SHOCK–CLOUD INTERACTION AND PARTICLE ACCELERATION IN THE SOUTHWESTERN LIMB OF SN 1006

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Abstract

The supernova remnant SN 1006 is a powerful source of high-energy particles and evolves in a relatively tenuous and uniform environment despite interacting with an atomic cloud in its northwestern limb. The X-ray image of SN 1006 reveals a wedge-like feature in the southwestern part of the shock front. The H I maps show an isolated (southwestern) cloud, having the same velocity as the northwestern cloud. The morphology of this cloud changes from isolated to a cloud with high interstellar absorption in regions of the southeastern rim that are closer to the cloud. We performed spatially resolved spectral analysis of a set of small regions in the southwestern nonthermal limb and studied the deep X-ray spectra obtained within the XMM-Newton SN 1006 Large Program. We also analyzed archive H I data, obtained by combining single-dish and interferometric observations. We found that the best-fit value of $N_{HI}$ derived from the X-ray spectra significantly increases in regions corresponding to the southwestern cloud, while the cutoff energy of the synchrotron emission decreases. The $N_{HI}$ variation corresponds perfectly with the H I column density of the southwestern cloud, as measured from the radio data. The decrease in the cutoff energy at the indentation reveals that the back side of the cloud is actually interacting with the remnant. The southwestern limb therefore presents a unique combination of efficient particle acceleration and high ambient density, thus being the most promising region for $\gamma$-ray hadronic emission in SN 1006. We estimate that such emission will be detectable with the Fermi telescope within a few years.

Key words: acceleration of particles – ISM: clouds – ISM: individual objects (SN 1006) – ISM: supernova remnants – X-rays: ISM

Online-only material: color figures

1. INTRODUCTION

The historical Type Ia supernova remnant (SNR) SN 1006 is an ideal target for studying the Fermi acceleration process in astrophysical shocks. It is a dynamically young remnant with a shock velocity of $v_x \sim 5000$ km s$^{-1}$ (Katsuda et al. 2009, 2013; Winkler et al. 2014). It has evolved in a tenuous medium ($n_0 \sim 0.035$ cm$^{-3}$) in the southeastern limb; see Miceli et al. (2012). It is spatially extended (radius $R \sim 15\prime$) and shows a rather simple bilateral nonthermal morphology, which allows us to study regions with highly efficient particle acceleration in the two opposed radio, X-ray, and $\gamma$-ray bright limbs, and in regions with less efficient particle acceleration in the northwestern and southeastern thermal limbs. Moreover, the X-ray spectrum of SN 1006 is characterized by a low interstellar absorption ($N_{HI} \sim 7 \times 10^{20}$ cm$^{-2}$; Dubner et al. 2002, hereafter D02)

The shape of the X-ray spectra extracted from the synchrotron limbs of SN 1006 reveals that the maximum energy achieved by electrons in the acceleration process is limited by their radiative losses (Miceli et al. 2013b). The presence of electrons with cutoff energies of $\sim 10$ TeV suggests that hadrons that do not suffer radiative losses can also be efficiently accelerated up to ultrarelativistic energies at the shock front. Miceli et al. (2012) found that the shock compression ratio increases from 4 up to $\sim 6$ in regions of the southeastern rim that are closer to the nonthermal limbs. This can be naturally interpreted as a result of shock modification induced by hadron acceleration. More recently, Nikolić et al. (2013) have revealed suprathermal hadrons in the northwestern limb of SN 1006 by studying the variations in the H$\alpha$ broad line widths and the broad-to-narrow line intensity ratios.

However, as shown by Acero et al. (2010), the TeV observations of SN 1006 obtained with the HESS telescope cannot be uniquely attributed to hadron emission (i.e., proton–proton interactions with $\pi^0$ production and subsequent decay). The data are consistent with a pure leptonic model (i.e., inverse Compton from the accelerated electrons), in agreement with the morphology of the $\gamma$-ray emission of SN 1006, which also favors a leptonic origin (Petruk et al. 2009a). On the other hand, Acero et al. (2010) have shown that a mixed scenario that includes leptonic and hadronic components also provides a good fit to the gamma-ray data and, according to the model by Berezhko et al. (2012), the hadronic and leptonic components in the $\gamma$-ray emissions are of comparable strength. The basic model of hadronic $\gamma$-ray production requires particles accelerated up to multi-TeV energies and a target of sufficient density. Therefore, the tenuous environment around SN 1006 ($n_0 < 0.05$ cm$^{-3}$; see Acero et al. 2007; Miceli et al. 2012) does not favor the proton–proton interactions that yield hadronic emission. A higher ambient density is observed in the northwestern rim where the shock is slowed down by interaction with dense material (hereafter, the northwestern cloud), producing a relatively bright and sharp H$\alpha$ filament (e.g., Ghavamian et al. 2002; Winkler et al. 2003; Raymond et al. 2007). However, particle acceleration is not very efficient therein, as revealed by the lack of nonthermal X-ray emission.

