COSMIC-RAY ACCELERATION EFFICIENCY VERSUS TEMPERATURE EQUILIBRATION: THE CASE OF SNR 0509-67.5

E. A. HELDER, D. KOSENKO, AND J. VINK
Astronomical Institute, Utrecht University, P.O. Box 80000, NL-3508 TA Utrecht, The Netherlands; e.a.helder@astro-uu.nl

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1. INTRODUCTION

Supernova remnants (SNRs) are generally thought to be the dominant sources of Galactic cosmic rays. For this to be true, SNRs need to transfer about 10% of their initial kinetic energy into cosmic rays. An open question is whether SNR shocks can reach these acceleration efficiencies averaged over their life time; recent TeV and GeV γ-ray observations give promising but ambiguous results (Ellison et al. 2010; Abdo et al. 2010).

Although the process of efficiently accelerating particles is well understood (Malkov & Drury 2001), observational verifications for efficient acceleration are scarce (e.g., Warren et al. 2005; Lee et al. 2007; Vink et al. 2006; Helder et al. 2009). These observations are essential for characterizing the efficiency of the acceleration. As the particles move ahead (i.e., upstream) of the shock, they form a so-called shock precursor, which compresses and pre-heats the upstream medium. This effectively lowers the Mach number of the main shock, thereby lowering the temperature behind the shock front (Ellison et al. 2004; Drury et al. 2009). This effect would ideally be characterized by the post-shock proton temperature ($T_{p,s}$), as $T_{e,p}$ is close to the plasma temperature, whereas the post-shock electron temperature $T_{e,s}$ might be lower (e.g., Ghavamian et al. 2007b). The latter implies that the electrons might constitute only a minor part of the thermal pressure behind the shock front.

For some SNRs, $T_{s,p}$ can be determined from hydrogen line emission at the shock fronts; these are so-called Balmer-dominated shocks. The hydrogen lines of a Balmer-dominated shock consist of two superimposed components: the narrow component emitted by neutral hydrogen after entering the shock front and the broad component by hot protons after undergoing charge exchange with incoming neutral hydrogen atoms. The width of the broad component reflects the proton temperature behind the shock front (Chevalier et al. 1980; Heng 2009).

In this Letter, we report on our study of SNR 0509-67.5, as this is a likely source of efficient cosmic-ray acceleration; recent studies show that the remnant resulted from a highly energetic Type Ia explosion (Hughes et al. 1995; Badenes et al. 2008; Rest et al. 2008). Its X-ray spectrum provides some evidence for non-thermal emission (Warren & Hughes 2004). In addition, hydrodynamical models show that the presence of highly energetic particles is likely not negligible (Kosenko et al. 2008).

SNR 0509-67.5 was discovered to have Balmer-dominated shocks by Tuohy et al. (1982), although the flux in the broad component was too low to be detected. A subsequent attempt by Smith et al. (1991) did not reveal any broad component either. The first detection of a broad component in the hydrogen line emission of this remnant was by Ghavamian et al. (2007a), who measured the width of the broad component of the Ly$\beta$ line to be 3700 ± 400 km s$^{-1}$, corresponding to a shock velocity ($v_s$) of 5200–6300 km s$^{-1}$. However, as the spectrum was taken from the entire remnant, it remains uncertain whether the obtained line width is broadened by the bulk motion of the plasma as well.

We report the detection of a broad component in the H$\alpha$ line emission of SNR 0509-67.5 at two locations of the shock front. We combine this with a shock velocity based on X-ray observations (Kosenko et al. 2008) to determine the fraction of the post-shock pressure contributed by cosmic rays.

