Observability and diagnostics in the X-ray band of shock-cloud interactions in supernova remnants

S. Orlando\textsuperscript{1}, F. Bocchino\textsuperscript{1}, M. Miceli\textsuperscript{2,1}, X. Zhou\textsuperscript{3,1}, F. Reale\textsuperscript{2,1}, and G. Peres\textsuperscript{2,1}

\textsuperscript{1} INAF - Osservatorio Astronomico di Palermo “G.S. Vaiana”, Piazza del Parlamento 1, I-90134 Palermo, Italy
\textsuperscript{2} Dip. di Scienze Fisiche & Astronomiche, Univ. di Palermo, Piazza del Parlamento 1, I-90134 Palermo, Italy
\textsuperscript{3} Department of Astronomy, Nanjing University, Nanjing 210093, China

Received ; accepted

Abstract

\textbf{Context.} X-ray emitting features originating from the interaction of supernova shock waves with small interstellar gas clouds are revealed in many X-ray observations of evolved supernova remnants (e.g. Cygnus Loop and Vela), but their interpretation is not straightforward.

\textbf{Aims.} We develop a self-consistent method for the analysis and interpretation of shock-cloud interactions in middle-aged supernova remnants, which can provide the key parameters of the system and the role of relevant physical effects like the thermal conduction, without the need to run ad-hoc numerical simulations and to bother of morphology details.

\textbf{Methods.} We explore all the possible values of the shock speed and cloud density contrast relevant to middle-aged SNRs with a set of hydrodynamic simulations of shock-cloud interaction, including the effects of thermal conduction and radiative cooling. From the simulations, we synthesize spatially and spectrally resolved focal-plane data as they would be collected with XMM-Newton/EPIC, an X-ray instrument commonly used in these studies.

\textbf{Results.} We devise and tune up two diagnostic tools, the first based on the mean-photon energy vs. count rate scatter plot and the second on the spectral analysis of the interaction region, that can be used to highlight the effects of thermal conduction and to derive the shock speed in case of efficient conduction at work. These tools can be used to ascertain information from X-ray observations, without the need to develop detailed and ad-hoc numerical models for the interpretation of the data.

\textbf{Key words.} Hydrodynamics – Shock waves – ISM: clouds – ISM: supernova remnants – X-rays: ISM

1. Introduction

Supernova remnants (SNRs) are known to be a privileged laboratory to investigate the physical and chemical evolution of the galactic interstellar medium (ISM) and the mass distribution of the plasma in the Galaxy. Multi-wavelength observations of evolved SNRs (e.g., Graham et al. 1995; Bocchino et al. 2000; Patnaude et al. 2002; Nichols & Slavin 2004; Miceli et al. 2005) can be a useful tool to investigate the physics of SNRs, for instance the interaction of the remnants with inhomogeneities (clouds) of the ISM. However, this interaction involves many non-linear physical processes (e.g. radiative losses and thermal conduction) which make the analysis of the observations quite difficult. A further limitation comes from the superposition of different emitting regions along the line-of-sight (hereafter LoS) and, in most cases, the data interpretation is not unique.

A powerful approach in the data analysis is based on hydrodynamic and MHD simulations of the shock-cloud interaction, which takes into account the most relevant physical mechanisms (e.g. thermal conduction, radiative cooling, etc.), and on the comparison of the model results with observations. Previous studies (Orlando et al. 2005, 2006, Miceli et al. 2006, Orlando et al. 2008) were devoted to investigate, through numerical modeling, the interaction of SNR shock fronts with small interstellar gas clouds. The scope includes: i) to investigate the role of the different physical processes at work on the dynamics and energetic of the shocked cloud, and ii) to analyze accurately the SNRs observations through their comparison with model results.

As a part of this project, we already investigated the role of thermal conduction and radiative cooling on the evolution of the shocked cloud in the unmagnetized limit. We explored two physical regimes in which each of the two physical processes in turn dominates (Orlando et al. 2008, hereafter Paper I) and found that, in general, the thermal conduction determines the evaporation of a fraction of the shocked cloud, forming a hot and tenuous gas phase (the corona) surrounding the cloud core. In the presence of an organized interstellar magnetic field, the thermal conduction is known to be inhibited across the magnetic field lines and the radiative cooling can be enhanced due to magnetic plasma confinement. We explored the role played by the magnetic-field-oriented thermal conduction and the radiative cooling during the shock-cloud interaction, considering different configurations of the magnetic field (Orlando et al. 2008). We found that the magnetized cases fall in between the limit of completely suppressed thermal conduction and the unmagnetized limit with conduction.

Our numerical models have also been used to make predictions on the expected X-ray emission from the shock-cloud interaction. We showed that the X-ray emitting structures do not trace the morphology of the flow structures originating from the shock-cloud interaction and that the shocked clouds are visible more easily during the early phases of their evolution (Orlando et al. 2006, hereafter Paper II).

