributing to the hard X-ray emission. Laming (2001a,b) has proposed that internal shocks produce lower hybrid plasma waves, which are responsible for accelerating electrons up to $\sim 100$ keV, where the observed X-ray spectrum has a cut-off. This predicted spectrum was found to be consistent with the hard X-ray spectrum obtained with a deep, 500 ks, BeppoSAX observation of Cas A (Vink & Laming, 2003, Fig. 4).

5. TeV EMISSION: EVIDENCE FOR HADRONIC COSMIC RAY ACCELERATION OR NOT?

So far our discussion has focused on electron cosmic rays, as they are most easily observed through synchrotron radiation and bremsstrahlung. However, hadronic cosmic rays are arguably the most important part of the cosmic rays, as they constitute the cosmic rays best observed at earth, and the ratio of hadronic to leptonic (electron) cosmic rays is roughly 100 : 1. The direct observation of ultra-relativistic in SNRs is therefore an important part of the proof that shock acceleration in SNRs is responsible for the observed cosmic ray spectrum up to the “knee”. This goal is coming nearer, or may even have been reached, with the recent advances made with telescopes observing Cherenkov radiation in the earth atmosphere caused by TeV $\gamma$-rays.

Although the electromagnetic radiation from relativistic ions is weak, ions colliding with background ions betray themselves by producing pions ($\pi^+, \pi^-, \pi^0$), which decay quickly into muons, positrons, electrons and neutrinos, except for $\pi^0$, which decays in 99% of the cases into two photons with energies of 68 GeV each in the $\pi^0$ rest frame.
Bremsstrahlung

Synchrotron

(interior)

IC

(shell)

IC

(interior)

Fig. 5. Observed continuum emission from Cas A (data points) and a simple model showing the expected contributions from electron cosmic rays (solid line). The emission is separated in two zones: 1) from a region near the outer shock with $B \sim 0.1 \text{ mG}$, which dominates the emission above 100 keV, and 2) from the interior of the remnant ($B > 0.5 \text{ mG}$), which dominates the radio synchrotron emission. The dashed line indicates inverse compton (IC), and the dashed-dotted line the bremsstrahlung contributions. The contributions from the shell and interior are separated. (Adapted from Vink & Laming, 2003).

The threshold for pion creation is 290 MeV. Well above the production threshold 30% of the particle energy will be transferred to the pion, and the emerging $\gamma$-ray spectrum will have a power law slope similar to the index of the particle spectrum.

Pion decay is the dominant component of the galactic background $\gamma$-ray emission above 1 GeV (Hunter et al., 1997). However, the situation for $\gamma$-ray emission from SNRs is not so clear. First of all, *CGRO-EGRET* detected only few of the known SNRs, most of which turn out to be older SNRs, like IC 443 and $\gamma$-Cygni (see Torres et al., 2003, for a review). Secondly, inverse Compton scattering of background photons by ultra-relativistic electrons is a very plausible, alternative, explanation for TeV $\gamma$-ray emission from young SNRs.

The first shell-type SNR detected above energies of 1.7 TeV is SN 1006 (Taninori et al., 1998). The discovery was made with the CANGAROO telescope. Less than two years before this detection the synchrotron nature of the X-ray emission had been established, so it was natural to suggest that the same electrons responsible for the X-ray synchrotron radiation were responsible for the $\gamma$-ray emission by means of inverse Compton scattering of cosmic microwave background (CMB) photons. As the normalization for inverse Compton scattering scales with $n_e n_{ph, CMB}$, and synchrotron radiation with $n_e B^{(\Gamma + 1)/2}$, with $n_{ph, CMB}$ the photon density, one can in principle infer the magnetic field from the ratio of the hard X-ray and TeV $\gamma$-ray emission, which turns out to be $B = 6.5 \pm 2 \mu \text{G}$ (Taninori et al., 1998).

