Elemental Composition and Distribution in SNRs: X-Ray Spectroscopy

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Abstract

I present a comparative review focusing on three young Supernova Remnants, Cas A, Tycho and Kepler, in the light of recent X-ray observations obtained with the *XMM-Newton* and *Chandra* satellites. Recently available, X-ray spectro-imagery of young Supernova Remnants is providing unique information on the interaction region between the ejected material and the ambient medium, as well as on their associated shocks. These observations offer crucial constraints to characterise:

- the initial density profile of the supernova.
- the elemental composition in the ejecta and the spatial distribution of these synthesized elements.
- the synchrotron emission from TeV accelerated electrons, the efficiency of particle acceleration at their shocks and the downstream magnetic field.

Key words: Supernova remnants; X-ray spectra; Cosmic rays
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1 Introduction

In young supernova remnants (SNRs), the main physical process is the interaction of high velocity material from the supernova with the ambient medium (either circumstellar or interstellar). This interaction gives rise to two shocks: while the forward shock is propagating outwards into the ambient medium, the reverse shock is moving inwards into the ejecta. Both shocks heat and compress their respective media producing a hot interaction region composed of shocked ejecta and shocked ambient medium. These regions emit copious X-rays (continuum and lines from highly ionized elements) with different characteristics depending on their physical conditions (temperature, composition,...).

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With the new generation of X-ray satellites (*XMM-Newton* and *Chandra*), it became possible to spatially separate these two components and to investigate the structure of the interaction region. This is an essential step towards the understanding of supernova remnants: this region retains crucial information regarding the products of supernova nucleosynthesis, the initial density structure of the supernova, the level of elemental mixing within the ejecta,... In addition to heating the gas, high Mach number shocks are also able to accelerate particles at least to energies up to hundreds of TeV and X-ray synchrotron emission from these TeV accelerated electrons is produced close to the shock. If this acceleration is efficient, the shock structure is modified and impacts the morphology and heating of the interaction region (Decourchelle et al. 2000, Ellison et al. 2003), offering potentially a way to quantify the level of particle injection to the acceleration process.

2 X-ray morphology of the interaction region

The interaction structure depends on the initial density profile of the supernova. For type II supernovae, the density profile is expected to be a power-law, it has been shown for SN 1987A (Arnett 1988) that it takes only a few hours for such a profile to be established after the supernova explosion). The inner part of the density profile, corresponding to the core, stays relatively flat. For Type Ia supernovae, the density distribution is usually assumed to be exponential. The resulting interaction structure is radically different depending on the initial profiles (Chevalier 1982, Dwarkadas and Chevalier 1998): while in the power-law case the density is increasing from the contact discontinuity to the reverse shock (and conversely for the temperature), the opposite behavior is obtained for the exponential profile.

From the X-ray data, we can measure the electronic temperature at different radii and this should in principle allow us to distinguish between these two cases. The relative distance between the shocks and the contact discontinuity can be derived from the X-ray morphology. This information is relevant for constraining the nature of the ambient medium: the presence of a circumstellar medium leads for example to a narrow shocked ejecta region (Chevalier 1982). It also provides constraints on the efficiency of particle acceleration at the shocks: the interaction region shrinks by a large factor when the acceleration is efficient (Decourchelle et al. 2000) and Rayleigh-Taylor fingers can reach and perturb the forward shock unlike in the test-particle case (Blondin and Ellison 2001).

The main characteristics of the three supernova remnants (Cas A, Kepler and Tycho) are given in Table 1. In the core collapse supernova Cas A, the forward shock (FS) is clearly located well in front of the contact discontinuity

Table 1

Name	SN date	Type	Distance	Angular size	Forward Shock velocity
Cas A	1680?	SN II/Ib	3.4 kpc	5 arcmin	5200 km/s [a]
Kepler	1604	SN Ib ?	4.8 kpc	3 arcmin	5400 km/s [b]
Tycho	1572	SN Ia	3.2 kpc	8 arcmin	4600 km/s [c]

[a] Vink et al. 1998.
[b] using an expansion timescale of 418 yrs (Hughes 1999) and an angular shock radius of 100".
[c] Hughes 2000.

(CD), as can be seen from the continuum image of Gotthelf et al. (2001) with approximately a radius ratio of $R_{FS}/R_{CD} \simeq 4/3$. In the southeastern section, fingers of ejecta (mainly made of iron, Hughes et al. 2000a, Hwang et al. 2000) are getting closer to the forward shock. Such features are even more pronounced in 1E0102.2-7219, another relatively young ($\simeq$ 1000 yrs) oxygen-rich SNR located in the Small Magellanic Cloud, where Rayleigh-Taylor fingers are reaching and perturbing the forward shock in the southern rim of the remnant (see Gaetz et al. 2000). Such behavior is expected when particle acceleration is efficient at the forward shock. Note that a local spectral study of the forward shock led also to invoking efficient acceleration in 1E0102.2-7219 (Hughes et al. 2000b).