However, the big effort done in the modeling of shock-cloud interaction and its X-ray emission has not been counterbalanced
by a rigorous methodology in the comparison between X-ray observations of SNR shells and models. The high resolution instruments on board XMM-Newton and Chandra have provided us with excellent images and spectra of SNRs which are always much more complicated than the ideal cases treated in numerical simulations. Therefore, a straightforward comparison between models and observations is still difficult, and this tends to hamper our understanding of the details of the physical processes which are at the base of the X-ray radiation from SNR shells. Miceli et al. (2006) made one of the first attempts in filling the gap between models and observations. They compared the X-ray observations of an isolated knot in the northern rim of the Vela SNR (Vela FilD; Miceli et al. 2005) with an ad-hoc hydrodynamic model; the comparison showed that the bulk of the X-ray emission in the knot originates in the cloud material heated by the transmitted shock front, but significant X-ray emission is also associated to the cloud material which evaporates in the intercloud medium, under the effect of the thermal conduction. While this strategy has proved to be winning, it is quite model-dependent, in the sense that it is based on an accurate and strict morphological and spectral comparison which may be time and resource consuming.

On the contrary, the idea behind this paper is that the exploration of the parameter space of the shock-cloud model already performed in Paper I and Paper II, along with the extension presented here toward still unexplored values of the cloud density contrast, may be used to devise a quick and effective methodology for the interpretation of current generation X-ray satellite observations of shock-cloud interactions, without the need of running ad-hoc numerical models. Our intent is to provide easy-to-use recipes that allow to extract from the data many of the key parameters governing the evolution of shocked clouds, by comparison with a set of model quantities normalized in a way to eliminate the dependence from unnecessary details, like e.g. the exact morphology of the hit cloud. In particular, our scope includes to devise a diagnostic tool able to quickly assess if the spectral results obtained in the interaction regions are dominated by thermal conduction, a physical effect whose contribution to the X-ray emission is modulated by the magnetic field and, therefore, still in debate and uncertain.

The paper is organized as follows: Sect. 2 briefly describes the numerical setup, the physical parameters of the problem, and the method to synthesize, from the numerical simulations, X-ray observations as they would be obtained with X-ray observatories; Sect. 3 presents the results of the numerical simulations; in Sect. 4 we describe the diagnostic tools devised in this paper and apply the methods, as an example, to X-ray observations reported in the literature; in Sect. 5 we draw our conclusions.

2. Hydrodynamic modeling

We model the three-dimensional interaction of a SNR shock front with an ISM cloud in the same way we have done in Paper I, to which the reader is referred to have more details. We summarize here the main model features. The cloud is assumed to be small compared to the curvature radius of the shock and in pressure equilibrium with the unperturbed isothermal and homogeneous ambient medium; we consider, therefore, a planar shock front and an isobaric cloud, spherical for simplicity. The shock propagates with a Mach number $M \gg 1$ in the ambient medium. The post-shock initial conditions are given by the strong shock limit (Zel’dovich & Raizer 1966). The fluid is assumed fully ionized, and is regarded as a perfect gas.

The plasma dynamics is described by solving numerically the time-dependent fluid equations of mass, momentum, and energy conservation (see Eqs. 1-5 in Paper I). The model takes into account the thermal conduction (Spitzer 1962) and the radiative losses from an optically thin plasma (e.g. Raymond & Smith 1977; Mewe et al. 1985, and Kaasstra & Mewe 2000). The thermal conduction includes the free-streaming limit (saturation) on the heat flux (Cowie & McKee 1977, Giuliani 1984, Borkowski et al. 1989, Fadeyev et al. 2002, and references therein). Our calculations also include a passive tracer associated with the cloud material to trace its motion during the evolution. A discussion of the assumptions of the model and their influence on the results is presented in Sect. 4.4.

The numerical code is FLASH (Fryxell et al. 2000), a multi-dimensional hydrodynamics code for simulating astrophysical plasmas, which uses the PARAMESH (MacNeice et al. 2000) library for block-structured adaptive mesh refinement (AMR), and has been customized with numerical modules that treat thermal conduction and optically thin radiative losses (see Paper I for details). The initial configuration, the boundary conditions, and the AMR setup of the simulations used here are the same as those adopted and discussed in Paper I.

We consider, as a reference case, the $M = 50$ shock model described in Paper I; we then explore the parameter space by varying, alternatively, either the Mach number, $M$, or the density contrast cloud/ambient medium, $\chi$. In the reference model (RCm50c10), the unperturbed ambient medium is at temperature $T_{\text{amb}} = 10^4 \text{ K}$ and particle number density $n_{\text{amb}} = 0.1 \text{ cm}^{-3}$, the spherical isobaric cloud has a radius $r_{\text{cl}} = 1 \text{ pc}$ and density contrast $\chi = 10$ (particle number density $n_{\text{cl}} = \chi n_{\text{amb}} = 1 \text{ cm}^{-3}$). The SNR shock front is planar at Mach number $M = 50$ and temperature $T_{\text{shock}} = 4.7 \text{ MK}$. In the other simulations, the Mach number varies in the range $40 \leq M \leq 60$ (corresponding to shock temperatures in the range $3 \text{ MK} \leq T_{\text{shock}} \leq 7 \text{ MK}$) and the cloud density contrast in the range $3 \leq \chi \leq 30$ (corresponding to particle number density of the cloud in the range $0.3 \text{ cm}^{-3} \leq n_{\text{cl}} \leq 3 \text{ cm}^{-3}$). We note that in Paper II, we have already partially explored the variation induced by a different choice of the shock speed (we have considered $M = 30$ and 50 at $x = 10$). Here, we present for the first time the results for different density contrasts. These ranges are representative of most of the shock-cloud interaction regions observed in evolved SNRs (e.g. Vela, Cygnus Loop, and G296.5+10.0).