However, this is only valid if the TeV emission is indeed due to inverse Compton scattering. Berezhko et al. (2002) recently argued that from a theoretical point of view a higher magnetic field is preferred, a point of view that seems to be supported by the magnetic field measurement by Bamba et al. (2003). This would mean that the relativistic electron density necessary to explain the X-ray synchrotron spectrum can be lower, which decreases the inferred inverse Compton scattering contribution and the maximum electron energy (Eq. 5). Berezhko et al. (2002) argue that therefore pion decay is the likely origin of the TeV $\gamma$-ray emission from SN 1006. An additional argument against dominant inverse Compton scattering above 1 TeV is that the $\gamma$-ray emission seems to come from the northeastern side of SN 1006, whereas the synchrotron radiation, caused by the same electrons that upscatter background photos, is observed from both the northeastern and southwestern rims of the remnants (Fig. 4). In the case of pion decay this asymmetry could be explained by the presence of a density enhancement in the vicinity of the northeastern rim.

Two other young remnants have been discovered by Cherenkov telescopes. Cas A was detected at the 4.9$\sigma$ level with the *HEGRA* telescope (Aharonian et al., 2001). For Cas A the case for pion decay as the origin for the TeV emission is even more compelling than for SN 1006, although still not conclusive. As explained in the previous section, the average magnetic field inside Cas A is $> 0.5 \text{ mG}$, which means that the electron synchrotron loss time is short, making it unlikely that most electron populations inside Cas A extend all the way up to 100 TeV, even if most of the hard X-ray emission is synchrotron radiation. This makes inverse Compton emission a less likely mechanism for
producing TeV emission. However, as Vink & Laming (2003) have shown (see previous section), the magnetic field near the shock front is $\sim 0.1$ mG, and the relativistic electron density is somewhat higher. Moreover, Cas A itself is a bright infrared source, so that more background photons are present, which have on average a higher energy as well (Atoyan et al., 2000). This gives rise to the additional complication of an anisotropic photon field. Despite these reservations, Vink & Laming (2003) argue that pion decay and not inverse Compton emission is the likely source for the TeV emission, but not by a wide enough margin to be completely confident that the inverse Compton scattering interpretation can be excluded (Fig. 5).

Of the three remnants detected above 1 TeV, RXJ 1713.7-3946 is the most surprising one. The remnant was discovered with ROSAT (Pfeffermann & Aschenbach, 1996), and ASCA spectra showed that the X-ray emission was dominated by non-thermal radiation (Koyama et al., 1997). The detection of TeV emission was made with the CANGAROO telescope (Muraishi et al., 2000).

One of the interesting features of RXJ 1713.7-3946 is that it is probably an old remnant, judged by its size of $\sim 34'$ and the likely association with a molecular cloud at a distance of roughly 6 kpc (Slane et al., 1999), whereas it is still a source of X-ray synchrotron radiation. The cosmic ray spectra in older remnants is likely to be loss limited, but the maximum electron energy is proportional to the shock velocity for loss limited models (Reynolds, 1998), which means that older remnants are not expected to produce considerable X-ray synchrotron radiation.

As pointed out by Slane et al. (1999) some of this problem may be alleviated, if RXJ 1713.7-3946 is a remnant evolving in stellar wind cavity. In that case the shock velocity remains high until it encounters the cavity wall, after which the remnant is believed to brighten rapidly and radiate most of its energy away in a relatively short time. Another surprising feature of this remnant is that no evidence has turned up yet that there is thermal X-ray emission coming from this remnant, unlike SN 1006. This is only possible, if either the electron temperature is very cool (below 0.1 keV), or the density inside the remnant is very low, (cf. SN 1006 which has $n_e \sim 0.1$ cm$^{-3}$).

