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Multi-phase interstellar clouds in the Vela SNR resolved with XMM-Newton

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Abstract

XMM-Newton spatial/spectral resolution and high effective area allow to deepen our knowledge about the shocks in Supernova Remnants and their interaction with the interstellar medium. We present the analysis of an EPIC observation of the northern rim of the Vela SNR and we compare the X-ray and optical morphology of the emission. We derive a description of the internal structure of the shocked interstellar clouds, arguing that the transmitted shock model is compatible with our data. We also suggest that thermal conduction between clouds and inter-cloud medium is very efficient and produces the evaporation of the clouds in the interstellar medium.

Keywords: X-rays: ISM; Supernova remnants; Vela SNR

1. Introduction and data

The evolution of Supernova Remnants (SNRs) is deeply influenced by their interaction with the inhomogeneities of the ambient medium which affect the speed and the direction of the expanding shock wave. The interaction of the shock with the clouds of the interstellar medium (ISM) produces the characteristic, patchy X-ray morphology and the filamentary optical emission of middle-aged SNRs.

From the analysis of optical and X-ray observations, three different physical scenarios have been suggested to explain the details of the shock–cloud interaction and of the observed emission. These scenarios all associate the optical emission with a transmitted shock which travels through the clouds, while the X-ray emission is associated: (i) with the evaporation of the clouds engulfed by the main blast wave (Fesen et al., 1982; Charles et al., 1985; Bocchino and Bandiera, 2003); (ii) with a reflected shock which further heats the shocked intercloud medium [1] (Graham et al., 1995; Levenson et al., 1996; Miyata and Tsunemi, 2001); (iii) with a transmitted shock which propagates through inhomogeneities with an inward increasing density profile (Bocchino et al., 2000; Patnaude et al., 2002; Levenson et al., 2003).

The Vela SNR is the nearest middle-aged SNR (distance $\sim$ 280 pc, Bocchino et al., 1999; Cha et al., 1999) so it is an ideal laboratory for a detailed study of the shock–cloud interaction which could allow one to discriminate between the three models.

In this paper, we discuss the analysis of an *XMM-Newton* EPIC observation of the northern rim of the Vela SNR. The observed region lies just behind the main shock front and, as shown by a previous ROSAT PSPC

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[1] The almost uniform component of the ISM which surrounds the clouds.

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observation (Bocchino et al., 1999), in this part of the shell there is a clear signature of the interaction of the shock with a relatively small and isolated cloud, named FilD. The aims of our work are: (i) to obtain a detailed description of the ISM clouds and of their internal structure; (ii) to obtain information about the physical properties of the shocked plasma, and (iii) to study the dynamics and evolution of the shock–cloud interaction.

Our data consist of a Guaranteed Time EPIC observation with pointing coordinates α (2000) = $8^h35^m44^s$, δ (2000) = $-42°35'29''$. We performed a time screening to eliminate the time intervals contaminated by soft-proton flares (characterized by rapid and strong variability in the light curve); the screened exposure times are 11.5 ks, for pn data, and 25.2 ks, for MOS1 and MOS2 data. We used the medium filter and the Extended Full Frame Mode (for pn) and the Large Window Mode (for MOS1 and MOS2).

2. Structure and physical parameters of the shocked clouds

Fig. 1 (top panel) shows the EPIC adaptively smoothed and vignetting corrected count rate image in the 0.3–10 keV energy band. The structure in the center of the field of view, composed of two bright knots, is the FilD cloud. At North-East another bright structure (named RegNE) is visible. The X-ray emission of FilD is quite soft (below 0.5 keV) while RegNE has a harder emission (almost entirely concentrated in the 0.5–1 keV band).

There is a clear relationship between the optical and X-ray emission in the FilD knot. Fig. 1 (bottom panel) shows a DSS archive image of the FilD region where the optical filament studied by Bocchino et al. (2000) is visible (near the bright star in the center of the image). We have superimposed the X-ray contour levels in the 0.3–0.5 keV band. The optical filament lies just between the two FilD regions (indicated with "a" and "b" in the top panel of Fig. 1) with the highest X-ray surface brightness. This relationship, observed also in the Cygnus Loop by Patnaude et al. (2002), suggests that the optical filaments represent the inner and denser part of the FilD cloud.

