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Shock-cloud interaction in the Vela SNR: the XMM-Newton view

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Abstract. We analyzed an EPIC observation of a small knot in the northern rim of the Vela SNR. Thanks to the combination of good spectral and spatial resolution of the EPIC camera, we derived a description of the internal structure of the observed ISM clouds and constrained their evolution scenarios, finding that the shock-cloud interaction determines the collapse of the inner part of the clouds and the evaporation of the outer part. We also derived an estimate of the O, Ne and Fe abundances inside the clouds.

1. Introduction and data

Supernova Remnants (SNR) play a leading role in the mass and energy exchange in the interstellar medium (ISM) and many observations performed by the past generations of X-rays satellites opened up the study of heating processes in the shock region (Graham et al. 1995, Levenson et al. 1996, Miyata & Tsunemi 2001, Patnaude et al. 2002). However, the analysis of these observations left many open issues about the morphology of the system and the detailed distribution of the plasma parameters (especially at small angular scale), because of the low spatial resolution ($> 5'$) at which spatially resolved spectral analysis was possible and the limited spectral resolution ($E/\Delta E < 2$) and effective area. *XMM-Newton* observations allow us to overcome this kind of problems and hence to study in greater detail the interaction of the blast wave shock of a middle aged SNR with the inhomogeneities of the interstellar medium. In this paper we present the analysis of an EPIC Guaranteed Time Observation (exposure time $\sim$ 30 ks) of the northern rim of the Vela SNR, pointing coordinates $\alpha(2000) = 8^h35^m44^s$; $\delta(2000) = -42°35'29''$. Vela SNR is $\sim$ 11000 yr old (Taylor et al. 1993) and its distance is $\sim$ 280 pc (Bocchino et al. 1999), so it is the nearest object of its kind and represents a privileged laboratory for the study of the shock-cloud interaction in the middle aged SNRs. At the Vela distance the diameter of the EPIC field of view corresponds to an extension of about 2.4 pc. The observed region lies just behind the blast wave shock front and, according to previous ROSAT (Bocchino et al. 1999), optical and UV (Bocchino et al. 2000) studies, this region presents all the characteristic features of a recently shocked, highly inhomogeneous plasma.

Figure 1 shows two EPIC vignetting-corrected count rate images in two different en-

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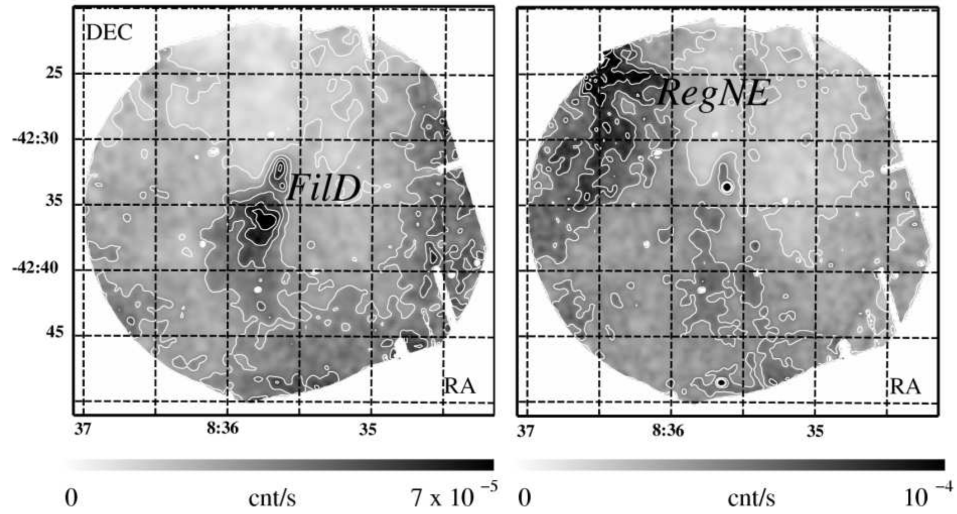