The fact that the X-ray emission from RXJ 1713.7-3946 is synchrotron dominated suggested, as it did for SN 1006, that the emission above 1 TeV is caused by inverse Compton emission. However, recent observations with CANGAROO showed that the 1-10 TeV $\gamma$-ray spectrum, in combination with the X-ray spectrum, is incompatible with inverse Compton emission, and that it is therefore likely that the $\gamma$-ray emission is the result of pion decay (Enomoto et al., 2002). The CANGAROO $\gamma$-ray spectrum would therefore be the first direct evidence that nucleons are accelerated by SNRs. However, shortly after the announcement that ultra-relativistic ions had finally been observed in SNRs both Reimer & Pohl (2002) and Butt et al. (2002) pointed out that the spectrum of a nearby and possibly associated CGRO-EGRET source, 3EG J1714-3857, was not consistent with a pion decay spectrum from RXJ 1713.7-3946, as the CGRO-EGRET data points lie below the pion decay model. Although an obvious objection is that 3EG J1714-3857 and RXJ 1713.7-3946 do not spatially coincide, it is hard to believe that CGRO-EGRET detected 3EG J1714-3857, whereas a brighter nearby source should have been missed.

6. THE COSMIC RAY INJECTION EFFICIENCY

One topic not yet addressed in this article is the injection process and injection efficiency of cosmic rays. Our knowledge of the injection process, especially for electrons, is limited, but some progress has been made over the last decade (e.g. Bykov & Uvarov, 1999), and computers are now powerful enough to simulate the microscopic processes with particle in cell methods (Schmitz et al., 2002a,b).

The cosmic ray efficiency is also of major importance for the hydrodynamical modeling of supernova remnants, because, if a major fraction of the shock energy goes into accelerating particles, the plasma may become cosmic ray dominated, possibly increasing the shock compression ratio and lowering the mean gas temperature (Eq. 2). If the acceleration is very efficient, high energy particles may diffuse away from the remnant altogether, making the shock essentially radiative, under which conditions the compression ratio may even exceed a factor of 7 (e.g. Decourchelle et al., 2000). This has in fact been claimed for the Small Magellanic Cloud remnant 1E 0102.2-7219, for which Hughes et al. (2000) has shown that the electron temperature is lower than can be expected, based on the observed shock velocity, even when allowing for slow electron-ion temperature equilibration.
However, it should be pointed out that in most cases, even if very efficient cosmic ray acceleration takes place, it is not likely that the shocks becomes radiative or even acts like a relativistic gas with $\gamma = 4/3$. The reason is that most cosmic ray spectral indexes are observed to be $\Gamma > 2$, for which the total cosmic ray energy is dominated by non-relativistic cosmic rays. This can be illustrated for Cas A, as the magnetic field strength measurement allows for the estimation of the electron cosmic ray density normalization, which turns out to be $\kappa \sim 5 \times 10^{-11}$ (cgs). If we integrate the number density, assuming a power law spectrum in momentum, we find that the number of particles above $p_0 = 0.01 m_p c$ (somewhat arbitrary, but following Bell [1987]) is $\sim 8 \times 10^{-4} (\zeta + 1)$, with $\zeta$ the ratio of nucleonic to electron cosmic rays. As the thermal particle density in Cas A is about 20 cm$^{-3}$ and $\zeta$ is generally believed to be in the range 1-100, we find a cosmic ray injection efficiency between $\phi = 4 \times 10^{-5}$ to $4 \times 10^{-3}$. Interestingly, this range in injection efficiencies coincides with the transition from thermally dominated pressure to cosmic ray dominated pressure (Bell [1987]), suggesting that perhaps the acceleration process is indeed self-regulating. Note, however, that for the steep cosmic ray spectrum of Cas A the cosmic ray pressure is dominated by non-relativistic nucleonic cosmic rays.

