Tests of Galactic Cosmic Ray Source Models

Report of working group 4

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1. Introduction

The problem of understanding the origin of the Galactic Cosmic Rays (GCRs) is an old and recalcitrant one. It is actually several distinct problems. First, there is the question of the origin of the energy. What powers the accelerator and how does it work? Second, there is the question of the origin of the particles which are accelerated. Out of what component of the Galaxy does the accelerator select particles to turn into cosmic rays? Third, there is the question of how much of the observed cosmic ray spectrum is in fact of Galactic origin. Over what energy range does the accelerator work and what spectral form does its output have? Finally, there is the question of how many different types of accelerator are required. Can one basic process explain all the data, or do we need to invoke multiple sources and mechanisms? Of course a satisfactory physical model for the origin of the GCRs should simultaneously answer all these questions, however, in the context of looking for observational tests, it is sensible to adopt a “divide and conquer” strategy and regard them as separate questions.

The only theory of particle acceleration which at present is sufficiently well developed and specific to allow quantitative model calculations, and which appears capable of meeting many of the observational constraints on any cosmic ray acceleration theory, is diffusive acceleration applied to the strong shocks associated with supernova remnants. Thus this report concentrates, faute de mieux, on tests of this hypothesis, described in more detail in the next section.

2. SNR shocks as sources of the GCR energy

The fact that the power required to maintain the GCR population is estimated as a few to several percent of the mechanical energy input to the Galaxy from SNe explosions, together with a distinct lack of other plausible energy sources (with the possible exception of gamma-ray bursts, which also meet energy requirement), is a strong hint that
the ultimate power source for the GCR accelerator is to be found in SNe. However if the GCR were accelerated in the explosion itself, the adiabatic losses experienced by the GCR particles in pushing aside the ambient interstellar medium (ISM) would raise the energy requirements to an impossible level. Thus the acceleration site must be located in the subsequent supernova remnant (SNR) and in diffusive shock acceleration we have a convincing mechanism for doing this.

2.1. Predictions of nonlinear nonthermal shock models of SNRs

There have been substantial developments in our understanding of diffusive shock acceleration, especially as applied to SNR shocks, in the last several years (e.g., Berezhko & Voelk 2000; Berezhko & Ellison 1999; Ellison et al. 1997; Meyer et al. 1997). The key advance has been improved understanding of the nonlinear reaction effects of the accelerated particles on the shock structure, an essential aspect if the process is to operate with high efficiency. One of the most promising aspects of this work is that, despite the uncertainties and the ad-hoc assumptions that still have to be made, there appears to be good agreement between the different approaches. Specific predictions of all nonlinear nonthermal shock models ranging from simple fluid models through various Monte Carlo and kinetic models to asymptotic analytic theories are the following:

- An extended precursor region on the upstream side of the shock in which the material flowing into the shock is decelerated, compressed and heated and where the magnetic field is strongly disturbed.

- A subshock, essentially a conventional shock, marking the transition from the upstream precursor region to the downstream region; relative to shock models without particle acceleration the overall compression ratio is significantly enhanced, but the subshock ratio is reduced.

- Lower postshock temperatures downstream (relative to shock models without particle acceleration), but preheating of the bulk plasma on the upstream side of the subshock both through adiabatic compression and dissipation of the intense magnetic turbulence.

- Accelerated particle momentum distribution functions which are close to power-law, but slightly concave and “hard”, over an extended region between the thermal peak and the upper cut-off.
Thermal and non-thermal ion populations which join smoothly through non-Maxwellian tails on the quasi-thermal shocked distribution and an energy content in the accelerated particle population which is a significant part of the shock energy budget.

The length and time scales associated with the precursor structure are determined by the diffusion of the accelerated particles in the shock neighbourhood. It is important to note that, because of the strongly perturbed magnetic field, the diffusion coefficients are very much smaller than in the general interstellar medium. The usual assumption which is made is that the diffusion obeys Bohm scaling with a mean free path which is of order the particle gyro-radius. If particles are efficiently accelerated up to the maximum energy allowed by the geometry and age of the shock, the precursor length-scale for the highest energy particles will typically be of order one tenth the shock radius and proportionally less at lower energies.

2.2. Observational tests of SNR source models

2.2.1. Radio diagnostics

Radio observations of electron synchrotron emission, because of the excellent sensitivity and angular resolution of modern radio telescopes, are powerful probes of the distributions of relativistic electrons and magnetic fields in and around SNRs. Unfortunately the magnetic fields are usually only poorly known and this considerably complicates the interpretation of the radio data in isolation. Another problem is that, since the characteristic emission frequency scales as the electron energy squared, a very wide spectral range of synchrotron emission must be observed to learn about any appreciable energy range of the electron spectrum. And of course the observations tell us nothing directly about accelerated ion populations. However, for conventional magnetic fields of a few $\mu$G and observing frequencies in the GHz range the emission is dominated by electrons of a few GeV energy, so the radio studies typically sample electrons of comparable energies and rigidities to the mildly relativistic protons which dominate the energy density of the Galactic cosmic rays and there is not reason to suppose that at these energies the transport and acceleration of electrons is very different to that of protons.

The simple test-particle theory of shock acceleration gives a fixed relation between the shock compression ratio $r$ and the electron differential energy spectral index, $s = (r + 2)/(r - 1)$, which in turn is related to the synchrotron spectral index, $\alpha \equiv (s - 1)/2$. If the equation of state is close to that of an ideal gas with a ratio of specific heats $\gamma = 5/3$, then all strong shocks have $r \approx 4$ and thus $s = 2$, ...
implying synchrotron spectral indices $\alpha = 0.5$. At radio frequencies, values below 0.5, commonly observed among Galactic shell remnants, then either require lossy shocks with compression ratios above 4 (either radiative shocks or efficient cosmic-ray-accelerating shocks), or confusion with flat-spectrum thermal radio emission. Values above 0.5 in the test-particle picture require weak shocks, unacceptably so for young remnants such as Tycho or Kepler (data in Green, 1998), or curved spectra (hardening to higher energies) as predicted by nonlinear acceleration models (Ellison and Reynolds, 1991). The curvature not only gives direct evidence for a modified shock and electron diffusion coefficient increasing with energy, but can in principle be used to find the mean magnetic-field strength (Reynolds and Ellison, 1992), though in practice the data are not of high enough quality to enable this.