2. OPTICAL DATA AND RESULTS

We observed SNR 0509-67.5 for 10932 s (four blocks of 2733 s) with FORS2, the low-dispersion spectrograph of ESO’s VLT (Appenzeller et al. 1998). The observations were made on 2009 October 15 and 20 and November 10 and 11. By centering the slit at a bright star at $\alpha = 05:09:28.793, \delta = -67:31:30.83$ (J2000), with a position angle of 42$^\circ$ (Figure 1), we obtained spectra of both the SW and NE rims with a single pointing. The width of the slit was 1.6" which, in combination with the 600RI grism and the 2 $\times$ 2 binned readout, corresponds to a resolution of $\approx$485 km s$^{-1}$ at H$\alpha$ (6563 Å). This resolution prevents us from resolving the narrow component of the H$\alpha$ line, but it increases the signal to noise sufficiently to detect and resolve the broad component. The data were corrected for bias, flat fielded, and the skylines and cosmic rays were removed. The wavelength calibration was done by fitting a fourth order polynomial to the spectral lines of He, HgCd, Ar, and Ne lamps, obtained during daytime. In addition, we checked our calibration against the position of three skylines (at 5577.3, 6864.0, and 7571.7 Å, respectively; Osterbrock et al. 1996). The absolute wavelength

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calibration has a systematic uncertainty of 0.5 pixel (37 km s$^{-1}$) and the errors on the data points were determined by tracing the error propagation through the reduction steps, starting from the raw data. For each observation block, obvious outliers, probably caused by erroneous skyline subtraction, were removed. The resulting spectra were fitted with two superimposed Gaussians and an offset, convolved with the slit width. The best-fitting parameters for both spectra are listed in Table 1. In order to determine the significance of the broad component in the NE spectrum, we compared the obtained $\chi^2$ value (464) with a fit in which we only fitted a single Gaussian to the spectrum (525). The difference indicates a significance of 7.8σ. The $\chi^2_{\text{red}}$ values are 2.03 and 2.56 for the SW and NE fits, respectively. These high values are mainly caused by the substructure of the narrow line: a fit to the broad component with a single Gaussian, excluding the central region (between $-100$ and 800 km s$^{-1}$), convolved with the resolution, gives $\chi^2_{\text{red}}$ of 0.51 for the SW and 0.76 for the NE. This substructure might either be caused by spatial surface brightness fluctuations of the remnant within the slit, or by errors in the skyline subtraction. We determine the 1σ errors on the parameters for the broad components by using the errors we determined in our data reduction. For the narrow component we first increased the errors such that $\chi^2_{\text{red}} = 1$, and then determined the 1σ errors, using $\Delta \chi^2 = 1$.

3. COMPARING WITH SHOCK VELOCITIES

To determine the shock velocity, we use the X-ray line width of $\sigma_{\text{RGS}} = 4900 \pm 4200$ km s$^{-1}$, as observed by the Reflection Grating Spectrometer (RGS) on board XMM-Newton (Kosenko et al. 2008). This line width is caused by both the thermal and bulk broadening of the plasma. We follow the method of Kosenko et al. (2010) to disentangle the bulk broadening from the thermal broadening to obtain the forward shock velocity, as described below.

As shown in Kosenko et al. (2010), $\sigma_{\text{RGS}}$ and $v_s$ are related as follows:

$$\sigma_{\text{RGS}} = (v_s/4)\sqrt{3r_{sh}^2 + 9r_{\text{bulk}}^2}, \quad (1)$$

where $r_{sh} = v_{sh}/v_s$ is the ratio of the reverse shock velocity to the forward shock velocity and $r_{\text{bulk}} = \epsilon_{\text{bulk}}/\epsilon_{\text{bulk}, \text{CSM}}$ is the gradient in the plasma bulk velocity from reverse to forward shock. We obtain $r_{sh} \approx 1$ (whole remnant) and $r_{sh} \approx 0.5$ (NE), from analytical models (Truelove & McKee 1999) with $M_{\odot} = 1.4M_{\odot}$, $E = 1.4 \times 10^{51}$ erg and an age of 400 years (Badenes et al. 2008; Rest et al. 2008). Additionally, we constrain the models with a forward shock radius of $15.9 \pm 0.8$ and $16.3 \pm 0.3$ for the entire remnant and the NE, respectively, and a reverse shock radius of $11.4 \pm 2.1$ and $13.5 \pm 0.2$ for the entire remnant and the NE, respectively, based on a deprojection of Chandra images (48.9 ks, ObsID: 776), following the procedure of Kosenko et al. (2010).