Our understanding would be greatly advanced if we could observe the injection spectrum directly. Vink et al. [1997] suggested that the the X-ray spectrum from certain parts of RCW 86, which are characterized by featureless spectra except for the presence of iron line emission at 6.4 keV, could be explained by a low temperature electron gas with a non-thermal bremsstrahlung tail, which also causes line emission from underionized iron (see also Vink et al., 2002). This non-thermal tail may be caused by the electron cosmic ray injection spectrum. However, Rho et al. (2002) have shown that such a bi-modal electron distribution will quickly evolve toward a Maxwellian distribution, resulting in more line emission. They prefer to explain the observed spectral features by assuming that the continuum is X-ray synchrotron radiation, whereas part of the plasma inside the remnants consists of a hot, low density, pure iron gas (see also Bamba et al., 2000; Borkowski et al., 2001; Bykov, 2002).

7. CONCLUDING REMARKS

I have reviewed the current observational evidence for efficient cosmic ray acceleration by the collisionless shocks in supernova remnants. For a long time the evidence consisted only of the observed non-thermal radio spectra, but the last decade the more important evidence has come from X-ray and $\gamma$-ray observations, which indicate that electrons are accelerated up to 100 TeV. However, direct evidence that SNRs accelerate cosmic rays up to, or beyond, the “knee”, and that both electrons and ions are accelerated, is not unambiguous yet. This situation is likely to improve considerably over the next five years, with new space missions like INTEGRAL and GLAST, and the completion of new Cherenkov telescopes, such as HESS.

ACKNOWLEDGEMENTS

It wish to express my gratitude to Martin Laming, Johan Bleeker, and Jelle Kaastra, my collaborators on some of the topics discussed here. This work is supported by the NASA through Chandra Postdoctoral Fellowship Award Number PF0-10011 issued by the Chandra X-ray Observatory Center, which is operated by the Smithsonian Astrophysical Observatory for and on behalf of NASA under contract NAS8-39073.

REFERENCES

Aharonian, F., et al., Evidence for TeV gamma ray emission from Cassiopeia A, Astron. Astroph., 370, 112-120, 2001.
Allen, G. E., et al., Evidence of X-ray synchrotron emission from electrons accelerated to 40 TeV in the supernova remnant Cassiopeia A, Astrophys. J., 487, L97-L100, 1997.

1This follows from the integration over the cosmic ray spectrum, $\int_{E_0}^\infty \kappa E^{-\Gamma} EdE$.

4See the previous footnote. $\kappa$ normalizes the total number of electron cosmic rays per cm$^{-3}$ (for Cas A $\Gamma = 2.55$).
Allen, G. E., Petre, R., & Gotthelf, E. V., X-ray synchrotron emission from 10-100 TeV cosmic-ray electrons in the supernova remnant SN 1006, Astrophys. J., 558, 739-752, 2001.

Atoyan, A. M., Aharonian, F. A., Tuffs, R. J., & Völk, H. J., On the gamma-ray fluxes expected from Cassiopeia A, Astron. Astroph., 355, 211-220, 2000.

Bamba, A., Koyama, K., & Tomida, H., Discovery of non-thermal X-rays from the shell of RCW 86, Publ. Astron. Soc. Japan, 52, 1157-1163, 2000.

Bamba, A., Yamazaki, R., Ueno, M., & Koyama, K., Fine structure of the thermal and non-thermal X-rays in the SN 1006 shell, submitted to Adv. Space Res.(these proceedings), 2003.

Bell, A. R., The acceleration of cosmic rays in shock fronts, Mon. Not. Roy. Astron. Soc., 182, 147-156, 1978.

Bell, A. R., The non-linear self-regulation of cosmic ray acceleration at shocks, Mon. Not. Roy. Astron. Soc., 225, 615-626, 1987.

Bell, A. R. & Lucek, S. G., Cosmic ray acceleration to very high energy through the non-linear amplification by cosmic rays of the seed magnetic field, Mon. Not. Roy. Astron. Soc., 321, 433-438, 2001.

Berezhko, E. G., Ksenofontov, L. T., & Völk, H. J., Emission of SN 1006 produced by accelerated cosmic rays, Astron. Astroph., 395, 943-953, 2002.