We studied in detail the distribution of the physical parameters of the post-shock plasma performing a spatially resolved spectral analysis (for the details of our analysis, see Miceli et al., submitted for publication). We analyzed the spectra extracted from 16 subregions (indicated in Fig. 2, top panel) which cover the whole FilD cloud, RegNE, the bright structure at the South-West and the dark area at the North. The subregions have an extension of a few arcminutes and in each subregion the mean photon energy can be considered almost uniform; in fact the mean photon energy in the pixels of any given subregion presents fluctuations <4%.

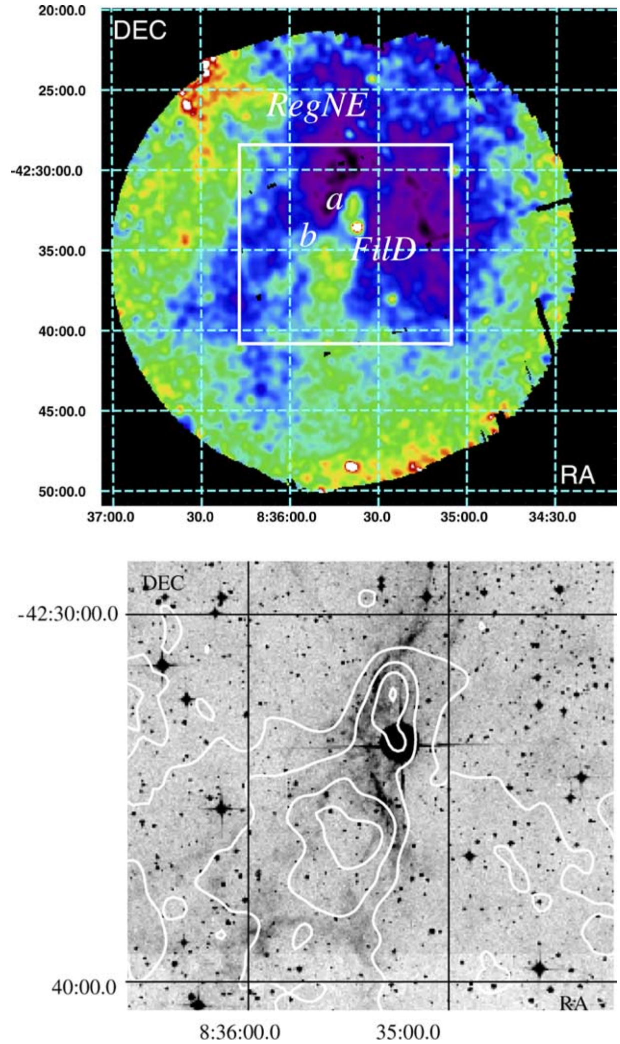

Fig. 1. *Top panel:* Adaptively smoothed count rate image in the 0.3–10 keV band. This image is a weighted average of the pn, MOS1 and MOS2 images (and is expressed in MOS-equivalent count rate), the bin size is 4″, North is up and East is on the left. *Bottom panel:* DSS archive image of the FilD region, the field of view is indicated by the white square shown in the left panel. We have superimposed (in white) 7 X-ray contour levels (equispaced between 0 and 7.1×10^{-5} cnt s^{-1} bin^{-1}) in the 0.3–0.5 keV band. The bright star is the optical counterpart of the X-ray point-like source visible in the left panel; this source is not related to the Vela SNR.

A single temperature model both in CIE or NEI is rejected in all the regions except for RegNE. All spectra are described (at 95% confidence level) by two MEKAL components of an optically-thin thermal plasma (Mewe et al., 1985, 1986; Liedahl et al., 1995). The fits with the PSHOCK non-equilibrium ionization model (Borkowski et al., 2001) do not significantly improve the quality of the fits and the best-fit τ_{NEI} values indicate that the plasma has already reached collisional ionization equilibrium. Fig. 2 (bottom panel) shows a representative spectrum together with its best-fit model. The temperature of each component is rather uniform in the field of view and is not related with the X-ray surface