Two areas of concern exist for this predicted curvature. First, in Cas A, the integrated radio spectral index is constant at about $-0.78$ from about 10 MHz to 100 GHz – a factor of 100 in electron energies, over which the spectrum is predicted to have measurable curvature (e.g., Ellison et al. 2000). Second, in radio supernovae, spectral indices of up to 1.0 are observed, which do not change with time as would be expected if increasing shock modification by energetic particles is occurring (Weiler et al., 1990; Gaensler et al., 1997; Montes et al., 1998, 2000).

In diffusive shock acceleration, electrons diffuse a significant distance ahead of the shock in the process of gaining energy – far enough ahead to produce a potentially observable synchrotron precursor in the radio. Achterberg, Blandford, & Reynolds (1994) used this effect, in conjunction with observations of several sharp-rimmed SNRs, to put a lower limit on the upstream electron diffusion length. They conclude that MHD turbulence upstream of shocks in four young SNRs must have amplitudes larger than those responsible for average galactic cosmic-ray diffusion (near 1 GeV) by factors of at least 60. Unfortunate magnetic-field geometry in all four cases could render larger precursors invisible, but alignment of the external magnetic field to less than $\sim 30^\circ$ of the line of sight would be required in all cases. This effect can be searched for in all radio observations of sharp-rimmed remnants; applications in larger, presumably older remnants (e.g., CTA 1; Pineault et al. 1997; Aschenbach & Leahy 1999) require intermediate levels of enhanced turbulence. In no case has a structure been seen in a radio SNR image which can be unambiguously identified as pre-shock synchrotron emission, though dimensionless amplitudes $\delta B/B \sim 0.1$ are adequate to render radio halos too thin to resolve. For remnants whose X-ray emission is dominantly synchrotron, halos must be observably large, but may be too faint to detect.
2.2.2. Optical and Ultraviolet diagnostics

Radiative shocks efficiently convert thermal energy to radiation in a cooling zone far downstream from the shock, and there most signatures of physical processes in the shock have been erased. More interesting are non-radiative shocks in which the gas does not cool appreciably after being shocked. In this case optical and UV lines are emitted from the narrow layer where the gas is ionized just behind the shock. These shocks are faint, but have been detected in about a dozen SNRs; UV imaging should show the positions of similar shocks in other remnants. The faint emission from non-radiative shocks yields important limits on electron-ion and ion-ion temperature equilibration and can also be used to investigate the precursor predicted by diffusive shock acceleration models.

The most complete diagnostics are available for shocks in partially neutral gas (Chevalier & Raymond 1978). A neutral hydrogen atom feels neither plasma turbulence nor electromagnetic fields as it passes through a collisionless shock. It will be quickly ionized in the hot post-shock gas, but it may be excited and produce a photon first. On average, it will produce \( q_{ex}/q_i \) photons (the excitation rate over the ionization rate) before being destroyed, or about 0.2 \( \text{H}\alpha \) photons per \( \text{H}^0 \) atom. Because the neutrals do not feel the shock itself, the \( \text{H}\alpha \) profile reveals the pre-shock velocity distribution of the H atoms. However, there is a substantial probability that the atom will undergo a charge transfer reaction before being ionized. This produces a population of neutrals having a velocity distribution similar to that of the post-shock ions, and they produce a corresponding broad component to the \( \text{H}\alpha \) profile.

Thus the line widths of the broad and narrow components of \( \text{H}\alpha \) measure the post-shock and pre-shock proton kinetic temperatures quite directly. In a few cases, UV lines of \( \text{He}\ II \), \( \text{C}\ IV \), \( \text{N}\ V \) and \( \text{O}\ VI \) are also detectable. These ions are affected by the shock, and the line widths directly measure the kinetic temperatures of those species. In the two cases measured so far, the UV lines imply roughly mass-proportional temperatures (Raymond et al. 1995; Raymond et al. 2000).

There are two ways to find \( T_e \) in these shocks. The intensity ratio of the broad and narrow components of \( \text{H}\alpha \) depends on the ratio of the charge transfer rate to the ionization rate, \( q_{ct}/q_i \), and the latter depends of \( T_e \). Ghavamian (1999) finds that \( T_e/T_p \) just behind the shock varies from more than 80% in the 350 km/s shock in the Cygnus Loop to 40-50% in the 620 km/s shock in RCW 86 and less than 20% in the 1800 km/s shock in Tycho. Another determination of \( T_e/T_p \) used the UV lines in SN1006 (Laming et al. 1996). Here, the \( \text{C}\ IV \), \( \text{N}\ V \) and \( \text{O}\ VI \) excitation rates are dominated by proton collisions, while the \( \text{He}\ II \) \( \lambda 1640 \) line is excited by electrons. The observed line
ratios imply $T_e/T_p < 0.2$. In both the Cygnus Loop and SN1006, the parameters derived from UV and optical lines agree well with analyses of the X-ray spectra. The tendency for a decreasing degree of electron-ion equilibration with increasing shock speed matches results for shocks in the solar wind (Schwartz et al. 1988).

Diffusive shock acceleration requires a precursor in which particles scatter back and forth between the shock jump and MHD turbulence (e.g. Blandford and Eichler 1987). Dissipation of the turbulence will heat and accelerate the gas upstream of the shock jump in a precursor. The only detailed model of a precursor in partially neutral gas is that of Boulares and Cox (1988).

The cosmic ray acceleration precursor should have four potentially observable effects on UV and optical lines: 1) The narrow component of H$\alpha$ will show the precursor temperature and turbulence rather than ambient ISM values; 2) Ionization in the precursor may reduce the hydrogen neutral fraction, and cut down the flux of neutrals reaching the shock; 3) A shock observed face-on should show a Doppler shifted narrow H$\alpha$ line; and 4) Compression and heating in the precursor may produce faint (narrow) H$\alpha$, [N II] and [S II].