Fig. 1. EPIC count rate images (MOS1 count rate equivalent) centered on the region of FilD, in the $0.3 - 0.5$ keV band (left) and $0.5 - 1$ keV band (right); North is up and East to the left. The images are obtained as a weighted sum of the PN, MOS1 and MOS2 images, and are vignetting corrected and adaptively smoothed. Seven contour levels, equispaced between 0% and 100% of the peak value (7×10^{-5} and 10^{-4} cnt s^{-1} pix^{-1} respectively, pixel size: 4″) are shown.

ergy bands. There are striking differences in the morphology of the emission in these two bands. In the soft band ($0.3 - 0.5$ keV), a bright structure, named FilD, dominates at the center of the field of view. FilD looks composed by two bright parts and comparison with a high resolution optical observation, reported in Bocchino et al. (2000), shows that an optical filament lies between them. In the harder image ($0.5 - 1$ keV), FilD is barely visible, while there is a bright harder structure (RegNE) that was not visible in the ROSAT PSPC observation of the same region.

2. Spectral analysis

To study in detail the distribution of the physical parameters of the plasma in the field of view, we analized the spectra extracted from 16 subregions which cover the whole FilD, RegNE, the bright structure at South-West and the dark area at North. In each subregion the mean photon energy $\overline{E}$ is almost uniform (deviations ¡4%). All spectra were modelled with the MEKAL model of optically thin plasma in equilibrium of ionization (Mewe et al. 1985) with updates (Mewe et al. 1986, Liedahl et al. 1995). In all the subregions, spectra are well described by two MEKAL components. These two components can be associated with two different phases of the ISM clouds: a core (which corresponds to the cooler component) surrounded by a hotter and less dense corona. We also derived information about the inter-cloud medium (the tenuous and almost uniform ISM phase which surrounds the clouds); in fact, introducing a third MEKAL component, we did not find any improvement of the quality of the spectral fittings, but we obtained an upper limit for the inter-cloud density and an estimate of its temperature.