We obtain $r_{\text{bulk}} = 0.95$ with numerical simulations (Sorokina et al. 2004; Kosenko 2006), using the above parameters. We use Equation (1) to estimate $v_s = 6000 \pm 300$ km s$^{-1}$ (whole remnant) and $v_s = 6600 \pm 400$ km s$^{-1}$ (NE). In the remainder of this paper, we use conservative $v_s$ estimates of 5000 km s$^{-1}$ for the SW and 6000 km s$^{-1}$ for the NE.

To check these shock velocities, we estimated the expansion with Chandra. Chandra observed SNR 0509-67.5 for three times, with the first observation in 2000 May (earlier used in this section to determine forward and reverse shock radii) and the latter two in 2007 May (29.5 and 32.7 ks; ObsIDs 7635 and 8554). Following the method of Vink (2008b), we find a shock velocity of $6700 \pm 400$ km s$^{-1}$ averaged over the azimuth of the remnant. Note that a full proper motion study of SNR 0509-67.5, using both Chandra and Hubble data, is underway (J. P. Hughes et al. 2010, in preparation). The dense material in the SW (Figure 1) suggests that the forward shock might have recently slowed down. However, we do not find any support for this scenario from the Chandra expansion study, nor from our XMM-Newton/RGS study. Moreover, as the RGS study is skewed toward the bright SW region, it is unlikely that the SW velocity is substantially lower than 6000 km s$^{-1}$.

4. INTERPRETATION

The centroid of the broad component in the SW of $-342 \pm 28$ km s$^{-1}$ indicates the bulk line-of-sight velocity of the shocked...
protons. Additionally, the Large Magellanic Cloud (LMC) is moving with 278 km s\(^{-1}\) away from us (Richter et al. 1987). This means that we are observing a part of the shell which is moving toward us with 620 km s\(^{-1}\) with respect to the LMC. Figure 1 shows a bright, inner shell close to the outer shock. Taking into account the seeing of 0′·8–1′·0, our spectrum is probably contaminated by emission from this shell. This part of the shell is likely to dominate the measurement by Ghavamian et al. (2007a), as they also measured a positive offset for the centroid of the broad component.

The flux in the broad component with respect to the flux in the narrow component \((I_n/I_b)\) declines as a function of shock velocity (Heng & McCray 2007; van Adelsberg et al. 2008). Our low values for \(I_b/I_n\) are therefore consistent with a high shock velocity with likely the highest shock velocity in the NE, which has the lowest \(I_b/I_n\). However, as the standard models for interpreting Balmer-dominated shocks do not include the effects of cosmic-ray acceleration, it is not appropriate to use the \(I_b/I_n\) values to determine the shock velocities of SNR 0509-67.5.

4.1. Interpreting the FWHMs

To determine the cosmic-ray pressure from our measurements, we need to determine \(T_{s,p}\) from the FWHM. For low temperatures and shock velocities, \(kT_{s,p} = m_\text{p} \sigma^2\) (Rybicki & Lightman 1979), with \(\sigma = \text{FWHM}/\sqrt{8 \ln 2}\) in cm s\(^{-1}\). However, as cross sections for charge exchange decline for high velocities (e.g., Figure 1 in Heng & McCray 2007), \(kT_{s,p} > m_\text{p} \sigma^2\) for higher temperatures and shock velocities. Recent studies focused on determining the FWHM as a function of \(v_s\) for non-accelerating shocks (e.g., Heng & McCray 2007; van Adelsberg et al. 2008; resulting in Figure 2). Here, we are interested in FWHM as a function of \(T_{s,p}\) for a given \(v_s\) instead. We approximate this concave function linearly between 0.0 and the \(\sigma^2\) and \(T_{s,p}\) expected for a non-accelerating shock in thermal equilibrium (Figures 2 and 3). In this way, we overestimate \(T_{s,p}\) and the corresponding thermal pressure, leading to a conservative measure of the cosmic-ray pressure behind the shock front.

We note that the \(\gamma\)-axis of Figure 5 of van Adelsberg et al. (2008) is labeled incorrectly (M. van Adelsberg 2010, private communication). Instead of showing the “broad H\(\alpha\) FWHM,” this figure plots the “broad neutral velocity distribution FWHM,” which is independent of the emission line considered. To model a specific emission line such as H\(\alpha\), one has to convolve the broad neutral velocity distribution with the relevant atomic cross sections. The FWHM–\(v_s\) relations we use in this study, obtained in electronic form from M. van Adelsberg & K. Heng, are plotted in Figure 2 and are based upon the same relations used to generate Figure 13 and Table 1 of van Adelsberg et al. (2008).