Observationally, 1) the H$\alpha$ narrow components are 30-50 km/s wide (Hester, Raymond and Blair 1994; Smith et al. 1994; Ghavamian et al 2000), much too wide to be an ambient ISM temperature, 2) the hydrogen neutral fraction required to match the observed H$\alpha$ brightness in the few cases analyzed limits the precursor thickness to $\sim 10^{16-17}$ cm (approximately the upstream diffusion length of a $10^{12}$ eV proton assuming $B \simeq 5 \mu G$, a shock speed of 1000 km/s, and strong scattering), 3) no Doppler shift is seen in long slit echelle image across the middle of an LMC Balmer-dominated SNR (Smith et al. 1994), and, 4) faint N II and [S II] detected at a Balmer line filament in the NE Cygnus Loop by Fesen and Itoh (1985) may arise in a precursor, while more extended emission (e.g. Bohigas, Sauvageot and Decourchelle 1999; Szentgyorgyi et al 2000) is likely to be a photoionization precursor.

Overall, the precursor needed in cosmic ray acceleration models matches the observations except for the lack of Doppler shift. An alternative explanation is a precursor due to escape of the fast component neutral hydrogen (produced by charge transfer with post-shock protons) out the front of the shock. This idea has not yet been developed in detail. The heating suggested by the observed H$\alpha$ profiles is smaller than that in the Boulares and Cox (1988) model, perhaps because Boulares and Cox assumed very efficient cosmic ray acceleration.

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1 This assumes there is time for the neutrals to feel the increasing temperature in the precursor.
2.2.3. X-ray diagnostics

Several SNRs are now known whose X-ray emission shows strong evidence for the presence of nonthermal emission: SN 1006 (Koyama et al. 1995), G347.3-0.5 (Koyama et al. 1997; Slane et al. 1999), RXJ 0852.0-0462 (Slane et al. 2001), Cas A (Allen et al. 1997; Favata et al. 1997; The et al. 1996), RCW 86 (Borkowski et al. 2001). In SN 1006, G347.3-0.5 and RXJ 0852.0-0462, the X-ray spectrum is almost featureless; Cas A shows many X-ray lines but a power-law continuum up to 80 keV; and RCW 86 shows anomalously weak lines best explained as a synchrotron continuum diluting a thermal spectrum. Nonthermal bremsstrahlung was suggested as a possible contributing process in Cas A (Asvarov et al. 1990; Laming 2001). However, in the former cases a synchrotron explanation is preferred to nonthermal bremsstrahlung, because of steepening or faint or nonexistent spectral lines. This synchrotron continuum can then provide powerful diagnostics of shock acceleration. However, nonthermal bremsstrahlung should become the dominant source of photons above some energy, and future observations should be able to discriminate.

2.2.3.1. Modifications of the thermal emission

For nonlinear shock acceleration the overall shock compression is increased. Thus higher downstream densities are expected, which can be derived in principle from the X-ray emission volume and ionization timescale. However, the difficulty is then to distinguish between a higher density ambient medium and a higher compression ratio. For that, an independent determination of the upstream density is required. A possible way is to derive the upstream density from the flux in the photoionized region surrounding some supernova remnants as was done by Morse et al. (1996) for N132D using optical observations. Other global information may give an indication of the upstream density like the location in the galaxy (high latitude for SN 1006 and Kepler) or the study of the environs of the remnant (e.g. Reynoso et al. 1999 for Tycho).

Efficient acceleration also lowers the downstream temperature, and the post-shock electron temperature can be estimated from the X-ray spectra. With no acceleration effects the dimensionless ratio

\begin{equation}
    x = \frac{1}{\langle \mu m_H \rangle} \frac{kT_e}{V_s^2}
\end{equation}

of the mean post-shock temperature to the square of the shock speed is equal to 3/16. In nonlinear shock acceleration, \( x \) drops well below this value (Ellison 2000, Decourchelle, Ellison, & Ballet 2000). Thus independent measurements of the shock velocity and post-shock temperature give a powerful diagnostic of efficient shock acceleration. The shock velocity can be estimated from X-ray expansion measurements.
(see Vink et al. 1998; Koraleski et al. 1998; Hughes 1999; Hughes 2000) and possibly from Doppler shifts of X-ray lines (or Balmer lines as well), while the post-shock electron temperature can be derived from spatially resolved X-ray spectra of the downstream region. However, as discussed in section 2.2.2 the electron temperature is most likely not in equilibrium with the ion temperature. The difficulty is then to distinguish the effects of efficient acceleration from a lack of temperature equilibration between electrons and ions.

The Chandra observation of 1E 0102.2-7219 in the Small Magellanic Cloud has allowed the determination of both the shock velocity and the post-shock electron temperature as demonstrated by Hughes, Rakowski, & Decourchelle (2000). The well known distance to the Small Magellanic Cloud allows a better determination of the shock velocity than for galactic supernova remnants, whose distance is often not well established. While the shock velocity is estimated to be \( \sim 6000 \) km/s, the post-shock electron temperature is 0.4-1 keV, which is almost 25 times lower than expected for a 6000 km/s test-particle shock. Hughes et al. (2000) have shown that even Coulomb heating alone would produce a higher electron temperature than observed unless a substantial fraction of the shock energy should have gone in accelerating particles, although the exact amount remains to be determined depending on the degree of equilibration between electron and ion temperatures.

In non-radiative shocks, optical and UV lines yield important constraints on this degree of equilibration (see section 2.2.2). Direct X-ray determinations of the ion temperature(s) are in principle possible, and will be available in future, once instruments have sufficient spectral resolution to measure the Doppler broadening of the X-ray lines.

2.2.3.2. Overall effects on the SNR geometry The nonlinear shock modification impacts not only the jump conditions, but also the overall structure of the remnant. The non negligible fraction of accelerated ions modifies the compressibility of the shocked gas, and gives rise to a modified structure of the shocked material (e.g. Chevalier 1983). In young supernova remnants, the interaction region (between the reverse shock and the forward shock) gets thinner with higher efficiency acceleration at the shocks, and has higher densities and lower temperatures as shown by Decourchelle, Ellison, & Ballet (2000). The position of the forward and reverse shocks with respect to the contact discontinuity (interface between stellar and ambient material) provides information on the efficiency of the acceleration at each shock (see Decourchelle et al. 2000). X-ray imaging instruments, which map the whole shocked region (and not simply the post-shock region), can give information on the location of both shocks and constrain their respective acceleration
efficiency. However, while the forward shock can be easily observed (see for example 1E 01012.2-7219, Gaetz et al. 2000), the exact position of the reverse shock is difficult to establish due to projection effects and density structure in the unshocked ejecta.