Table 1. Parameters of the simulated shock-cloud interactions.

| Run     | $M$  | $\chi$ | $w_{\text{sh}}$ | $T_{\text{shock}}$ | $\tau_{\text{cl}}$ | Therm. |
|---------|------|--------|-----------------|---------------------|---------------------|--------|
| HYm40c10 | 40   | 10     | 458             | 3.0                 | 6.75                | no     |
| HYm50c10 | 50   | 10     | 574             | 4.7                 | 5.41                | no     |
| HYm60c10 | 60   | 10     | 688             | 6.7                 | 4.50                | no     |
| RCm40c10 | 40   | 10     | 458             | 3.0                 | 6.75                | yes    |
| RCm50c10 | 50   | 10     | 574             | 4.7                 | 5.41                | yes    |
| RCm60c10 | 60   | 10     | 688             | 6.7                 | 4.50                | yes    |
| RCm50c03 | 50   | 03     | 574             | 4.7                 | 2.96                | yes    |
| RCm50c30 | 50   | 30     | 574             | 4.7                 | 9.37                | yes    |

$^a$ Shock Mach number. $^b$ Density contrast cloud/ambient medium. $^c$ Velocity of the SNR shock. $^d$ Temperature of the post-shock ambient medium. $^e$ Cloud crushing time (Klein et al. 1994).
The effects of thermal conduction on the shocked cloud evolution have been fully investigated in Papers I and II. Since we are interested in deriving some diagnostic to be used in real X-ray observations, we have compared runs with this physical process (hereafter RC runs) with other runs without it (hereafter HY runs). As shown in a previous work (Orlando et al. 2008), shock-cloud interactions in an organized interstellar magnetic field fall in between these two limits (i.e. HY and RC cases). A summary of all the simulations discussed in this paper is in Table 1, while Fig. 2 shows the simulations in the \( \chi - M \) parameter space. As discussed in Paper I (cfr. Fig. 2 in Paper I), this plot can be used to evaluate if radiative cooling is competitive with respect to thermal conduction for a given run. For example, the shock transmitted into the cloud is strongly radiative in runs RCm40c10 and RCm50c30. On the other hand, the thermal conduction dominates over the radiative losses in all the other cases (i.e. RCm50c03, RCm50c10 and RCm60c10): the cloud is expected to evaporate on a time-scale comparable (in RCm50c03 and RCm50c10) or shorter (in RCm60c10) than \( \tau_{cc} \).

### 2.1. Synthesis of the X-ray observations

The output of the numerical simulations is the evolution of temperature, density, and velocity of the plasma in the spatial domain. From the density and temperature values, we synthesize spatially and spectrally resolved X-ray observations with the XMM-Newton/EPIC-pn X-ray imaging spectrometers (Strüder et al. 2001). The method can be easily extended to other X-ray instruments.

The emission measure in the \( j \)th domain cell is calculated as:

\[
e_{\text{em}} = n_{e,j} V_j,
\]

where \( n_{e,j} \) is the particle number density in the cell, and \( V_j \) is the cell volume. We assume that the direction of the LoS corresponds to the \( y \) axis (in the Cartesian coordinate system), perpendicular to the direction of propagation of the SNR shock front, and that the depth along the LoS is 10 pc (a typical value for the shell of evolved SNRs, such as in Vela and in Cygnus Loop). We then derive the distributions of emission measure versus temperature, \( \text{EM}(T) \), integrated along the LoS for each \( (x,z) \), in the temperature range \( 5 < \log T (K) < 7 \) (divided into 50 bins, all equal on a logarithmic scale). From the \( \text{EM}(T) \) distributions, we synthesize maps of X-ray emission and X-ray spectra, using the MEKAL spectral synthesis code (Mewe et al. 1982, Kastra 1992, Kastra & Mewe 2001), assuming solar metal abundances (Grevesse & Anders 1991).

We assume the source to be at a distance \( D_{\text{snr}} = 500 \) pc (as, for instance, in the case of Cygnus Loop) and we filter the spectra through an ISM absorption column density, \( N_H = 5 \times 10^{20} \) cm\(^{-2} \) (Morrison & McCammon 1983), according to typical values derived from SNR observations at that distance (e.g. Patnaude et al. 2002). The absorbed X-ray spectra are then folded through the instrumental response to obtain focal plane spectra. The exposure time is assumed to be \( t_{\text{ex}} = 10 \) ks for EPIC-pn (see, for instance, Miceli et al. 2005). The photon counts are randomized in each energy instrumental channel of the focal-plane spectra according to Poisson statistics, using the rejection method applied to the Poisson distribution (Press et al. 1986). X-ray emission maps are produced in selected energy bands, assuming a spatial resolution of 4 arcsec: the X-ray images are convolved with the corresponding point spread function (PSF), as given by Ghizzardi (2002) for EPIC-pn.

The final products are X-ray simulated observations, spatially and spectrally resolved, in a format virtually identical to that of real observations collected with EPIC-pn. To such data, we apply the standard methods of analysis commonly used for X-ray observations.