Following Vink (2008a) and Helder et al. (2009), we interpret \(T_{s,p}\) and \(v_s\) in terms of cosmic-ray pressure behind the shock front and cosmic-ray energy flux leaving the system (respectively \(w_{CR} = P_{CR}/P_{\text{tot}}\) in which \(P_{\text{tot}}\) is the total pressure behind the shock front \((x\)-axis in Figure 4) and \(\epsilon_{\text{esc}} = F_{\text{esc}}/F_{\text{tot}}\) in which \(F_{\text{tot}}\) is the energy flux entering the shock; \(7\rho_{\text{ISM}}v_s^2\) \((y\)-axis of Figure 4)). To conservatively estimate the post-shock cosmic-ray pressure, we assume the electrons and ions to be in thermal equilibrium. We add \(w_{CR}\) and \(\epsilon_{\text{esc}}\) to the equations of conservation of mass, momentum, and energy over the shock front, which leads to

\[
kT_{s,p} = \frac{1}{\chi} \left(1 - \frac{1}{\chi}\right) \mu m_\text{p} v_s^2.
\]

Formally, \(\mu\) is the number-averaged mean particle weight (≈0.54 for a fully equilibrated and fully ionized plasma with LMC abundances), when considering \(kT_{s,p}\), we can treat \(\mu\) as well as a measure for the temperature equilibration behind the shock front, where \(\mu = 1\) indicates no temperature equilibration, and \(\mu = 0.54\) indicates a fully equilibrated plasma. In addition, \(\chi\) is the total shock compression ratio. For a non-accelerating, adiabatic shock, \(\chi = 4\) and hence \(kT_{s,p} = \frac{7}{4} \mu m_\text{p} v_s^2\). We define \(\beta \equiv kT_{s,p}/\frac{7}{4} \mu m_\text{p} v_s^2\) to characterize the influence of cosmic-ray acceleration on \(T_{s,p}\). Figure 4 shows \(\beta\) in the \((w_{CR}, \epsilon_{\text{esc}})\) frame. The “max” line indicates the ratio of the cosmic-ray pressure and escaping cosmic-ray energy for the most efficiently accelerating shock according to theory (Malkov 1999; Drury et al. 2009). Hence, the hashed region is excluded.
pressure behind the shock front of at least 20% (Figure 4).

2. For the SW, we can only explain the line width if we allow for a contribution of >20% of the post-shock pressure by cosmic rays.

3. For the NE shock, we have two options: either the shock has a $T_{s,e}/T_{s,p} > 0.2$, breaking with the earlier reported trend of $T_{s,e}/T_{s,p} \propto 1/v_s^2$ for $v_s > 400$ km s$^{-1}$ (Ghavamian et al. 2007a), or if we assume $T_{s,e}/T_{s,p} < 0.1$, the cosmic-ray pressure behind the shock front is at least 7% of the total pressure.

This research, together with our previous study (Helder et al. 2009), shows that more than 10% of the pressure in young SNRs can be contributed by cosmic rays. This is more than the requirement that 10% of the available energy needs to be in cosmic rays. On the other hand, the cosmic-ray acceleration efficiency may decline for older SNRs, as indicated by a recent study of the Cygnus Loop (Salvesen et al. 2009). So a higher efficiency at a young age may be needed to have an average efficiency of 10% over the whole lifetime of an SNR.

5. CONCLUSIONS

We investigated the cosmic-ray acceleration efficiency of the 0509-67.5 SNR in the LMC, by comparing $T_{s,p}$, determined from the Hα line widths of the SW and NE shocks with shock velocities of respectively 5000 km s$^{-1}$ and 6000 km s$^{-1}$ for the SW and NE, based on X-ray observations. Our study gives the following results.

1. We measured widths of the broad components of the Hα lines of SNR 0509-67.5 to be 2680 ± 70 km s$^{-1}$ for the SW and 3900 ± 800 km s$^{-1}$ for the NE.