2.2.3.3. Effects from low-energy suprathermal electrons

Shock acceleration predicts an extended suprathermal tail to the downstream electron energy distribution instead of the exponential cutoff characteristic of a thermal Maxwellian (e.g., Bykov and Uvarov 1999; Baring et al. 1999). The entire electron distribution will radiate bremsstrahlung photons, an electron with energy $E$ typically producing a photon of energy $E/3$. This low-energy end of the nonthermal electron distribution can also produce potentially observable effects through collisional ionization and excitation.

The nonthermal-bremsstrahlung continuum should have a concave-upward curvature. This has not been seen, either because of the presence of synchrotron emission, or because thermal bremsstrahlung still dominates. In most cases, however, one expects that above about 10 keV any synchrotron component must be dropping away rapidly. Images and spectra of SNRs in the range of tens of keV with adequate sensitivity should certainly find nonthermal bremsstrahlung, whose analysis will give important direct information on the production of low-energy cosmic-ray electrons and on the details of the injection mechanism.

Ionization and excitation rates from electron impact are calculated by integrating energy-dependent cross sections over the electron energy distribution and will differ most from those calculated for a strictly Maxwellian distribution. Similar calculations have been done for the solar corona and other stellar coronae (e.g., Owocki & Scudder, 1983) and differences in the ionization balance have been found. Hampering this effort is our poor understanding of electron injection, so that there is no unambiguous prediction for the shape of the low-energy end of the nonthermal electron distribution. Calculations for power laws are not unreasonable at this stage. This has recently been done for a range of possible power laws (Porquet, Arnaud, & Decourchelle 2001): the increase of the ionisation rates depends on the fraction of nonthermal electrons above the ionisation potential and can reach several order of magnitudes. The ionisation balance can be affected significantly, in particular at low temperatures, but the effects are less for the ionizing plasmas expected in young supernova remnants.

The new generation of X-ray spectrometers (Chandra/HETGS and XMM-Newton/RGS) is providing high spectral resolution spectra of the brightest and smallest angular size supernova remnants like 1E
0102.2-7219 (see Rasmussen et al. 2001), which will allow precise line diagnostics, relevant for constraining nonthermal ionisation and line excitation.

2.2.3.4. Synchrotron continuum  If no lines are present, or if the continuum steepens and can be shown not to be thermal by other arguments, synchrotron emission is the most likely possibility. Simple considerations (e.g., Reynolds 1996) show that one can readily expect synchrotron emission to photon energies above 10 keV from remnants up to and perhaps beyond $10^4$ years in age. However, in all SNRs observed in both radio and X-rays, the X-rays (thermal or not) fall below the extrapolation of the radio spectrum, indicating that the electron spectrum has begun to steepen at what turn out to be energies of no more than about 10 TeV in most cases (Reynolds and Keohane 1999). While this rolloff may be due to radiative losses in some cases, for all five historical remnants in the sample, the radiative-loss limit is higher than the one actually observed, indicating that the cutoff is due to some other process and is presumably the same for ions as for electrons. Unless the older remnants improve unexpectedly in their ability to accelerate particles to the highest energies, (perhaps through magnetic field amplification as recently suggested by Lucek and Bell, 2000) the ability of SNRs to produce power-law spectra up to the “knee” is in question. As we discuss below, Cas A, because of its extremely high inferred magnetic field ($\sim 1000 \mu$G), should be able to accelerate protons to well above $10^{15}$ eV (Allen et al. 1997).

Where synchrotron X-rays are required to explain part or all of the observations, power laws have mainly been used for the analysis. Over the limited spectral range of current X-ray satellites, this is a reasonable approximation, though it is not expected physically. The sharpest cutoff naturally arising through shock acceleration is an exponential in electron energy (Webb, Drury, & Biermann 1984; Drury 1990) and in a real remnant, spatial inhomogeneities and time dependent effects will result in a rolloff even broader than this. Extensive models have been calculated in Reynolds (1998). A few of the simpler ones are available in the X-ray spectral fitting package XSPEC (v.11) and have been applied to SN 1006 (Dyer et al. 2000) and RCW 86 (Borkowski et al. 2001). Rolloff frequencies found in these fits imply electron energies of the same order as the upper limits cited above, of tens of TeV. Similar results are found in more complete models (Berezhko, Ksenofontov, & Petukhov 1999) which calculate the cosmic ray acceleration self-consistently and match the broad-band continuum emission including the GeV and TeV gamma-ray observations (see also Ellison, Berezhko, & Baring 2000).
Morphological information on synchrotron X-rays can also be important. X-ray emitting electrons have energies of order 100 TeV and, should diffuse observable distances ahead of the shock as they are accelerated. These synchrotron halos are similar to the precursors expected in radio, but on a larger scale corresponding to larger diffusion lengths. Unlike radio halos, they should always be large enough to resolve, but unfavorable upstream magnetic-field geometry (a magnetic field primarily along the line of sight to the observer) might make them unobservably faint. Behind the shock, X-rays should come from a narrower region than in the radio because of radiative losses; however, projection effects may make this effect difficult to observe.

2.2.4. Gamma-ray diagnostics
The radio and X-ray synchrotron emission probes the accelerated electron population, as do the non-thermal bremsstrahlung and inverse Compton components. They tell us nothing directly about the nuclear component which dominates in the GCR. Detection of gamma-ray emission from SNRs clearly produced by $\pi^0$ decay would be unambiguous direct proof of the existence of accelerated nuclei in SNRs (e.g., Drury et al., 1994; Naito and Takahara, 1994; Berezhko & Völk 2000).