The picture is completely different in Tycho's SNR, a prototype of type Ia remnant. As can be seen in X-rays (Decourchelle et al. 2001, Hwang et al. 2002) and in radio (Reynoso et al. 1997), the forward shock and the contact discontinuity are extremely close to each other ($R_{FS}/R_{CD} \simeq 11/10$), as if particle acceleration was extremely efficient at the forward shock. This feature is also observed in Kepler's SNR ($R_{FS}/R_{CD} \simeq 11/10$, Cassam-Chenai et al. 2003) and both remnants exhibit Rayleigh-Taylor instabilities extending closely behind the forward shock. However, this common feature does not seem to be related to a common supernova type: although Kepler's SN has been proposed in the past to be a type Ia, it seems difficult to avoid a more massive progenitor in view of the presence of circumstellar material.

3 Spatially resolved X-ray spectroscopy of the ejecta

In addition to their ability to image at good spatial resolution, *XMM-Newton* and *Chandra* satellites are providing spatially resolved spectra, which is essential for investigating the structure of the interaction region in young supernova remnants. The X-ray spectra of Cas A, Tycho and Kepler SNRs are overall similar with numerous lines of ionised ions (O, Ne, Mg, Si, S, Ar, Ca and Fe). But, they differ in their respective relative line ratios and line intensities. In particular, the iron K/L line ratio is smaller in Cas A than in the others, and the iron line intensities are the strongest in Kepler. Willingale et al. (2002) have shown that the patterns of abundance ratios in Cas A were consistent with a core collapse of a 12 $M_\odot$ star (22 $M_\odot$ main sequence star).

There is a good overall correlation between the silicon K and iron L emission line images, except in particular knots in Kepler and Tycho, and in the southwest of Cas A where an inversion of the iron and silicon layers is observed (Hughes et al. 2000a). The line emission is clearly asymmetrical in the three remnants (Hwang et al. 2000, Willingale et al. 2002, Decourchelle et al. 2001, Cassam-Chenai et al. 2003), but as discussed below for different reasons in each case. In Cas A, the data show clear indication of asymmetry in the explosion of the supernova (jet, high velocity ejecta material, patchy elemental distribution). Both Tycho and Kepler share the property of a much brighter rim in the north than elsewhere in the rim. In Tycho, the regular and smooth X-ray continuum emission associated with the forward shock indicates that the remnant is evolving in an almost uniform ambient medium (except locally in the west, Reynoso et al. 1997). The line emission asymmetry in Tycho should then be related to the supernova explosion in terms of spatial variations of the elemental composition (or/and indirect temperature effects). Indeed, variations of the relative abundance of silicon and iron are clearly observed in the southwestern knots (Decourchelle et al. 2001). In Kepler, both the continuum and line emission are brighter in the north as shown in Figure 1. Maps of silicon and iron line equivalent width (Cassam-Chenai et al. 2003) confirm that this is the result of a denser ambient medium. The remnant is encountering higher density material in the north than in the south, most probably of circumstellar origin as suggested by the presence of optical knots, enriched in nitrogen.

Inspection of the spatial distribution of iron L and iron K lines indicates that the iron K line peaks distinctly at a lower radius than Fe L. This implies that the temperature is higher toward the interior both in Tycho and Kepler. This is inconsistent with the temperature profile expected for a pure power-law initial density distribution (see sect. 2). While exponential profiles do predict such behavior, they are unable to account for the large temperature gradient derived from the modeling of the spectra (Hwang et al. 1998, Kinugasa and Tsunemi 1999), unless a circumstellar medium is present (Dwarkadas and Chevalier 1998). A model with a plateau density for the core and a power-law density profile for the outer ejecta will produce a much higher temperature in the center than in the outer ejecta, provided that the reverse shock is already propagating in the plateau. This is a viable scenario for both remnants.