Here we report the detection of a dense atomic cloud interacting with the southwestern synchrotron rim of SN 1006 (hereafter, the southwestern cloud), where efficient particle...
acceleration is at work. The location of this cloud near an efficient site of particle acceleration makes the southwestern limb a very promising source of γ-ray hadronic emission.

2. RESULTS

Here we analyze the EPIC data of the XMM-Newton Large Program of observations of SN 1006 (together with older XMM-Newton archive observations). The data and the reduction process are described in detail in Miceli et al. (2012, 2013b). The interstellar environment around SN 1006 was studied using the H\textsc{i} observations presented in D02. The radio data were obtained using the Australia Telescope Compact Array and were combined with single-dish data from the Parkes telescope (see D02 for further information).

2.1. Imaging Analysis

Figure 1 shows the EPIC map of the southwestern quadrant of SN 1006 in the 0.3–2 keV band. The bin size is 2\degree and the image is background-subtracted and adaptively smoothed to a signal-to-noise ratio of 10. The regions selected for the spectral analysis of the rim are superimposed: from A to L along the shock and the faint bulge ahead (red dashed line). The cyan curves indicate the contours of the column density (at 1.9 \times 10^{20} cm\textsuperscript{-2}, 2.25 \times 10^{20} cm\textsuperscript{-2}, and 2.7 \times 10^{20} cm\textsuperscript{-2}) derived from the H\textsc{i} observations in the [+5.8, +10.7] km s\textsuperscript{-1} velocity range. (A color version of this figure is available in the online journal.)

Figure 1. EPIC count-rate images (MOS and pn mosaic) of the southwestern part of SN 1006 in the 0.3–2 keV band. The bin size is 2\degree and the image is background-subtracted and adaptively smoothed to a signal-to-noise ratio of 10. The regions selected for the spectral analysis of the rim are superimposed: from A to L along the shock and the faint bulge ahead (red dashed line). The cyan curves indicate the contours of the column density (at 1.9 \times 10^{20} cm\textsuperscript{-2}, 2.25 \times 10^{20} cm\textsuperscript{-2}, and 2.7 \times 10^{20} cm\textsuperscript{-2}) derived from the H\textsc{i} observations in the [+5.8, +10.7] km s\textsuperscript{-1} velocity range. (A color version of this figure is available in the online journal.)

Figure 1. Both of these features peak at v_{\text{LSR}} \sim +10 km s\textsuperscript{-1} and are clearly visible in Figure 3(b) of D02. By assuming that the neutral gas is optically thin (as D02 did), we infer the atomic column density. Figure 1 shows the contours of the column density estimated in the [+5.8, +10.7] km s\textsuperscript{-1} velocity range. In spite of the excellent morphological agreement, D02 had proposed that another H\textsc{i} concentration at v_{\text{LSR}} \sim -5 km s\textsuperscript{-1} was a better candidate, although neither the gas at -5 km s\textsuperscript{-1} nor the one at +10 km s\textsuperscript{-1} had the expected systemic velocity for Galactic gas placed at \sim 2 kpc. Revisiting the same data, it is now evident that the northwestern and southwestern clouds coincide with the northwestern and southwestern lobes of SN 1006. In this picture, the elongated, flat structure of the southwestern cloud naturally appears as the origin of the sharp H\alpha filaments observed all along the northwestern flank, thus this gas must be in the local environment of SN 1006.