### 3. Results

#### 3.1. Light-curves

The detectability of the shock-cloud collision in the X-ray band is expected to depend on the \( M \) and \( \chi \) parameters. From our simulations, we derive the X-ray light curves of the region associated to the shocked cloud, to understand at which stage of the interaction the visibility of the cloud is maximum. Such a region is selected in each synthesized EPIC-pn count rate image in the [0.3 – 2.0] keV band (typically selected for the analysis of evolved SNR shock-cloud interaction; see, for instance, Miceli et al. 2005), by considering all the pixels having a median energy of X-ray photons, \( \chi \) (Hong et al. 2004), which is less than 90% of the \( \bar{\chi} \) derived for the surrounding medium: from these pixels, then, we evaluate the average counts s\(^{-1}\) per pixel, \( F_{X} \), normalized to the value derived for the intercloud medium. The X-ray light curves reported in Fig. 2 show when the shocked cloud is detectable (when the normalized \( F_{X} \) is higher than 1) and its X-ray luminosity is maximum.

In general, we find that the higher is \( M \), the higher the normalized \( F_{X} \) at each stage of the evolution (see Fig. 2). In most cases, the shocked cloud is visible in the X-ray band in the interval \( 0.1 \tau_{cc} < t < 1.5 \tau_{cc} \). The thermal conduction makes the shocked cloud brighter than in cases without conduction, broadening the peak in the X-ray light-curve for any Mach number. In fact, the conduction contributes to the cloud heating, increasing the amount of cloud material above 1 MK and emitting in the X-ray band. Note also that the conduction makes the shocked cloud material expected to be cooler than the surrounding medium.
The shocked cloud is detectable with EPIC-pn during the early phases of the shock-cloud interaction ($t < 1.5 \tau_{cc}$; see Fig. 2) as a bright knot surrounded by a diffuse region (see right panels in Fig. 3). We focus the spectral analysis in the interval $0.4 \tau_{cc} \leq t \leq 1.4 \tau_{cc}$ when the shocked cloud is the brightest in all the models. For each sampled X-ray image, we select spatial sub-regions in the computational domain and analyze the X-ray spectra extracted from each of them. To select spectrally homogeneous regions, we derive maps of the median energy of X-ray photons, $\bar{E}$, from the EPIC-pn data that allows to convey at the same time both spatial and spectral information on the emitting plasma (Hong et al. 2004). Since the shocked cloud is cooler than the surrounding medium, the median photon energy, $\bar{E}$, of the bright region is lower than that of the surroundings (see left panels in Fig. 3). Thus we select subregions with a median photon energy $0.5 \text{keV} < \bar{E} < 0.6 \text{keV}$ (to identify the knot), and subregions with $0.6 \text{keV} < \bar{E} < 0.7 \text{keV}$ (for the diffuse region, DR). The knot corresponds to the brightest portion of the X-ray image in Fig. 3 and the DR selects the intermediate brightness region surrounding the knot (compare left and right panels in Fig. 3).

It is important to stress that this definition of the extraction regions for spectral analysis are completely independent from the morphology of the X-ray emission. This has the great advantage that it can be straightforwardly applied to any current X-ray telescope observation for which the mean photon energy map can be computed. Moreover, it makes the spectral analysis independent, in first approximation, from the details of the shape of the ISM clouds, which in reality may be much more complex than the ideal spherical cloud proposed in our model.

The extracted spectra have a total number of photons ranging between $10^6$ and $4 \times 10^5$, adequate for a detailed spectral analysis. The focal plane spectra have been analyzed using the spectral fitting package XSPEC (Arnaud 1996) and applying a multi-temperature fit to each spectrum. All the extracted spectra are well fitted with two MEKAL components of an optically-thin thermal plasma in collisional ionization equilibrium (Mewe et al. 1985, Kaastra & Mewe 2000), with solar abundances, and filtered through the interstellar absorption (Morrison & McCammon 1983). We have applied this procedure to any model listed in Table 1 and in the interval $0.4 \tau_{cc} \leq t \leq 1.4 \tau_{cc}$ in step of $\delta t = 0.1 \tau_{cc}$. We present here, as an example, the results obtained in the reference models HYm50c10 and RCm50c10.

Figure 2 shows the temperature, $T$, and the emission measure per unit area, $em = EM/A_{reg}$ (where $A_{reg}$ is the area of the selected region), of the isothermal components fitting the EPIC-pn spectra. When the thermal conduction is completely suppressed (run HYm50c10), the spectra of both the knot and the DR at the different epochs are described, in general, by two isothermal components with temperatures $T_{low} \approx 1 \text{MK}$ and $T_{high} \approx 4.5 \text{MK}$; the emission measure of the hot component is $em_{high} \approx 5 \times 10^{19} \text{cm}^{-2}$ in all the spectra, whereas $em_{low}$ ranges between $3 \times 10^{19}$ and $8 \times 10^{19} \text{cm}^{-2}$. Note that the temperature of the hot component is close to the temperature of the shocked ambient plasma $T_{phs} \approx 4.7 \text{MK}$, whereas $T_{low}$ is slightly higher than the temperature of the shock transmitted into the cloud, $T_{isc} \approx 0.8 \text{MK}$ (see Paper 1).