Biermann, P. L. & Cassinelli, J. P., Cosmic rays. II. Evidence for a magnetic rotator Wolf-Rayet star origin, Astron. Astroph., 277, 691-706, 1993.

Blandford, R. D. & Ostriker, J. P., Particle acceleration by astrophysical shocks, Astrophys. J., 221, L29-L32, 1978.

Bleeker, J. A. M., Willingale, R., van der Heyden, K., Dennerl, K., Kastra, J. S., Aschenbach, B., & Vink, J., Cassiopeia A: On the origin of the hard X-ray continuum and the implication of the observed O VIII Ly-α/Ly-β distribution, Astron. Astroph., 365, L225-L230, 2001.

Borkowski, K. J., Rho, J., Reynolds, S. P., & Dyer, K. K., Thermal and nonthermal X-Ray emission in supernova remnant RCW 86, Astrophys. J., 550, 334-345, 2001.

Butt, Y. M., Torres, D. F., Romero, G. E., Dame, T. M., & Combi, J. A., Supernova-remnant origin of cosmic rays?, Nature, 418, 499-499, 2002.

Bykov, A. M., X-ray line emission from supernova ejecta fragments, Astron. Astroph., 390, 327-335, 2002.

Bykov, A. M. & Uvarov, Y. A., Electron kinetics in collisionless shockwaves, J. Theoretical and Experimental Phys., 88, 465-476, 1999.

Cowsik, R. & Sarkar, S., A lower limit to the magnetic field in Cassiopeia-A, Mon. Not. Roy. Astron. Soc., 191, 855-861, 1980.

Decourchelle, A., Ellison, D. C., & Ballet, J., Thermal X-Ray emission and cosmic-ray production in young supernova remnants, Astrophys. J., 543, L57-L60, 2000.

Delaney, T. & Rudnick, L., The first measurement of Cassiopeia A’s forward shock expansion rate, Astrophys. J., in press, 2003.

Dyer, K. K., Reynolds, S. P., Borkowski, K. J., Allen, G. E., & Petre, R., Separating thermal and nonthermal X-rays in supernovae remnants. I. Total fits to SN 1006 AD, Astrophys. J., 551, 439-453, 2001.

Eichler, D., Particle acceleration in collisionless shocks - Regulated injection and high efficiency, Astrophys. J., 229, 419-423, 1979.

Enomoto, R. et al., The acceleration of cosmic-ray protons in the supernova remnant RX J1713.7-3946, Nature, 416, 823-826, 2002.

Favata, F., Vink, J., Dal Fiume, D., Parmar, A. N., Santangelo, A., Mineo, T., Preite-Martinez, A., Kaastra, J. S., & Bleeker, J. A. M., The broad-band X-ray spectrum of the Cas A supernova remnant as seen by the BeppoSAX observatory., Astron. Astroph., 324, L49-L52, 1997.

Ghavamian, P., Raymond, J., Smith, R. C., & Hartigan, P., Balmer-dominated spectra of nonradiative shocks in the Cygnus Loop, RCW 86, and Tycho supernova remnants, Astrophys. J., 547, 995-1009, 2001.

Ghavamian, P., Winkler, P. F., Raymond, J. C., & Long, K. S., The optical spectrum of the SN 1006 supernova remnant revisited, Astrophys. J., 572, 888-896, 2002.

Gotthelf, E. V., Koralessky, B., Rudnick, L., Jones, T. W., Hwang, U., & Petre, R., Chandra detection of the forward and reverse shocks in Cassiopeia A, Astrophys. J., 552, L39-L43, 2001.

Hamilton, A. J. S., Sarazin, C. L., & Szymbkowiak, A. E., The X-ray spectrum of SN 1006, Astrophys. J., 300, 698-712, 1986.

Huba, J. D., NRL Plasma Formulary, 2002.