As noted before, these structures have anomalous kinematical velocities. However, a velocity deviation from a Galactic circular rotation model is not surprising for gas placed almost 600 pc above the Galactic plane where the connection with the disk rotation is very unlikely. Also, in this part of the Milky Way, it is known that the disk bends toward more negative Galactic latitudes (Burton 1976), increasing the z distance of these clouds from the Galactic arms. Moreover, by supposing that these structures follow the circular rotation model, we obtain a very unlikely outcome since they would be giant clouds (larger than \sim 100 pc), placed as far as \sim 15 kpc in the halo of the Milky Way (\sim 3.7 kpc above the Galactic plane), in perfect agreement with different portions of the border of SN 1006 only by chance. On the other hand, if we consider the hypothesis of cloud disruption as a consequence of the SNR expansion, a departure of \sim 40 km s\textsuperscript{-1} from the systemic velocity would be naturally explained. The X-ray spectral analysis described in the next section will further confirm that the southwestern cloud cannot be located farther than SN 1006. By assuming that the southwestern cloud is at the same distance as SN 1006 (2.2 kpc), we estimate an atomic gas density of about 9–16 cm\textsuperscript{-3}, by assuming an extension of the cloud along the line of sight of 8.5–15.5 (i.e., the minimum–maximum angular extension in the plane of the sky).

2.2. Spatially Resolved Spectral Analysis

We perform a spatially resolved spectral analysis of the X-ray emission originating from regions A to L of Figure 1 to search for variations along the rim of column density and synchrotron cutoff energy h\nu_{\text{cut}}. We model the nonthermal emission with the loss-limited model developed by Zirakashvili & Aharonian (2007; highly suited for SN 1006, as shown by Miceli et al. 2013a, 2013b). Spectral analysis was performed in the 0.3–7.5 keV band by using XSPEC V12.8.

Since we are interested in measuring N_{\text{H}} (the interstellar absorption is modeled through the TBABS model), it is important to correctly describe the soft thermal emission (mainly associated with O vii and O viii line complexes). To model the thermal emission, we included a VPSHOCK component (Borkowski et al. 2001), with the same abundances as the ejecta component in region e of Miceli et al. (2012). We first focused on region A of Figure 1, where the thermal emission is the highest, and determined the best-fit values of the temperature, kT = 0.6^{+0.2}_{-0.1} keV, and ionization timescale, \tau = 1.5^{+1.0}_{-0.6} \times 10^{10} s cm\textsuperscript{-3}. We then fixed these values when fitting the other spectra, and let the plasma emission measure as a free parameter. We refer to this procedure as approach 1. We verified that we do not find...
pronounced variations in the best-fit parameters, even if we model the thermal line emission with two narrow Gaussians (hereafter approach 2; see Miceli et al. 2013b). In particular, the values of $N_{\text{HI}}$ (and $h_{\nu_{\text{cut}}}$) derived with the two approaches follow the same azimuthal trend and are all consistent within 2σ, except for regions A, B, C, where the $N_{\text{HI}}$ derived by adopting approach 2 are unrealistically low ($\sim 5 \times 10^{20} \text{ cm}^{-2}$). Therefore, in the following, we report only the results obtained by adopting approach 1. All the spectra are very well described by our model and the reduced $\chi^2$ ranges between 1.00 and 1.10 (with 1100–2000 degrees of freedom (dof)).

Figure 2 shows the azimuthal variations of the best-fit values of $N_{\text{HI}}$ for regions $A$–$L$. We observe a clear increase in the absorbing column in regions $G$–$L$, corresponding to the location of the southwestern cloud (see Figure 1). In these regions, $N_{\text{HI}}$ is significantly higher than the characteristic value of $\sim 7 \times 10^{20} \text{ cm}^{-2}$, estimated by D02 integrating the H I radio emission in the $[0, -20] \text{ km s}^{-1}$ range (see the dashed blue curve in Figure 2, derived by sampling the $N_{\text{HI}}$ values inferred from the H I observations). If we also include the contribution of the southwestern cloud (derived from H I observations in the $[+5.8, +10.7] \text{ km s}^{-1}$ velocity range) to the column density, we find that the azimuthal profile of $N_{\text{HI}}$ obtained from the radio observation is in amazing agreement with that derived using X-ray spectral analysis. This result further confirms that the southwestern cloud lies at a distance compatible with that of SN 1006 (and the foreground), and not at 15 kpc as estimated from a blindly applied circular rotation model.