In run RCm50c10, the spectra are again described by two isothermal components, but with some differences due to the thermal conduction. In particular, $T_{low}$ is higher and $T_{high}$ is...
Figure 3. Median energy maps (left) and EPIC-pn count rate images (right) in the [0.3 - 2.0] keV band derived for run RCm50c10 at the three labeled times during the evolution. The pixel size is $\sim 4$ arcsec and the exposure time is 10 ks. The images are smoothed with a boxcar of width $\sigma \approx 12$ arcsec. The white contours mark the cross-section of the cloud on the plane of the image, identified by zones consisting of the original cloud material by more than 90%: the contours superimposed to the median energy maps mark the bright knot (red) and the diffuse region (diffuse region, DR; black).

Figure 4. Best-fit values of temperature (upper panel) and emission measure per unit area (lower panel) for the EPIC-pn spectra extracted from the bright knot and from the diffuse region (DR) in runs HYm50c10 (blue) and RCm50c10 (red) at different epochs between 0.4 and 1.4 $T_{cc}$. The dashed lines in the upper panel mark the temperatures expected for the shock transmitted into the cloud ($T_{scl} \approx 0.8$ MK) and for the shocked ambient plasma ($T_{psh} \approx 4.7$ MK).

<figure>
</figure>

In general, we find that the cold component is the most sensitive to the thermal conduction, showing the largest differences between HYm50c10 and RCm50c10. The origin of these differences is explained by comparing the results of the spectral fitting with the distributions of emission measure per unit area versus temperature, $\text{em}(T)$, from which the extracted spectra originate.

Figure 5 shows these $\text{em}(T)$ distributions together with the results of the spectral fitting. In general, the distributions of both the knot and the DR are bi-modal. The cold peak around $T \approx 2$ MK is due to the shocked cloud gas; the hot peak at $T \approx 5$ MK is due to the shocked ambient plasma surrounding the cloud. The best-fit values are localized around these maxima and, therefore, can be associated to the shocked cloud gas (cold component) and to the shocked ambient plasma (hot component).

In HYm50c10, the $\text{em}(T)$ distributions of both the knot and the DR do not change significantly during the evolution (except at $t \sim 1.2 \ T_{cc}$, when the shocks transmitted from the front and from the rear of the cloud interact; see Paper II), with the two bumps steadily centered around the temperatures expected for the shock transmitted into the cloud ($T_{scl} \approx 0.8$ MK) and for the shocked ambient plasma ($T_{psh} \approx 4.7$ MK), respectively. By comparing HYm50c10 with RCm50c10, the main effects of the thermal conduction are: i) to smooth the $\text{em}(T)$ distributions, because of a transition region formed between the inner part of the cloud and the ambient medium in which the density decreases and the temperature increases smoothly in the radial direction (see Paper II); and ii) to shift the first bump to higher temper-
atures due to the gradual thermalization of the shocked cloud material to the temperature of the shocked ambient plasma (see also Paper II).

As a result of the conduction effects, the amount of plasma above 1 MK increases in RCm50c10, making the shocked cloud brighter in the X-ray band (see Fig. 2). Also, the changes in the em(T) distributions due to the thermal conduction determine the differences in the results of the spectral fitting for HYm50c10 and RCm50c10 (see Fig. 4), for instance, the shift of the first bump in em(T) to higher temperatures leads to higher T_{low}, and the smoothing of em(T) leads to lower em_{low} in RCm50c10. Note also that the effects of the thermal conduction are the largest in the em(T) distribution of the DR, being the plasma of the corona surrounding the cloud core subject to efficient heat conduction. As a consequence, the cold fitting component in the DR is, in general, hotter than that in the knot (see also Fig. 4), whereas the opposite is true in HYm50c10 (i.e. the temperature of the shocked cloud material is never higher than the temperature of the shock transmitted into the cloud).

4. Diagnostics

4.1. Median energy vs. count-rate scatter plot

Since the thermal conduction modifies the temperature and density structure of the shocked cloud (see Paper I), its effects may be expected in the comparison of E maps (related to the spatial distribution of temperature) with count rate maps (related to the spatial distribution of mass density). We derive, therefore, \( \overline{E} \) versus count rate scatter plots (see, for instance, [Miceli et al. 2005]). We first divide the range of count rates \([0.01 - 0.20] \text{ cnts s}^{-1}\) into 100 bins (all equal on linear scale); then, from the EPIC-pn count rate images in the \([0.3 - 2.0]\) keV band, we derive the median photon energy of all the pixels belonging to the same count rate bin. Fig. 6 shows the scatter plots derived for HY (upper panel) and RC (middle and lower panels) runs at selected epochs between \(0.4 \tau_{cc} \leq t \leq 1.4 \tau_{cc}\) (when the shocked clouds are visible; see Fig. 2). All these plots are characterized by a clear descending trend and, then, in most of the cases, by a much flatter fall (cold plateau): the higher the count rate, the lower is the median energy and, therefore, the lower is the average temperature along the LoS. The descending branch and the cold plateau are the signature of the shock-cloud collision: the former roughly corresponds to the DR and the latter to the bright and cold knot defined in Sect. 3.2.