If TeV gamma rays can be shown (for instance, from spectral evidence) to be inverse-Compton upscattered CMB photons, the factor $R$ by which the extrapolation of the radio spectrum to TeV energies exceeds the TeV flux can give the magnetic field (if synchrotron and IC occupy the same volume, unlikely to be exactly the case):

$$R = 3.72 \times 10^3 B_{\mu G}^{1.6}.\$$

In SN 1006, $R \sim 1.4 \times 10^5$ (Tanimori et al. 1998; Green 1998) implying $\langle B \rangle = 9.6 \mu$G. A more accurate model involving calculating the electron density everywhere also gives $\langle B \rangle = 9 \mu$G, and implies an efficiency of electron acceleration of about 5%. As more TeV observations of SNRs become available, similar calculations will be possible for more objects. Nondetections, or attributions of TeV emission to other processes such as $\pi^0$ decay or bremsstrahlung, give lower limits on the mean magnetic field.

It is important to note that the diffusive shock acceleration mechanism is expected to place a larger fraction of the available ram kinetic energy into ions than electrons (perhaps 10 times as much or more). If electron efficiencies as high as 5% are inferred for SN1006 and other SNRs, these objects may be producing cosmic rays with very high efficiencies. If this is the case, test-particle models will be clearly inadequate and nonlinear models of particle acceleration will need to be applied to both the SNR dynamics and the particle spectra (De-
2.2.5. Charged particle diagnostics
There are three aspects of particle spectra that need consideration in matching cosmic ray observations: (1) the shape, (2) the maximum energy, and (3) the possibility of features (i.e., bumps) caused by individual nearby sources dominating the spectrum.

The accelerated particle spectrum at the source is predicted to be at least as hard or even somewhat harder than an $E^{-2}$ energy spectrum over a wide energy range. The actual source spectra inferred from observations after propagation corrections tend to be softer (steeper) than this, spectral exponents around 2.1 being favoured by propagation models with negligible reacceleration and values as soft as 2.4 being required for the models with significant reacceleration. This is a worrying discrepancy.

The upper energy limit of acceleration is determined essentially, as is evident on dimensional grounds, by the product of shock radius, shock velocity and magnetic field; as the famous Hillas plot shows this severely restricts the possible Galactic acceleration sites. Specifically, the maximum energy, $E_{\text{max}}$, can be estimated by first using a model of SNR evolution (e.g., Truelove & McKee 1999 which continuously maps between the free expansion and Sedov phases) to give the shock parameters (i.e., speed, $V_{sk}$, and radius, $R_{sk}$) as a function of explosion energy, $E_{\text{SN}}$, ejecta mass, $M_{ej}$, and remnant age, $t_{\text{snr}}$. The maximum momentum where the spectrum cuts off is then estimated by setting the diffusive shock acceleration time, $t_{\text{acc}}$, equal to $t_{\text{snr}}$, or by setting the upstream diffusion length equal to some fraction of the shock radius, whichever produces the lowest $E_{\text{max}}$. In fact, an accurate determination of $E_{\text{max}}$ in an evolving remnant requires a more complete model than this (Berezhko, 1996), which keeps track of the history of particles, adiabatic losses, and the numbers of particles accelerated at a given epoch. However the results of the more sophisticated model agree within factors of order 2 with the simple estimates.

For electrons, $E_{\text{max}}$ is equal to that of the protons or to the value determined from combined synchrotron and inverse-Compton losses, whichever is less (see Baring et al. 1999 for details).

Recent studies of SN1006 (Reynolds 1996; Berezhko et al. 1999; Ellison, Berezhko, & Baring 2000) and Kepler’s SNR (Ellison 2000) indicate that, while these SNRs accelerate particles to TeV energies, they do not produce particle energies anywhere close to $10^{15}$ eV. Cas A on the other hand, because of its extremely large magnetic field ($B \sim 1000\mu\text{G}$) should be easily able to produce particles with energies
of $10^{15}$ eV or higher. This suggests that only some subclass of SNRs can provide the knee particles while most SNRs have spectra cutting off at considerably lower energies (Reynolds and Keohane 1999). This, in turn, suggests that features may be observable in the GCR spectrum even well below the knee and that the number of local sources contributing to the knee region may be quite small (cf Erlykin and Wolfendale, 2000).

3. CR Compositional tests

There has been much debate about the origin of the material accelerated to form the GCR. The inferred chemical composition of the GCR at source (that is after slightly model-dependent corrections for propagation) is now rather well determined for all the major species and even many minor ones. The composition is basically quite close to solar, but with significant differences as reviewed in J-P Meyer’s talk.

3.1. Acceleration fractionation effects

The nonlinear shock acceleration models make quite specific predictions about the composition of the accelerated particles compared to the composition of the medium into which the shock is propagating. Firstly, any seed population of pre-existing nonthermal particles in the upstream medium will be picked up and accelerated by the shock with essentially no fractionation (this is basically the original linear test-particle picture of shock acceleration). Secondly, and much more interestingly, the nonlinear theory requires that the shock-heated particle distribution contain a nonthermal tail extending to very high energies. The transition from the thermal population to the nonthermal tail defines what is usually called the “injection” rate. This is perhaps the most important point about nonlinear shock acceleration, there is no need for a separate injection process, a shock propagating in a given medium accelerates particles out of that same medium. In fact the important point about this injection process is not that it is difficult, but rather, as has been emphasised recently by Malkov, that it is too easy. The problem is that there is simply not enough energy to accelerate very many particles to relativistic energies. Thus the nonlinear reaction effects on the shock structure and the dissipative processes operating in the subshock have to conspire to throttle back the effective injection rate to a reasonable value. In the case of SNR shocks this means that the effective injection rate for protons has to be of order $10^{-4}$.

The protons are the key species because they dominate the energy budget. Because the shock is a collisionless plasma shock dominated
by magnetic field effects the throttling back must be done by what is
basically a gyroradius filtering effect whereby the injection of particles
with magnetic rigidity of order that of a shock-heated proton is strongly
suppressed. However particles of higher rigidity and larger gyroradius
do not interact as strongly with the small scale fields and structures
responsible for this suppression and therefore are more efficiently in-
jected. Although the details are complicated, and not really understood,
there is a clear qualitative prediction. For a shock propagating in a
multispecies medium, but one dominated in mass density by hydrogen,
the composition of the accelerated particles relative to the preshock
medium should show a fractionation which is a smooth monotonically
increasing and then saturating function of initial particle mass to charge
ratio (this is often referred to as an $A/Q$ effect and, in fact, the $A/Q$
enhancement may not be strickly monotonic for extremely low Mach
number shocks, e.g., Ellison, Drury, & Meyer (1997)). Of course this
refers only to the nuclear and other heavy species with mass to charge
ratios greater than that of the proton; the problem of the electron
injection rate is much more complicated.

