Letter to the Editor

BeppoSAX LECS/MECS X-ray spectroscopy of the young supernova remnant N132D

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Abstract. We have analyzed an observation of the supernova remnant N132D in the Large Magellanic Cloud, performed with the Low Energy Concentrator Spectrometer (LECS) and the Medium Energy Concentrator Spectrometer (MECS) instruments on board the X-ray satellite BeppoSAX. Thanks to the good sensitivity of the LECS/MECS combination over the range 0.3–8.5 keV we were able to detect the presence of an additional hotter plasma with respect to what had been previously assumed for this remnant. This hotter component is the source of the Fe-K line emission visible in the spectrum. Using a two component NEI plasma model we find that the best fitting abundance values indicate that N132D is also O-rich from the X-ray point of view. We briefly discuss the origin of the hot component and tentatively associate it with a radio bright region.

Key words: ISM: abundances; ISM: individual objects: N132D: ISM: supernova remnants: X-rays: ISM

1. Introduction

N132D is a radio and X-ray bright, relatively young ($\simeq$ 3000 yr, Morse et al. 1996b) supernova remnant (SNR) located in the Large Magellanic Cloud (LMC). The optical spectrum of the ejecta shows evidence for a very high oxygen abundance, as well as for large expansion velocities. This indicates that N132D belongs, like the well known galactic remnant Cas A, to the class of O-rich remnants. Even at the distance of the LMC ($\simeq$ 50 kpc), the soft X-ray and UV flux at Earth of N132D is relatively large, and as a consequence the remnant has been observed by many low-energy X-ray instruments, both with dispersive (the

Einstein Focal Plane Crystal Spectrometer — FPCS) and non-dispersive spectrographs (e.g. the *Einstein* Solid State Spectrometer — SSS, the ROSAT PSPC and the ASCA SIS). A comprehensive analysis of all the X-ray spectra from the different *Einstein* instruments has been presented by Hwang et al. (1993) — hereafter H93 —, who have made full use of the relatively high spectral resolution of the SSS. They have shown that the spectrum, at the SSS resolution, is well modeled with a relatively cool single-temperature non-equilibrium ionization (NEI) model, and have determined best-fit abundance values and ionization time scales for the remnant.

While the χ^2 of the single-component H93 model is satisfactory, their result has one remarkable feature: the derived best-fit metal abundances for the plasma are lower than the mean abundances for the LMC. While detailed abundance studies for the local neighborhood of N132D have not been performed, such a low abundance is surprising, since the emission would be expected to come from a mixture of the supernova ejecta, heated by the reverse shock and of the shocked interstellar or circumstellar medium (ISM/CSM), similar to what has been observed for Cas A itself. The fast moving O-rich knots observed in the optical and UV (Blair et al. 1994) are obviously pure ejecta components, showing the products of recent nucleo-synthesis. It is thus unclear how a mixture of plasmas with high (the ejecta) and local (CSM/ISM) abundances can produce an X-ray spectrum with abundances lower than the local value (ISM).

Given the fact that N132D is one of the brightest X-ray sources in the LMC and that it has a small spatial extent (with an X-ray diameter of $\simeq$ 110 arcsec in the *Einstein* HRI images), it was chosen as a calibration target for the Science Verification Phase (SVP) of the BeppoSAX program (Boella et al. 1997a). In this paper we discuss the X-ray spectrum of N132D obtained with the Low Energy Concentrator Spectrometer (LECS; Parmar et al. 1997) and the Medium Energy Concentrator Spectrometers (MECS; Boella et al. 1997b) on board BeppoSAX. The good spectral resolution of the LECS (comparable to the

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resolution of CCD detectors at energies below 0.5 keV) and its good sensitivity down to 0.1 keV, in combination with the high sensitivity of the MECS above 2 keV the broad band X-ray spectrum of N132D to be studied, from the low-energy interstellar cut-off at $\simeq 0.3$ keV up to $\simeq 8$ keV.

The combined LECS/MECS spectrum of N132D clearly shows the presence of the Fe K complex at $\simeq 6.7$ keV, implying that some of the plasma has a temperature higher than found from the analysis of the *Einstein* data, making it necessary to fit the spectrum with two plasma components. As will be shown, this results in higher metal abundances for the best-fit model, which remove the apparent discrepancy with LMC ambient abundances.

2. Data reduction

The BeppoSAX SVP observation of N132D took place on November 22, 1996, and it resulted in 15 ks of effective exposure time in the LECS and 33 ks in the MECS (the difference being due to the LECS being operated during Earth night only). The LECS data were reduced through the LECS pipeline software (SAX-LEDAS 1.4.0), while the MECS data were reduced using the XAS V. 2.0.1 package. The reduction was performed separately for each unit. The source spectra were extracted from a circle centered on the source itself of radius 8 arcmin and 4 arcmin respectively for the LECS and the MECS. Publicly available detector response matrices (known as "December 31, 1996" issue) were used for the MECS, while the LECS response matrix was computed with the LEMAT package (V. 3.2.0). To subtract the background the standard LECS and MECS background files obtained by adding up a set of "empty sky" observations were used, extracted from the same circular regions as the source spectrum. The source spectrum was re-binned so to have at least 20 counts per re-binned channel. For the LECS, channels with energies between 0.3 and 5.0 keV were retained for the spectral analysis, while the range was 1.6–8 keV for the MECS. The resulting (background-subtracted) source count rate is 0.96 cts s^{-1} for the LECS and 0.42 cts s^{-1} for the MECS. Given the current uncertainties on the absolute calibration of the various detectors, the relative normalization of the MECS detectors with respect to the LECS has been left as an additional free parameter in the fit. The fit converges to a relative normalization of the MECS detectors $\simeq 25\%$ higher than the LECS, in line with the expected calibration uncertainties at this stage and with the results from other SVP targets.