In HY runs, scatter plots derived for \( \chi = 10 \) and different \( M \) show a similar shape, characterized by a very steep descending branch and a well defined cold plateau (see upper panel in Fig. 6). The descending branch shows an abrupt transition between the intercloud material (highest \( \overline{E} \)) and the shocked cloud material (lowest \( \overline{E} \)). In RC runs (see middle panel in Fig. 6), the thermal conduction makes the slope of the descending branch flatter than that of HY runs, being the absolute value of the slope smaller for higher \( M \). The flattening of the descending branch reflects a smooth temperature and density structure of the shocked cloud due to the heat conduction that leads to the grad-
Figure 6. Median photon energy, $\bar{E}$, versus count rate scatter plot derived from the EPIC-pn data in the period $0.4 \tau_{cc} \leq t \leq 1.4 \tau_{cc}$. Upper panel: runs without thermal conduction (HY runs) with $\chi = 10$ and $\mathcal{M} = 40, 50, 60$. Middle panel: runs with thermal conduction (RC runs) with $\chi = 10$ and $\mathcal{M} = 40, 50, 60$. Lower panel: RC runs with $\mathcal{M} = 50$ and $\chi = 3, 10, 30$. The dashed lines in the upper and middle panels show the slope of the $\bar{E}$, versus count rate scatter plot derived from the analysis of EPIC data of Vela FilD (Miceli et al. 2005).

In summary, these scatter plots can be very useful to determine the role of the thermal conduction through the slope of the descending branch and to derive hints about the speed of the shock (in case of efficient conduction at work). On the other hand, the plots are poorly useful to infer the actual density contrast of the cloud.

4.2. Temperature and emission measure ratios

The spectral analysis discussed in Sect. 3.2 suggests that the cold fitting components describing the knot and the DR are sensitive to the thermal conduction; we propose, therefore, to use them as a diagnostic tool to trace the efficiency of conduction. Fig. 7 compares the temperature and emission measure values derived for the knot with those derived for the DR (and reported in Fig. 4) in runs HYm50c10 and RCm50c10. The runs with/without thermal conduction are clearly separated in the plot, the thermal conductive case being localized in the bottom-right quadrant and the pure hydrodynamic case in the top-left quadrant. This result is determined by the development of the thermally conducting corona in RCm50c10 and, therefore, is expected to be general. In particular, as discussed in Sect. 3.2, the thermal conduction smooths the first bump in the em($T$) distributions and shifts it to higher temperatures, being this effect larger for the DR than for the knot. As a result, the cold fitting component derived for the DR is, in general, hotter (i.e. $T_{low}^{DR} > T_{low}^{knot}$) whereas the opposite is true (i.e. $T_{low}^{DR} < T_{low}^{knot}$) if the conduction is suppressed. Also, the smoothing of the em($T$) distribution due to the conduction is the largest for the DR (because the corona surrounding the cloud core is subject to efficient heat conduction), leading to the smallest values of em$_{low}$ (see also lower panel in Fig. 4).

In summary, the temperature and emission measure ratios are an excellent way to determine the role of the thermal conduction in the evolution of the system.
4.3. An example of model vs. observation comparison

Our study shows that evidence of thermal conduction at work during the shock-cloud interaction may be found in the spectral analysis of X-ray data. As discussed in the previous sections, the $E_{\text{ss}}$ vs. count-rate scatter plot and the temperature and emission measure ratios can be efficient diagnostic tools to derive the shock speed and the role of thermal conduction, which, in turn, is linked to the magnetic field configuration, as shown by Orlando et al. (2003). In this section, we challenge the above diagnostic tools and show that they can be easily used in the analysis of X-ray data, by comparing our model results with X-ray observations reported in the literature.

In particular, we focus on a well-studied region, the "FilD region"; that is an isolated, bright X-ray knot in the northern rim of the Vela SNR. Because of its proximity ($\sim 250$ pc; Bocchino et al. 1999; Cha et al. 1999). Vela is an ideal target for this kind of study, allowing us to observe the interaction of the SNR shock front with relatively small clouds, like FilD ($\sim 2 \times 10^{15}$ cm; see Miceli et al. 2005 in great detail. The analysis of an XMM-Newton observation of FilD (Miceli et al. 2005) has shown that its X-ray spectra can be modeled by an optically-thin plasma with two thermal components (at $\sim 1$ MK and $\sim 3$ MK, respectively) with inhomogeneous volume distributions along the line of sight. The cold component dominates in the brightest region that is surrounded by a diffuse region with harder X-ray emission. To interpret these results. Miceli et al. (2005) developed a detailed hydrodynamic model of FilD, synthesized X-ray emission maps and spectra from the model, and compared them with the data. Their analysis has shown that the X-ray and optical emission of FilD can be explained as the result of the interaction of a SNR shock (with Mach number $M = 57$) with an ellipsoidal cloud 30 times denser than the intercloud medium; the estimated interaction time is $0.32 \tau_{\text{cc}}$. Miceli et al. (2005) proved that the two components originate in the cloud material heated by the transmitted shock front and by heat conduction between the cloud and the hotter, shocked intercloud medium. FilD, therefore, is an ideal benchmark for our model, being a case for which the thermal conduction has been proved to be at work. Since the parameters used in our simulations are slightly different from the parameters deduced from the observations (including the shape of the cloud), we do not expect a perfect match, but the comparison will nonetheless give us much useful information.