Hughes, J. P., Rakowski, C. E., & Decourchelle, A., Electron heating and cosmic rays at a supernova shock from Chandra X-ray observations of 1E 0102.2-7219, Astrophys. J., 543, L61-L65, 2000.

Hunter, S. D., et al., EGRET observations of the diffuse gamma-ray emission from the galactic plane, Astrophys. J., 481, 205-240,
Itoh, H., Temperature relaxation in supernova remnants, revisited, *Astrophys. J.*, 285, 601-606, 1984.

Jones, T. J., Rudnick, L., DeLaney, T., & Bowden, J., The identification of infrared synchrotron radiation from Cassiopeia A, *Astrophys. J.*, in press, 2003.

Koyama, K., et al., Discovery of non-thermal X-rays from the northwest shell of the new SNR RX J1713.7-3946, *Publ. Astron. Soc. Japan*, 49, L7-L11, 1997.

Koyama, K., Petre, R., Gotthelf, E. V., Hwang, U., Matsuura, M., Ozaki, M., & Holt, S. S., Evidence for Shock Acceleration of High-Energy Electrons in the Supernova Remnant SN:1006, *Nature*, 378, 255-258, 1995.

Lagage, P. O. & Cesarsky, C. J., The maximum energy of cosmic rays accelerated by supernova shocks, *Astron. Astroph.*, 125, 249-257, 1983.

Laming, J. M., Accelerated electrons in Cassiopeia A: An explanation for the hard X-ray tail, *Astrophys. J.*, 546, 1149-1158, 2001a.

Laming, J. M., Accelerated electrons in Cassiopeia A: Thermal and electromagnetic effects, *Astrophys. J.*, 563, 828-841, 2001b.

Laming, J. M., Raymond, J. C., McLaughlin, B. M., & Blair, W. P., Electron-ion equilibration in nonradiative shocks associated with SN 1006, *Astrophys. J.*, 472, 267-274, 1996.

Longair, M. S., High Energy Astrophysics. Vol.2: Stars, the Galaxy and the Interstellar Medium, Cambridge: Cambridge University Press, 2nd ed., 1994.

Malkov, M. A., Analytic solution for nonlinear shock acceleration in the Bohm Limit, *Astrophys. J.*, 485, 638-654, 1997.

McKee, C. F. & Hollenbach, D. J., Interstellar shock waves, *Ann. Rev. of Astron Astroph.*, 18, 219-262, 1980.

Muraiishi, H. et al., Evidence for TeV gamma-ray emission from the shell type SNR RX J1713.7-3946, *Astron. Astroph.*, 354, L57-L61, 2000.

Pfeffermann, E. & Aschenbach, B., in Roentgenstrahlung from the Universe, eds. Zimmermann, H.U., Trümper, and Yorke, H., 267-268, 2003.

Reed, J. E., Hester, J. J., Fabian, A. C., & Winkler, P. F., The three-dimensional structure of the Cassiopeia A supernova remnant. I. The spherical shell, *Astrophys. J.*, 440, 706-721, 1995.

Reimer, O. & Pohl, M., No evidence yet for hadronic TeV gamma-ray emission from SNR RX J1713.7-3946, *Astron. Astroph.*, 390, L43-L46, 2002.

Reynolds, S. P., Models of synchrotron X-rays from shell supernova remnants, *Astrophys. J.*, 493, 375-396, 1998.

Reynolds, S. P. & Ellison, D. C., Electron acceleration in Tycho’s and Kepler’s supernova remnants - Spectral evidence of Fermi shock acceleration, *Astrophys. J.*, 399, L75-L78, 1992.

Reynolds, S. P. & Keohane, J. W., Maximum energies of shock-accelerated electrons in young shell supernova remnants, *Astrophys. J.*, 525, 368-374, 1999.

Rh, J., Dyer, K. K., Borkowski, K. J., & Reynolds, S. P., X-ray synchrotron-emitting Fe-rich ejecta in supernova remnant RCW 86, *Astrophys. J.*, 581, 1116-1131, 2002.