Qualitatively, this fits the general overabundance of heavy elements
in the GCRS composition relative to solar, but it is impossible to get a
good quantitative fit using equilibrium ionisation models of a gas phase
ISM with standard composition (however if only volatile elements are
considered, $A/Q$ does allow a good fit; (Ellison et al., 1997), (Meyer et
al., 1997))

3.1.1. Dust

In much of the ISM the refractory elements are not in the gas-phase
but condensed into small interstellar dust grains. These grains are elec-
trically charged and will behave like very heavy ions. Because of their
enormous gyroradius they are injected with essentially unit efficiency, but
are only very slowly accelerated. Detailed estimates of the acceleration
and other length and time scales show that the accelerated dust particle
distribution will cut-off at dust velocities about ten times that of the
shock because of frictional losses. The collisions between the gas atoms
and the dust grains which are responsible for this friction also induce a
certain amount of sputtering of secondary ions from the grain surface,
and because the grains are diffusing on both sides of the shock some of
these secondary ions are produced in the upstream region just ahead of
the shock. Detailed estimates show that, independent of dust, gas and
shock parameters, this yields a seed ion population upstream which is $O(10^{-3})$
suppressed relative to the top end of the accelerated dust
distribution. These ions are swept into the shock and accelerated with
little or no further fractionation, and because the protons are sup-
pressed relative to the bulk material by about $10^4$ the final effect is that the sputtered dust component is expected to show roughly an order of magnitude enhancement relative to hydrogen with little fractionation.

3.1.2. Ionization state

The volatile species accelerated out of the gas phase, on the contrary, are expected to show a strong $A/Q$ fractionation effect. The problem here is to estimate the effective charge state of these species. Except in the very hot phases of the ISM it is unlikely that the mean charge is more than +1 or +2, however in the shock precursor region photo-ionization by radiation from behind the shock is probably also important. This is one area where a detailed study would be very useful. For the moment if one simply assumes that the volatile ISM species are unlikely to have lost more than one or two electrons, the mass can be taken as a proxy for the effective $A/Q$ value. The prediction of shock acceleration out of a dusty ISM is then that two components should be visible in the compositional data. The volatiles should lie on a rather smooth fractionation line which is a monotonically increasing function of atomic mass. In addition, there should be a refractory component from dust which shows little or no mass dependent fractionation, but which is globally enhanced by a factor of about ten relative to hydrogen. This appears to be in very good agreement with all the data on the chemical composition of the GCRS. In particular, 10% of oxygen must be in grains from dust chemistry, and we know that substantial amounts of carbon are also in grains as well as the gas phase so that these two elements should fall between the two bands, exactly as observed.

3.1.3. FIP

The alternative “explanation” of the pattern of elemental abundance variations observed between the GCRS and solar is the so-called FIP effect. It is known that in the solar corona elements with first ionization potentials (FIP) below about 10 eV are enhanced by about an order of magnitude and there is evidence that the same effect occurs in the coronae of other cool stars. This effect biases the composition of solar energetic particles and produces a composition which is remarkably similar to that of the GCRS. This has lead to suggestions that the source of the GCR material is to be found in coronal mass ejections from solar-like stars, but it is difficult to make a plausible quantitative model along these lines. Somehow one has to produce a large sea of low energy particles from dwarf stars which survive long enough to encounter strong SNR shocks and be accelerated without being swamped by fresh particles accelerated by the shock out of the ISM. The close resemblance of a FIP-biased composition to that predicted for particles
accelerated by a shock from a dusty ISM results of course from the fact that FIP correlates strongly with chemistry. The reactive elements which form strongly bound chemical compounds and condense out of the gas phase are mostly those with low first ionization potentials.

This is often presented as a FIP versus volatility debate, but this is not really correct. The comparison should be between the specific physical model of acceleration by an SNR shock of particles from a dusty ISM with standard bulk composition and grain chemistry, and a more speculative scenario of injection of FIP-biased material from young dwarf stars with high levels of flaring activity followed by subsequent SNR shock acceleration of this material.

3.2. $^{22}\text{Ne}$ and Wolf–Rayet stars

There is now strong observational evidence that the (isotopic) composition of the Galactic Cosmic Rays (GCRs) exhibits some significant deviations with respect to the abundances measured in the local (solar neighbourhood) interstellar medium (ISM) (see Lukasiak et al. 1994; DuVernois et al. 1996; Connell & Simpson 1997; George et al. 2000; Wiedenbeck 2000). The most striking difference between the isotopic composition of the Galactic Cosmic Ray Sources (GCRS) and the solar system is the factor $\sim 3$ enhanced $^{22}\text{Ne}/^{20}\text{Ne}$ ratio observed in the GCRS, while isotopic ratios involving heavier isotopes like magnesium or silicon have near solar values. Wolf–Rayet (WR) stars appear as a promising source for the $^{22}\text{Ne}$ excesses. Indeed, during the WC phase, a particular stage during the WR phase (see e.g. the review on the WR stars by Willis 1999), stellar models predict that $^{22}\text{Ne}$ is significantly enhanced in the stellar winds. Let us emphasize here that the predicted $^{22}\text{Ne}$ excesses in the winds of the WC stars have been recently confirmed observationally (Willis et al. 1998; Dessart et al. 2000).

Two scenarios have been proposed in order to account for the differences (‘anomalies’) in the isotopic composition of the GCRSs. In both, WR stars play an important role as the source of the $^{22}\text{Ne}$ excess. The first scenario invokes two distinct components to be accelerated to GCR energies (e.g. Arnould 1984; Prantzos et al. 1987, and references therein). The first component, referred to as the ‘normal component’, is just made of ISM material of ‘normal’ solar composition, while the other one emerges from the nuclear processed wind of massive mass–losing stars of the WR type, and is referred to as the ‘wind component’. It has been demonstrated that this type of scenario is able to account in a natural way for the excess of $^{22}\text{Ne}$. Typically, the fractional contribution of the wind component to the bulk GCRs found by imposing the model reproduction of the observed GCR $^{22}\text{Ne}/^{20}\text{Ne}$ ratio (adopted here equal
to 3) ranges between about 2 and 10%, depending upon the model star (see the contribution by Meynet et al. in this volume).