Among the runs presented here, the one matching the density contrast of the shock-cloud interaction is RCm50c30 (see Tab. 1). As already discussed, the shocked cloud with such a density contrast ($\chi \sim 30$) would not be detectable in X-rays if the thermal conduction is suppressed, being its estimated temperature $T_{\text{coll}} \approx 3.5 \times 10^5$ K. On the other hand, inspecting Fig. 6, we note that, in run RCm50c30 (dashed line in the lower panel), the shocked cloud is visible in X-rays for a short time interval (0.1 – 0.6 $\tau_{\text{cc}}$) and has the largest surface brightness at the evolutionary stage estimated for FilD ($0.32 \tau_{\text{cc}}$). We expect a brighter emission for higher values of $M$ (see middle panel in Fig. 4). As shown by our simulations, the detected X-ray emission originates in the cloud material dominated by thermal conduction, confirming the relevance of conduction in the evolution of FilD.

Miceli et al. (2005) analyzed the spectra extracted from the knot and the DR composing the FilD region. Thus, we can derive the temperature and emission measure ratios of the cold components derived by these authors and plot them in Fig. 7. The observed values lie in the bottom-right quadrant of the figure, confirming once again that in FilD the thermal conduction is efficient, in perfect agreement with the independent conclusion of Miceli et al. (2006). The diagnostics in Fig. 7 is of easy implementation and we suggest it as a standard to check for the role of conduction.

Miceli et al. (2005) derived also a $E_{\text{ss}}$ versus count rate scatter plot for FilD that can be compared directly with the corresponding scatter plots derived with our models. We overplotted a best-fit power-law model (with index $=-0.25$) to the data of the FilD region reported in Fig. 4 of Miceli et al. (2005), considering the count rate as a free parameter, a reasonable choice if we consider that the actual value of the count rate depends on the actual LoS extension, which is poorly known. The slope of the observed scatter plot is rather flat and cannot be reproduced by models without the thermal conduction (see upper panel in Fig. 6). On the other hand, the observed slope is reproduced quite well by our RC runs, in agreement with the evidence that the thermal conduction plays an important role in the evolution of FilD. $M = 60$ seems to be the model which best reproduces the slope, in very good agreement with the value obtained by Miceli et al. (2005) ($M = 57$) with a detailed analysis.

4.4. Limits of the model

In our simulations, we parametrize the thermal conductivity using the classical Spitzer’s conductivity and the saturation limit, assuming essentially laminar thermal conduction in the all spatial domain. However, regions of strong turbulence of different strength and extent can develop in the system (especially in shock-cloud interactions dominated by radiative cooling), for instance at the shear layers along the cloud boundary or at the vortex sheets in the cloud wake. The turbulence in these regions may have a significant effect on the thermal conduction, leading to significant deviations of thermal conductivity from its laminar values (e.g. Kulsrud 1983; Narayan & Medvedev 2001; Lazarian 2006). As a result, the thermal conduction may be inhomogeneous due to the presence of turbulence. On the other hand, the deviations of thermal conductivity from its laminar values are expected to be relevant in the shocked intercloud medium, thus not affecting our main conclusions on the effects of thermal conduction on the shocked cloud and on the applicability of the diagnostics devised here.

In our model, we do not account for the possible effect of the back-reaction of accelerated cosmic rays on shock dynamics. In the case of high Mach number shocks, a part of the shock power may be dissipated into cosmic rays acceleration, resulting in the increase of the shock compression ratio. The distribution function of non-thermal particles and the bulk flow profile in the shock upstream region are sensitive to the total compression ratio. Thus, even a moderate efficiency of particle acceleration may reduce the post-shock ion and electron temperatures (see, e.g. Eq. 18 in Bykov et al. 2008), with implications on the X-ray emission. This effect is expected to be large for shocks with high Mach number (as, for instance, in young SNRs), but not in middle-aged SNRs (to which this paper is focussed on) for which no non-thermal emission has been detected. Even if particle acceleration were not negligible, the effect relevant to our diagnostics would only be to slightly reduce the efficiency of the thermal conduction because of the lower post-shock temperature. As in the case of magnetized clouds (Orlando et al. 2008), shocked clouds with considerable particle acceleration would fall in between the limit of completely suppressed thermal conduction (HY runs) and the unmagnetized limit with conduction (RC runs) discussed in this paper.
Recently Pittard et al. (2009) have demonstrated that the turbulence plays an important role in shockcloud interactions, and that environmental turbulence adds a new dimension to the parameter space. In particular these authors have shown that the turbulence is mainly generated around the cloud boundary and in the cloud wake after $\sim \tau_{cc}$: the main effect is that clouds subject to a highly turbulent post-shock environment are destroyed significantly quicker than those within a smooth flow: the larger the cloud density contrast $\chi$, the higher is the effect of turbulence (for instance, for $\chi \approx 100$, the effect of the post-shock turbulence dominates in the shock-cloud interaction). On the other hand, an efficient thermal conduction makes the cloud boundary very quickly (see Paper I), and the turbulence grows more slowly around clouds with a smooth density profile (Pittard et al. 2009).