The morphology of the southwestern cloud, perfectly corresponding to the concave shape of the southwestern shock front, strongly suggests that the back side of the cloud actually interacts with SN 1006. If this is the case, we expect the shock to be slowed down by this interaction. A direct consequence would be a net decrease in the cutoff frequency of the synchrotron emission in the interaction region because in SN 1006 the maximum electron energy is limited by radiative losses and in the loss-limited scenario $h_{\nu_{\text{cut}}}$ depends on $v_s^2$ (Zirakashvili & Aharonian 2007). Figure 3 shows the azimuthal profile of the best-fit values of $h_{\nu_{\text{cut}}}$ in regions $A$–$L$. Indeed, we find that the cutoff frequency abruptly drops down in regions $G$, $H$, $I$, i.e., exactly where the shock front is indented. Some hints for the presence of this dip in the azimuthal profile of the cutoff energy can be found in Rothenflug et al. (2004) and Miceli et al. (2009), though in these papers the large regions selected for the spatially resolved spectral analysis prevent a significant detection like the one presented here. We conclude that the bulk of the southwestern cloud lies in the foreground (as shown by the $N_{\text{HI}}$ variations in Figure 2) and part of it (i.e., regions $G$, $H$, $I$) is physically interacting with SN 1006.

We searched for thermal emission from the interstellar medium (ISM) in region $H$ (where the ambient density is expected to be at its maximum), but the spectrum is synchrotron-dominated therein and very well described by our model (reduced $\chi^2 = 1.0$ with 1203 dof), so an additional thermal component is not statistically needed and the ISM temperature, $kT_{\text{ISM}}$, is unconstrained. However, we derived some temperature-dependent upper limits for the ISM post-shock density (deduced from the emission measure as in Miceli et al. 2012). We found $n_{\text{ISM}} < (12, 3, 0.3) \text{ cm}^{-3}$ for $kT_{\text{ISM}} = (0.05, 0.25, 2) \text{ keV}$, respectively. The values obtained for low temperatures (expected in the case of propagation in a dense environment) are in agreement with the shock–cloud interaction scenario and similar to those derived from the H I analysis. The shock is probably interacting with the outer border of the cloud (where we expect lower densities) since the amount of the indentation indicates that the interaction is recent and the shock has not yet entered into the bulk of the cloud. We notice that the $H\alpha$ emission in the southwestern limb is quite faint and noisy (Winkler et al. 2003) and the lack of a clear $H\alpha$ filament can be due to a heavily ionized preshock medium and/or an unfavorable (not edge-on) orientation of the emitting sheet.

We obtain a heuristic estimate of the value that $h_{\nu_{\text{cut}}}$ would have had in the case of no interaction by performing a fourth degree polynomial fit to all the points but $G$, $H$, $I$ (the best

\footnote{This is because this approach underestimates the low energy thermal continuum.}
fit curve is shown in Figure 3). We verified that this simple (unphysical) polynomial form also provides a good description of the $h_{\text{cut}}$ profile in the northeastern limb. The cutoff frequency in region $H$ is reduced by a factor of $f \sim 1.7$. Since $h_{\text{cut}} \propto v_z^2 \propto n_{\text{ISM}}^{-1}$, one may suppose that in region $H$ the ambient density is higher by the same factor $f$ and therefore is slightly lower than 0.1 cm$^{-3}$ (assuming $n_{\text{ISM}} \sim 0.03$–0.05 cm$^{-3}$ elsewhere). This value is much smaller than the average density of the southwestern cloud estimated by the H1 data and seems insufficient to produce the observed indentation in the shock. However, we notice that other (non-interacting) parts of the shell, whose projected location falls within region $H$, may contribute to the observed synchrotron emission, thus producing a biased overestimation of $h_{\text{cut}}$ (relatively high $h_{\text{cut}}$ have been observed well inside the shell by Rothenflug et al. 2004) and an underestimation of $n_{\text{ISM}}$. In any case, in the concave region of the southwestern shock front, $h_{\text{cut}}$ is significantly lower than in the adjacent region, in agreement with what we expect in the case of shock–cloud interaction.

The red dashed region in Figure 1 also shows low values of $h_{\text{cut}}$ and high $N_H$. It may be associated with a non-interacting region located behind the cloud, or to particles leaving the remnant and diffusing inside the cloud. Further investigation is necessary to ascertain the origin of this “bulge.”