A second scenario has been proposed in order to explain the GCR composition anomalies (Woosley & Weaver 1981; Maeder 1984; Meynet & Maeder 1997; Meynet et al. in this volume). This model, envisions the acceleration of ISM material whose composition is different from the normal one used for comparison (i.e. the ISM in the solar neighbourhood). More specifically, it is assumed that the accelerated ISM originates from the inner regions of the Galaxy, where the star formation and supernova rates are higher than in the solar neighbourhood. As a consequence, the metallicity is higher and the ISM isotopic composition is very likely to be different as well.

Whilst several observational data can be accounted for, both models still face difficulties. In the two–components scenario, it remains to be seen if the WR wind component can be accelerated with a large enough efficiency in order to contaminate at a high enough level the normal component made of ISM matter of typical local (solar neighbourhood) composition. The metallicity–gradient model faces more specific problems related to the construction of reliable chemical evolution models of the Galaxy, and in particular to the predictions of composition gradients in the galactic disc.

On the observational side, further data, concerning in particular heavy s–process nuclides, would certainly be very helpful in constraining the models.

4. Superbubbles as GCR sources

As recalled above, energetic considerations make SN explosions a very probable energy source for GCRs. SN explosions, however, are not random in the Galaxy, and show strong spatial and temporal correlations resulting from the concentration of the vast majority of (core-collapse) SN progenitors into OB associations, formed on a short timescale from the collapse of a giant molecular cloud (e.g. Blitz, 1993). The explosion of the first SN among such an association is thus to be followed by several tens of others within a few million years, at approximately the same location. This results in the formation of a ‘multiple supernova remnant’, powered by both the SN explosions and the strong winds of Wolf-Rayet stars in the OB association, which grows as a large bubble of hot, tenuous plasma known as a superbubble (e.g. MacLow & McCray, 1988; Tomisaka 1998; Korpí et al. 1999). Superbubbles (SBs) are commonly observed in X-rays in our and nearby galaxies.
The impact of multiple SNe on their environment is large, and if SN explosions are indeed the GCR source of energy, the fact that most SNe occur in groups should incite us to take their collective effect into account when considering cosmic ray acceleration. In particular, it seems natural to expect an intense supersonic turbulence inside the accelerator, due to the interaction of individual SN shocks and strong stellar winds in the SBs.

4.1. Particle acceleration inside superbubbles

The theory of diffusive shock acceleration described above applies to the ‘regular’ shocks of distinct, isolated SNRs. For most SN explosions occurring inside SBs, however, the ‘well-ordered SNR’ stage may be relatively short due to the interaction with the pre-existing strong turbulence (primary and secondary shocks from previous SNe and stellar winds). Assuming a length scale of about 10 pc between two major shocks, and a large ambient magnetic field strength \( \gtrsim 30 \mu G \), the timescale for the disruption of a SN shock inside a SB can be roughly estimated as \( \sim 1000 \) years. Given the very low ambient density \( \lesssim 10^{-2} \text{part.cm}^{-3} \), only a small amount of matter can flow through the forward shock of a SN before it encounters another strong shock or a clump of denser material and generates a series of secondary shocks by reflection, eventually leading to the mentioned strong turbulence. The mass contained inside a sphere of 10 pc with a density of \( 10^{-2} \text{cm}^{-3} \) is only 1 solar mass! However, particle acceleration does not cease when the strong magnetic turbulence develops. On the contrary, it is expected to become very efficient, and SBs have been considered as very plausible sites of nonthermal particle acceleration (Bykov & Fleishman, 1992; Parizot, 1998; Higdon, Lingenfelter & Ramaty, 1998).

The acceleration mechanism in SBs should enable an efficient conversion of the MHD energy of large scale shocks and plasma motions into CRs. The SB acceleration model is based on the kinetic equation for the particle distribution functions in the stochastic velocity field with multiple shocks inside SBs. It has been developed by Bykov & Toptygin, 1987; Bykov & Fleishman, 1992; Bykov, 1999. The models account for the creation of a nonthermal population of nuclei with a hard low-energy spectrum, containing a substantial part of the kinetic energy released by SNe and massive stellar winds. Test particle calculations pointed at the importance of nonlinear effects, and a nonlinear model accounting for the reaction of the accelerated particles on the shock turbulence inside the SB has thus also been developed by Bykov (1999) (see also Bykov 2000, this volume), the outcome of which is a strong temporal evolution of the energetic particle spectrum. The
energy contained in the superbubble MHD turbulence is converted into nonthermal nuclei with an efficiency estimated as $\gtrsim 20\%$.

4.2. Superbubbles and light element production

Up to now, the SB acceleration model has been mostly applied to light element nucleosynthesis and Galactic evolution. Among the light elements (Li, Be and B), the isotopes $^6\text{Li}$, $^9\text{Be}$ and $^{10}\text{B}$ (and maybe $^{11}\text{B}$ as well) are produced exclusively by spallation of heavier nuclei, mostly C and O. Recent studies have shown that the original Galactic nucleosynthesis scenario (Reeves et al., 1970; Meneguzzi et al., 1971) in which CR protons interact with C and O nuclei in the ISM was much too inefficient in the early Galaxy (where C and O are very rare). On the other hand, the possibility of accelerating particles out of the enriched material inside SBs, filled with stellar wind and SN ejecta, led people to consider the so-called superbubble model for Li, Be and B production (see the articles by Parizot and Ramaty in the present volume, and references therein). This model proved capable of accounting for all the current observational constraints pertaining to light element nucleosynthesis and evolution, which no other known mechanism can do. In particular, particle acceleration at the shocks of individual SNe, even when taking into account the ejecta accelerated at the reverse shock, is unable to explain the observed very efficient production of Li, Be and B in the early Galaxy (Parizot & Drury, 1999a,b).