Equilibrium may not be complete early during the shock-cloud interaction at early evolutionary stages for $\tau_{cc} \leq 0.4$. The effects of turbulence poorly influence the shock-cloud interaction at early evolutionary stages for $t \approx \tau_{cc}$) and smooth density profiles (i.e. the growth of turbulence around clouds is slow), that we considered here.

Finally, our model does not account for the incomplete electron-ion temperature equilibration in the post-shock region. Equilibrium may not be complete early during the shock-cloud interaction ($t \approx 0.1 \tau_{cc}$). In that phase emission models including non-equilibrium should be applied and the initial part of the light-curves presented in Fig. [2] may change. On the other hand, the diagnostics discussed in this section refer to the shock-cloud interaction at 0.4 $\tau_{cc} \leq t \leq 1.4 \tau_{cc}$, when the hypothesis of temperature equilibration can be considered realistic for the shock velocities explored here (Rakowski et al. 2003).

5. Summary and conclusion

In a series of previous paper (Paper I, II, Orlando et al. 2008), we have investigated the X-ray emission arising from the interaction of SNR shock waves with isolated gas clouds with the scope of identifying the plasma structures that mainly contribute to X-ray emission and structure with prototypical X-ray instruments. In this work, we extend our parameter space considering clouds with different value of density contrast and devise diagnostics in the X-ray band revealing the shock speed, which is one of the fundamental parameter governing the shock-cloud interactions, and the cloud evaporation under the effect of the thermal conduction.

In particular, by performing a series of spectral fittings to the simulated data of the shock-cloud interaction region, we proved that there are at least two interesting diagnostic diagrams that can be used:

- the median energy vs. count rate scatter plot (Fig. 6), which gives a direct estimate of the shock speed and a hints about the effects of the thermal conduction;
- the temperature and emission measure ratios between the knot and diffuse region of the cloud (Fig. 7), which gives a direct estimate of the role of the thermal conduction in the evolution of the system.

We stress that the regions (the knot and the DR) which must be selected to derive the diagnostic diagrams are defined entirely on the basis of mean photon energy maps, and not on the actual shape of the X-ray emission. Therefore, the method is very well-posed and independent, in first approximation, to the actual shape of the ISM clouds, which could be more complex that the ideal spherical cases considered in our hydrodynamic simulations. While this method cannot be considered a substitution for a detailed approach to the study of shock-cloud interactions based on the developing of ad-hoc (and time-consuming) numerical models, nevertheless, we have demonstrated that the diagnostic diagrams we have presented can be very useful to derive some of the parameters of the system and the role of thermal conduction in a very quick and straightforward way. These information can be used in turn for a more detailed model, if necessary.

The method can be applied to imaging X-ray observations of middle-aged thermal SNR shells (like Vela or Cygnus Loop), as for instance those obtained by the XMM-Newton and Chandra X-ray satellites. We used as a benchmark the XMM-Newton/EPIC observations of the Vela FilD region of Miceli et al. (2005), from which, independently, Miceli et al. (2006) have found strong evidence of thermal conduction at work during the shock-cloud interaction, using a detailed ad-hoc numerical model. We found that our method is quite effective in recovering quickly the shock speed and the effects of the thermal conduction.

Acknowledgements. We thank the referee for constructive and helpful criticism. The software used in this work was in part developed by the DOE-supported ASC / Alliance Center for Astrophysical Thermonuclear Flashes at the University of Chicago. The simulations have been executed at CINECA (Bologna, Italy) in the framework of the INAF-CINECA agreement on “High Performance Computing resources for Astronomy and Astrophysics”, and on the SCAN (Sistema di Calcolo per l’Astronomia Numerica) HPC facility of the INAF-Osservatorio Astronomico di Palermo. This work was supported in part by Ministero dell’Universita e della Ricerca and by Istituto Nazionale di Astrofisica.
Orlando, S., Bocchino, F., Peres, G., Reale, F., Plewa, T., & Rosner, R. 2006, A&A, 457, 545 (Paper II)
Orlando, S., Bocchino, F., Reale, F., Peres, G., & Pagano, P. 2008, ApJ, 678, 274
Orlando, S., Peres, G., Reale, F., et al. 2005, A&A, 444, 505 (Paper I)
Patraude, D. J., Fesen, R. A., Raymond, J. C., et al. 2002, AJ, 124, 2118
Pittard, J. M., Falle, S. A. E. G., Hartquist, T. W., & Dyson, J. E. 2009, MNRAS, 394, 1351
Press, W. H., Flannery, B. P., Teukolsky, S. A., & Vetterling, W. T. 1986, Numerical Recipes (Cambridge University Press, Cambridge)
Rakowski, C. E., Ghavamian, P., & Hughes, J. P. 2003, ApJ, 590, 846
Raymond, J. C. & Smith, B. W. 1977, ApJS, 35, 419
Spitzer, L. 1962, Physics of Fully Ionized Gases (New York: Interscience, 1962)
Strüder, L., Briel, U., Dennerl, K., et al. 2001, A&A, 365, L18
Zel’dovich, Y. B. & Raizer, Y. P. 1966, Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena (New York: Academic Press, 1966)