Schmitz, H., Chapman, S., & Dendy, R. O., Electron preacceleration mechanisms in the foot region of high alfvenic Mach number shocks, *Astrophys. J.*, 579, 327-336, 2002a.

Schmitz, H., Chapman, S., & Dendy, R. O., The influence of electron temperature and magnetic field strength on cosmic-ray injection in high Mach number shocks, *Astrophys. J.*, 570, 637-646, 2002b.

Slane, P., Gaensler, B. M., Dame, T. M., Hughes, J. P., Plucinsky, P. P., & Green, A., Nonthermal X-Ray emission from the shell-type supernova remnant G347.3-0.5, *Astrophys. J.*, 525, 357-367, 1999.

Slane, P., Hughes, J. P., Edgar, R. J., Plucinsky, P. P., Miyata, E., Tsunemi, H., & Aschenbach, B., RX J0852.0-4622: Another nonthermal shell-type supernova remnant (G266.2-1.2), *Astrophys. J.*, 548, 814-819, 2001.

Smith, R. C., Kirshner, R. P., Blair, W. P., & Winkler, P. F., Six Balmer-dominated supernova remnants, *Astrophys. J.*, 375, 652-662, 1991.

Stephenson, F. R. & Green, D. A., Historical Supernovae and their Remnants, Oxford: Clarendon Press, 2002.

Tanimori, T. T., et al., Discovery of TeV gamma rays from SN 1006: Further evidence for the supernova remnant origin of cosmic rays, *Astrophys. J.*, 497, L25-L28, 1998.

Torres, D. F., Romero, G. E., Dame, T. M., Combi, J. A., & Butt, Y. M., Supernova remnants and gamma-ray sources, *Physics Reports*, in press, 2003.

van der Laan, H., Expanding supernova remnants and galactic radio sources, *Mon. Not. Roy. Astron. Soc.*, 124, 125-140, 1962.

Vink, J., Bleeker, J., Kaastra, J., Heyden, K. v. d., Rasmussen, A., & Dickel, J., Non-thermal bremsstrahlung as the dominant
hard X-ray continuum emission from the supernova remnant MSH14-63 (RCW 86), astroph/0202210, 2002.

Vink, J., Bloemen, H., Kaastra, J. S., & Bleeker, J. A. M., The expansion of Cassiopeia A as seen in X-rays, *Astron. Astroph.*, 339, 201-207, 1998.

Vink, J., Kaastra, J. S., & Bleeker, J. A. M., X-ray spectroscopy of the supernova remnant RCW 86. A new challenge for modeling the emission from supernova remnants, *Astron. Astroph.*, 328, 628-633, 1997.

Vink, J., Kaastra, J. S., Bleeker, J. A. M., & Preite-Martinez, A., The BeppoSAX X-ray spectrum of the remnant of SN 1006, *Astron. Astroph.*, 354, 931-937, 2000.

Vink, J. & Laming, J. M., On the magnetic fields and particle acceleration in Cassiopeia A, *Astrophys. J.*, 584, 758-769, 2003.

Vink, J., Laming, J. M., Gu, M. F., Rasmussen, A., & Kaastra, J., Slow temperature equilibration behind the shock front of SN 1006, *Astrophys. J.*, 587, L31-L34, 2003.

Vink, J., Laming, J. M., Kaastra, J. S., Bleeker, J. A. M., Bloemen, H., & Oberlack, U., Detection of the 67.9 and 78.4 keV lines associated with the radioactive decay of $^{44}$Ti in Cassiopeia A, *Astrophys. J.*, 560, L79-L82, 2001.

Zeldovich, Y. & Raizer, Y. P., Elements of Gasdynamics and the Classical Theory of Shock Waves, New York: Academic Press, edited by Hayes, W.D.; Probstein, Ronald F., 1966.