3. DISCUSSION AND CONCLUSIONS

We have found several evidences for a shock–cloud interaction in the southwestern limb of SN 1006: (1) the southwestern shock presents a sharp indentation in X-rays (as well as in the radio band, see Figure 3 in Petruk et al. 2009b), (2) the indentation corresponds to the position of an H I cloud, (3) this cloud has the same velocity as the northern cloud, which is interacting with SN 1006, (4) the variations in $N_H$ derived from the X-ray spectra show that the southwestern cloud lies in the foreground, and (5) in the indentation region the synchrotron cutoff energy is significantly lower than in adjacent regions. The southwestern limb, characterized by a highly efficient particle acceleration, therefore presents a unique combination of efficient particle acceleration and high target density, thus being the most promising region for $\gamma$-ray hadronic emission in SN 1006.

We estimate the expected hadronic $\gamma$-ray emission from the southwestern limb of SN 1006 by adopting the phenomenological model described in Acero et al. (2010). The $\pi^0$ production from the shock/cloud region is calculated by following Kelner et al. (2006) and the particle distribution is assumed to follow a power law ($\Gamma = 2.0$ for electrons and hadrons) with an exponential cutoff, from which we also calculate the leptonic emission (synchrotron, bremsstrahlung, and inverse compton scattering). The fundamental parameters of our model are the particle total energy ($W_{\text{p}}$), the particle distribution cutoff energy ($E_{\text{c,p}}$), and the ambient density. Considering that the shock is probably not yet interacting with the bulk of the cloud, we assume a downstream density of 10 cm$^{-3}$ (i.e., a pre-shock density smaller by at least a factor of four to six), in agreement with the H I data analysis results and the upper limits provided by the X-ray spectral analysis (Section 2). We assume that the total hadronic energy is 10% of a canonical explosion energy of $10^{51}$ erg. This value was derived by considering that (near the nonthermal limbs) the shock compression ratio is $r \sim 6$ (Miceli et al. 2012) and the model by Vink et al. (2010; Equation (15), therein, for Mach number $M \gg 1$) shows that this $r$ corresponds to a 10% of the available energy transferred to cosmic rays. Also, we verified that the MHD models of SN 1006 performed by Orlando et al. (2012)—in particular, their best-fit models EX-C3.5-D2-QPAR-G1.3 and PL-C3.5-D2-QPAR-G1.3, both including shock modification—provide a similar estimate of the hadronic energy drain ($\sim 9\%$). To derive the hadronic emission from the southwestern cloud, we finally scale the hadronic energy by the proper geometric factor 1/128 (obtained by considering the solid angle corresponding to the southwestern cloud). We assume that the bulk of the TeV $\gamma$-ray emission from the whole southwestern limb is leptonic (fitted parameters $W_{\text{c}} = 5 \times 10^{46}$ erg and $E_{\gamma} = 15$ TeV) and we derive the best-fit value $E_{\gamma} \sim 3$ TeV for the shock/cloud hadronic component (in the interaction region).

Figure 4 shows the comparison between our model of the $\gamma$-ray spectrum (hadronic and leptonic contributions are highlighted) and the HESS spectral information of the southwestern limb (Acero et al. 2010). We predict that the hadronic emission from the southwestern cloud shows a marked peak at $\sim 10$ GeV, reaching a flux $>5 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ in the 3–30 GeV band. This value is slightly below the current sensitivity achieved by Fermi/LAT, which corresponds to less than $8 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ in the 3–30 GeV band (see F. Acero et al. in preparation for further details). We verified that even in the unlikely scenario where the whole HESS spectrum from the southwestern limb has a hadronic origin, the expected flux in the 3–30 GeV does not change significantly, only decreasing to $\sim 4 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ (the proton cutoff energy increases to 60 TeV).

We point out that the Fermi/LAT sensitivity improves rapidly with time. Moreover, the upcoming Fermi-LAT event reconstruction technique (Pass-8) will offer a marked increase in the effective area, better angular resolution, and lower background contamination (Atwood et al. 2013). We conclude that the hadronic emission from the southwestern limb of SN 1006 (if any) will be detectable within a few years. In addition, the Cherenkov Telescope Array (Actis et al. 2011; Acharya et al. 2013) will be able to perform spatially resolved spectroscopy to reveal possible signatures of hadronic emission in the interacting region.

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