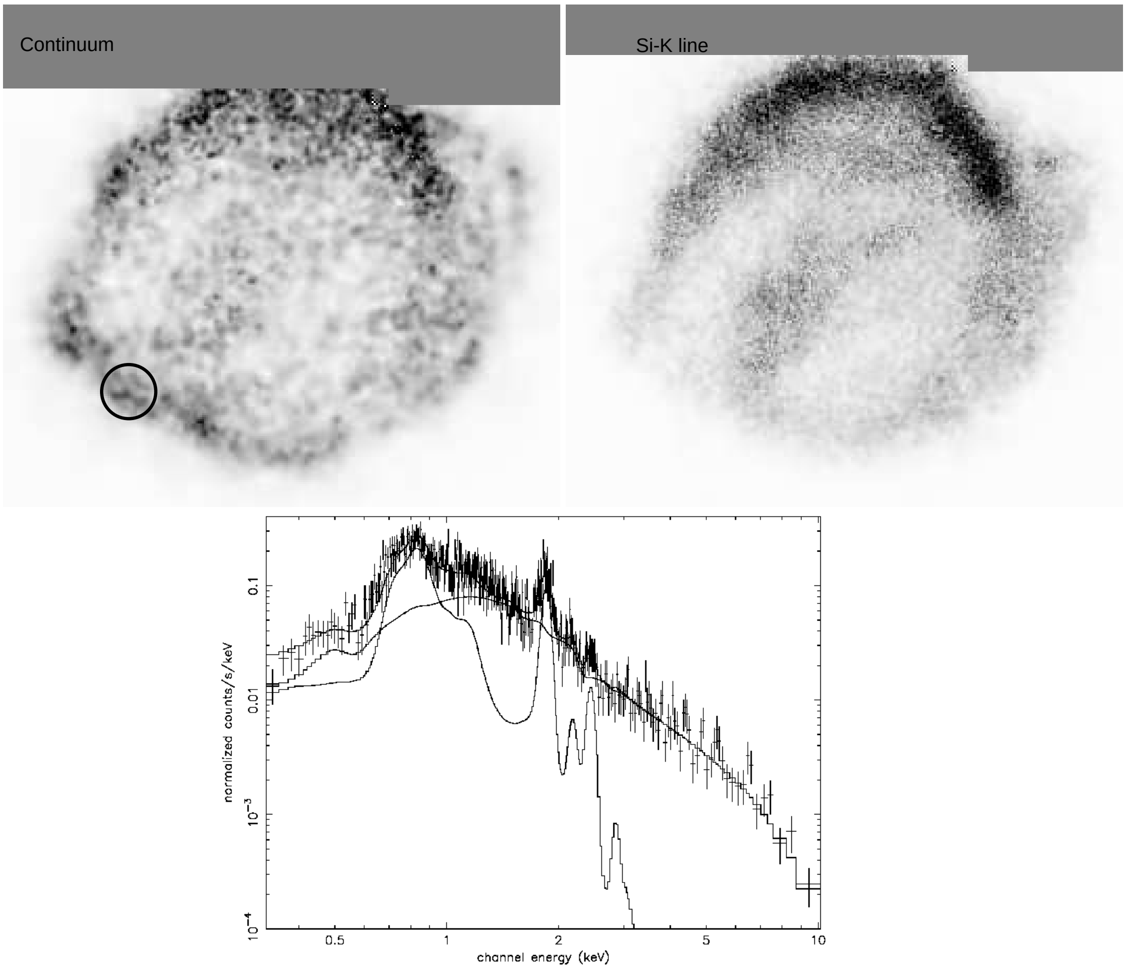

Fig. 1. **Top panel**: *XMM-Newton* image of Kepler's supernova remnant (left) in the continuum (4.1-5.8 keV) and (right) in the Si K line (1.75-1.94 keV) (Cassam-Chenai et al. 2003). **Bottom panel**: XMM-Newton EPIC/PN spectrum of the forward shock in the southern rim of the remnant (see solid circle in top panel).

4 Spectroscopy of the forward shock: particle acceleration

With *XMM-Newton* and *Chandra*, for the first time it became possible to extract the spectrum of the forward shock in a number of young supernova remnants. These measurements are extremely important to investigate the physics of the shocks like particle acceleration or temperature equilibration between electrons and ions. The best observational result was obtained for Tycho where a featureless spectrum was observed along the rim (Hwang et al. 2002). The spectrum is compatible either with a thermal plasma with a strong ionisation delay (which prevents any line to be emitted in the X-ray regime) or with a non-thermal population of accelerated electrons with energies up to 1-12 TeV. However, the narrow width of the X-ray filament observed at the shock is inconsistent with a thermal interpretation as it would imply an unexpected steep decrease of the downstrean density. Similar results were obtained in Cas A (Vink and Laming 2003) and Kepler (Cassam-Chenai et al. 2003). Both the X-ray spectrum and X-ray morphology of the forward shock in these three SNRs (shown for Kepler's SNR in Fig. 1) are compatible with a synchrotron interpretation. The narrow width of the filaments observed with *Chandra* (1.5-4") are explained by invoking a limited lifetime of the TeV electrons (responsible for the X-ray synchrotron) due to synchrotron losses as they are advected away from the shock front. This imposes a high value of the magnetic field (0.06-0.12 mG) in these three remnants, much larger than the standard interstellar magnetic field. As this is the case for the three remnants considered, it is difficult to attribute it to a particular circumstellar environment with higher magnetic field, but rather implies that the magnetic field must have been amplified at the shock (Lucek and Bell 2000).

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