Now if the collective effects of multiple SNe inside SBs dominate in the early Galaxy, it is natural to ask whether this is not also the case in present times, since most SNe do explode inside SBs. This would result in a harder energy spectrum at low energy (which incidentally makes the spallation reactions more efficient), with most of the system energy being imparted to particles in the 0.1–1 GeV/n range. Another consequence would be a substantial enrichment of the cosmic rays by freshly synthesized nuclei, from SN ejecta and Wolf-Rayet stellar winds. This would offer a natural way to solve the Ne isotopic ratio problem.

4.3. Superbubbles and GCRs

Most of what has been acquired from the study of CR acceleration by diffusive shock acceleration in isolated SNRs applies also in the context of superbubbles. According to the model developed by MacLow & McCray (1988) for the dynamical evolution of a SB, the material inside a SB (and thus entering the acceleration process) is composed mostly of the swept-up ISM, contaminated by a few percent of enriched material of stellar origin. This is in very good agreement with the conclusions
of the study of light element nucleosynthesis (Parizot, 2000, and this volume). Therefore, according to this scenario, the basic material from which the CRs are accelerated is close to the mean ISM, just as in the scenario involving individual SNRs (although the composition inside SBs was much richer than the mean ISM in the early Galaxy). Most importantly, the SB lifetime and density are too small for the ionisation equilibrium to be reached and the dust grains are probably not destroyed in the imparted time, in spite of the very high ambient temperature. Therefore, the mechanism described above (and in Ellison et al., 1997) resulting in the enhanced injection of refractory elements into the acceleration process should work equally well in the ISM and at the strong shocks inside SBs. However, if most of the GCRs originate from SBs, then the ‘abnormally’ high abundance of $^{22}\text{Ne}$ among GCRs may be more easily understood. Indeed, Meynet has shown that the Neon isotopic ratio observed among GCRs requires that about 6% of the accelerated material is made of Wolf-Rayet winds (see Meynet’s article, this volume). This is remarkably close to what is expected inside SBs, from the study of both SB dynamics and light element nucleosynthesis.

In addition, superbubbles might provide an acceleration mechanism drawing its energy from the SN explosions, just like the standard SNR model, but allowing for a higher energy cut-off, extending beyond the knee, notably because of their larger dimension. The problem of VHE CR acceleration in the superbubble model, has been addressed by Bykov & Toptygin (1997) in the framework of CR acceleration by multiple shocks. They estimated the maximal energies of accelerated nuclei as $\sim 10^{18}$ eV, in the presence of amplified fluctuating magnetic fields in the bubble interior of order 30 $\mu$G. In this model, the spectrum beyond the knee and up to $10^{18}$ eV is dominated by heavy nuclei.

4.4. Observational evidence

The SB acceleration mechanism appears natural from the theoretical point of view, since most of the SNe are indeed known to occur in this kind of environments, and is supported by the study of LiBeB production and evolution in the Galaxy. Interestingly enough, it now seems to be receiving direct observational support as well.

Recent observations of interstellar Li abundances (Knauth et al., 2000) have shown evidence of newly synthetized lithium in the Perseus OB2 Cloud, the value of the $^6\text{Li}/^7\text{Li}$ ratio being found both 10 times higher than in the standard ISM and very close to the spallation ratio. This could indicate that a very significant Li production by spallation has recently taken place about the Perseus OB2 association, on
a timescale shorter than the chemical homogenization timescale. The huge Li production required to locally overtake the standard Li production accumulated since the beginning of Galactic chemical enrichment could be explained within the SB model, and pleads in favour of an efficient particle acceleration inside superbubbles.

Another observation by Cunha et al. (2000) reported an unexpected anti-correlation of B and O abundances in the Orion OB1 association. Since both $^{16}$O and $^{11}$B are thought to be produced by SNe, one would expect instead a positive correlation of their abundances. However, Cunha et al. (2000) have shown that the anticorrelation can be explained if a strong B production by spallation has recently occurred in the neighbourhood. Since the Orion clouds are just at the border of a typical example of a SB being blown by repeated SNe, the unexpected B-O anticorrelation would be rather natural in the context of the SB model for particle acceleration.

A confirmation of this interpretation of the B-O anticorrelation in Orion is in progress, through the observation of the Be abundance in the same stars. Conclusive evidence for the particle acceleration inside SNe would be provided by the observation of X-ray and gamma-ray line emission from the SB shell and/or neighbouring molecular clouds. The detection of these K lines and nuclear de-excitation lines, possibly with INTEGRAL, would also allow one to determine more precisely the composition and spectrum of the SB energetic particles, and provide strong constraints on the SB acceleration mechanism.

5. Nasty Problems

The standard picture, that the bulk of the GCR originate from shock acceleration associated with strong SNR shocks, can justifiably claim a number of notable successes, however there remain a number of nasty problems which we wish, in conclusion, to point out (cf also Kirk and Dendy, 2001).

5.1. O-star wind termination shocks

A decade ago Lozynskaya (1991) pointed out that the terminal shocks in the winds from O-stars are very similar to SNR shocks, yet there is no evidence for non-thermal effects associated with O-star wind bubbles. What causes this difference?
5.2. THE KNEE AND BEYOND

The standard picture makes a clear prediction that the GCR spectrum should start to cut-off at rigidities of about $10^{14}$ V or less for all species and drop exponentially as one goes to higher energies. The data, on the contrary, shows only a very slight feature, the famous “knee” starting at about $10^{15}$ V and continues to at least the “ankle” region of $10^{18}$ V.

5.3. SOFT SOURCE SPECTRA

The nonlinear acceleration models do not produce precise power-law spectra, but they do put roughly as much, if not more, energy per logarithmic interval into the region near the upper cut-off as into the region around 1 GV where the protons are mildly relativistic. Thus the effective differential energy spectral index is close to 2.0, distinctly harder than the 2.3 to 2.4 range favoured by reacceleration models for Galactic propagation.

6. Conclusions

The prospects for interesting science are very good. On the one hand, observing capabilities are improving rapidly. On the other, the models are making definite predictions of potentially observable effects. And as the list of “nasty” problems shows, there is much that we do not understand. Contrary to the general “folklore” it is by no means certain that SNRs are the source of the GCR and in fact the existence of the “knee” and the particles above the “knee” is fairly clear proof that something else is required.

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