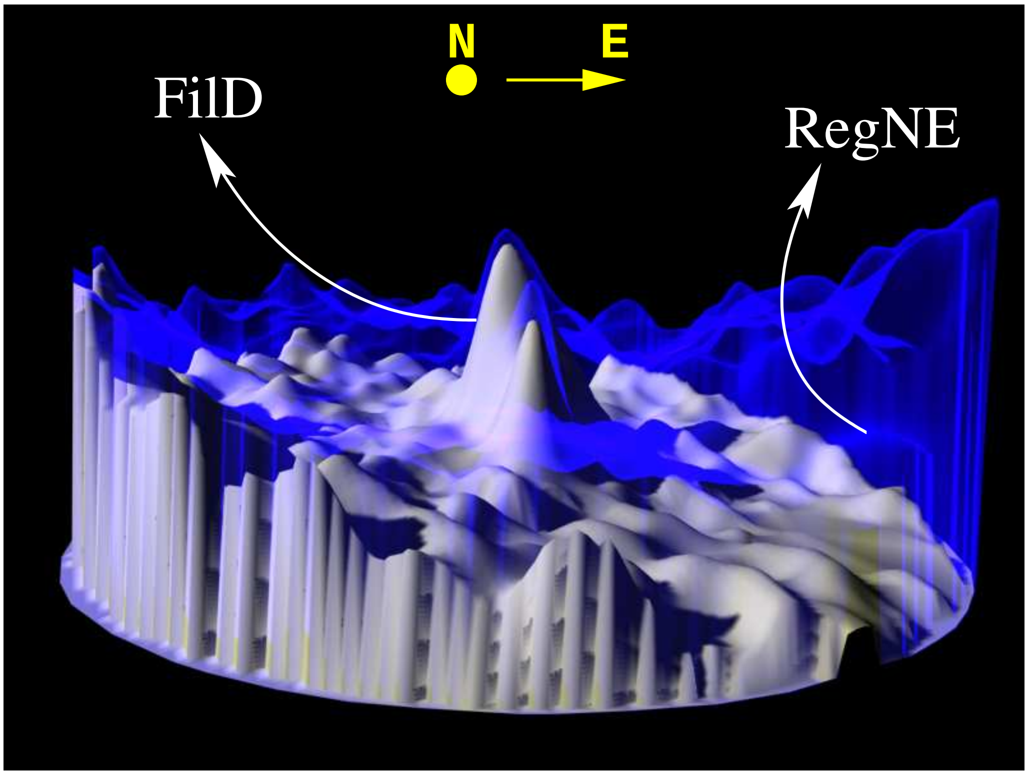

Fig. 2. 3-D map of the observed plasma: the height of the features in the map is proportional to the extension along the line of sight of the cores (white) and of the coronae (semi-transparent gray). North and East directions are also indicated. Notice that FilD is composed by a huge core surrounded by a thin corona, while RegNE is almost totally formed by a thick corona.

3. Results and discussion

The temperature of the cloud cores is uniform in the field of view and also all the observed coronae have almost the same temperature. Assuming that the temperature is uniquely determined by the local density, the similarity of the temperatures implies almost uniform densities within the cores and within the coronae. We found that the inhomogeneous X-ray emission is instead due to large variations of the emission measure of both components. This indicates different volume distributions along the line of sight and allowed us to draw for the first time a 3-D map of the observed plasma. In this map (Figure 2) we report the extension along the line of sight of the observed cores and coronae, resolving structures at all scales between ~ 0.1 pc and a few pc. Moreover we obtained the following estimates of the O, Ne and Fe abundances (mean values between all regions): $O/O_\odot = 1.0 \pm 0.1$; $Ne/Ne_\odot = 1.7 \pm 0.2$ and $Fe/Fe_\odot = 0.39 \pm 0.05$.

The only optical filament present in the field of view lies between the two FilD peaks visible in Figure 2 and probably represents the FilD inner and denser part. We therefore conclude that ISM inhomogeneities can be described as structures with an inwards increasing density profile (from the intercloud medium up to the optical filament) and an inwards decreasing temperature profile. Figure 3 is a sketch which summarizes all the ISM phases we identified on the basis of optical and X-rays data, we also report the values of temperature and particle density of each phase.

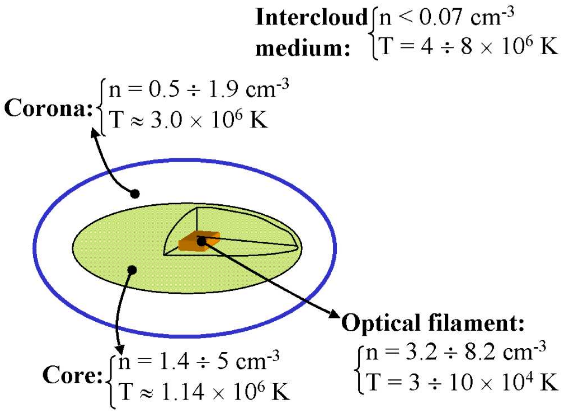

Fig. 3. Schematic representation of the structure of an ISM cloud. We report the mean values (between all regions) of the particle density *n* and of the temperature *T* of the plasma; the values of the optical filament temperature and density are taken from Bocchino et al. (2000).

Since we did not see any enhancement in the X-ray emission "behind" the optical filament, nor inhomogeneities in the plasma temperature and density, we argue that there is no evidence of reflected shocks, therefore the clouds must be heated by the transmitted shocks which travel through the inhomogeneities. As for the dynamics and evolution of the shocked clouds, the heated plasma is governed by the competition of two different physical processes: *radiative cooling* and *thermal conduction*. From the characteristic time scales τ_{rad} and τ_{cond} for both this processes we found that the cores are dominated by radiative cooling and collapse in a time scale of a few 10^4 yr. The evolution of coronae is instead dominated by thermal conduction from the hotter intercloud medium. This heating starts up evaporation effects. We estimated that the corona of FilD will be totally evaporated in about a century and RegNE in a few 10^3 yr.

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