2. We investigated the cosmic-ray acceleration efficiency of the 0509-67.5 SNR in the LMC, by comparing $T_{s,p}$, determined from the Hα line widths of the SW and NE shocks with shock velocities of respectively 5000 km s$^{-1}$ and 6000 km s$^{-1}$ for the SW and NE, based on X-ray observations. Our study gives the following results.

3. We derived a lower limit for the cosmic-ray acceleration efficiency of 1% for the SW. For the NE, β is determined assuming $T_{s,e}/T_{s,p} < 0.1$.

A remaining question is whether the magnetic field pressure makes a contribution to the post-shock pressure. As SNR 0509-67.5 is at a distance of 50 kpc, we cannot resolve filaments of X-ray synchrotron emission, which are often used for determining post-shock magnetic field strengths (Vink & Laming 2003). However, Völk et al. (2005) showed that a typical value for the magnetic field pressure is around 3.5% of the total post-shock pressure. Moreover, according to Bell’s theory (Bell 2004) the magnetic field energy density scales as $B^2/8\pi \sim \frac{1}{2}v_{\perp}U_e/c$, with $U_e$ being the cosmic ray energy density. This means that the magnetic field energy density is expected to be about 1% of the cosmic-ray energy density.
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ERRATUM: “COSMIC-RAY ACCELERATION EFFICIENCY VERSUS TEMPERATURE EQUILIBRATION: THE CASE OF SNR 0509-67.5” (2010, ApJ, 719, L140)

E. A. HELDER, D. KOSENKO, AND J. VINK
Astronomical Institute Utrecht, Utrecht University, P.O. Box 80000, NL-3508 TA Utrecht, The Netherlands; e.a.helder@astro-uu.nl

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In a recent email, K. Heng informed us that the curves he provided, which were used for Figure 2 of the published article, are incorrect. More specifically, Figure 5 of van Adelsberg et al. (2008) was the correct figure, in contrast to what was written in Helder et al. (2010).

Figure 2 here is the updated version of the corresponding published figure, utilizing the correct curves from van Adelsberg et al. (2008). This updated figure differs in two respects from the published figure. First, our measured FWHM and velocity for the NE

![Figure 2](image1)

**Figure 2.** FWHM of the broad Hα component as a function of $v_s$ for shocks without cosmic-ray acceleration, for different values for $T_e/T_p$. The overplotted data points are the estimated $v_s$ and FWHM for both the SW and NE shocks.

![Figure 4](image2)

**Figure 4.** Values for $\beta = \left( \frac{k_T s}{\mu m_p v_s^2} \right)$ in the $(w_{CR}, \epsilon_{esc})$-frame, with $w_{CR}$ being the fraction of the post-shock pressure contributed by cosmic rays, and $\epsilon_{esc}$ the escape of cosmic-ray energy flux, normalized to the incoming energy flux. The $x$-lines indicate the compression ratio of the plasma behind the shock front. The hashed region requires a shock, more efficient than can be explained with current theoretical models. The red line indicates the lower limit for $\beta$ for the SW.

(A color version of this figure is available in the online journal.)
shock now overlap all the curves for different $T_{s,p}/T_{s,e}$. This implies that from our measurement, we do not find evidence for a substantial cosmic-ray pressure behind the NE shock. Note however, that this does not necessarily mean that efficient cosmic-ray acceleration is excluded, as the measured shock velocity is a lower limit, and the large uncertainty on the measured FWHM includes the possibility that the FWHM is lower than predicted for a non-accelerating shock. Future proper motion studies of the shock will help to clarify this.

The measured FWHM and shock velocity for the SW shock still do not overlap any of the curves and hence, this implies that the SW shock is an efficient cosmic-ray accelerator. However, the lower limit for the $\beta$ value for the SW will be higher than originally reported: 0.7 instead of 0.58, and the measured FWHM now leads to a post-shock proton temperature of $19.2 \pm 1.1$ keV. Figure 4 here is the updated version of the corresponding published figure and shows that the cosmic-ray pressure ($w_{CR}$) behind the SW shock is $>15\%$ of the total post-shock pressure.

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