3. Spectral analysis

The spectral analysis was performed using the SRON SPEX (V. 1.10) package, which contains state-of-the-art plasma emission models as well as NEI models which are well suited to the analysis of the X-ray emission from supernova remnants (Kaastra et al. 1995).

The LECS spectrum alone, given its low signal-to-noise at the higher energies, allows a reasonable fit to the data with an isothermal NEI model with a temperature around 1 keV and

metal abundances compatible with H93, although the harder part of the spectrum is not very well described by this fit and the LECS data alone already suggest the presence of a Fe K line. This is confirmed by the MECS spectrum, in which a line at $\simeq 6.7$ keV is evident, implying emission due to the Fe K complex (see Fig. 1), and indicating the presence of plasma at higher temperatures. Detailed comparison of the ROSAT HRI X-ray images of the remnant with narrow-band HST optical images (Morse et al. 1996a) show that no X-ray emission is coming from the expanding ejecta inside the shell (which are well visible in the HST images), and that the X-ray emission is rather associated with the swept-up circumstellar medium (which may however be mixed with some ejecta material). In this regard N132D is thus different from the Cas A remnant.

To fit the combined LECS/MECS spectra we have therefore used a two-temperature NEI model, in which the abundance of O, Ne, Mg, Si, S, Ar and Fe are allowed to individually vary. As we assume that both components originate in the swept-up CSM, the abundances for each element were coupled across the two components. The other free parameters were the interstellar column density and the emission measure, temperature and ionization parameter ($n_e t$) for each component. The last parameter indicates the ionization stage of a plasma of density n_e at time t after it was shocked to the plasma temperature. Note that in reality temperature and density may have varied since the first time the plasma was shocked. The abundances of He, C, N, Ca and Ni were set to the LMC values (Russell & Dopita 1992). None of the elements whose ratios have been constrained a priori have sufficiently strong or well resolved lines in the X-ray spectrum to allow their determination to be derived from the spectrum itself. At the same time, their abundance cannot be allowed to freely vary, as they would influence the rest of the abundances in non-physical ways. In particular Ca and Ni are in such a relatively soft spectrum more constrained by there L-shell lines below 1 keV than by their K-shell emission at higher energy (this is always true for Ni). There, they tend to fill up gaps in the model, arising from uncertainties in instrumental response and in the plasma emission code (e.g. in the Fe L-shell emission) or from statistical noise. For the interstellar absorption we used the Morrison & McCammon (1983) model.

The best-fit parameters for the two temperature NEI model are shown in Table 1. This model, which yields a reduced χ^2 of 1.1, is plotted, together with the source spectrum, in Fig. 1. Note that the best-fit parameters do not significantly depend on the assumed C and N abundances, which are fixed here to the LMC canonical values (0.52 and 0.37 times solar, respectively). Assuming values in the range 0.1–1.0 times the solar value does not significantly influence the fit. The best-fit abundances thus obtained are in line with the canonical LMC abundances derived from optical spectroscopy (with the exception of Si whose X-ray determined abundance is still slightly lower than the canonical LMC value), showing that the SNR is not metal-deficient with respect to the ambient medium.

The higher best-fit metal abundances with respect to the single-component NEI model are linked to the addition of the hotter plasma component. Among other effects, this induces a
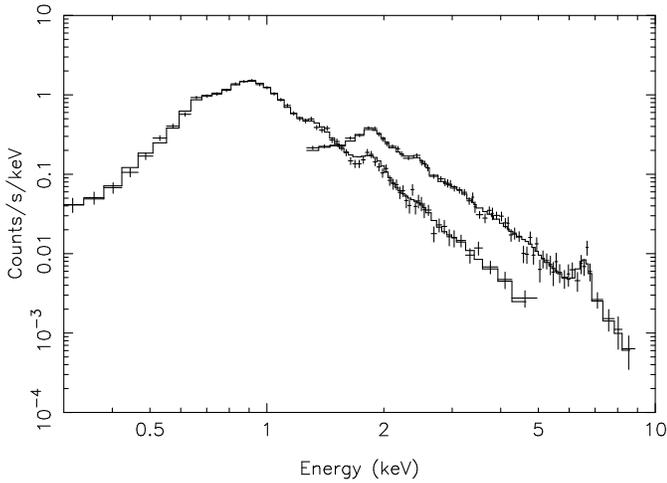
Fig. 1. The observed BeppoSAX LECS and MECS spectra of N132D, together with the best-fit two-component NEI model described in the text.

lower predicted line-to-continuum ratio around the O VIII line complex, because for the hot plasma component O is almost completely ionized. The same is more or less true for Ne and Mg. Another important difference with respect to the single-component model is that we find a best fit (though not very well constrained) interstellar column density $N_H = 3 \times 10^{21}$ cm^{-2}, whereas H93 obtained a best fit value $N_H = 0.6 \times 10^{21}$ cm^{-2}. A higher column density implies more emission below 1 keV, and since the continuum is, in such an absorbed X-ray spectrum, mainly determined by line-free regions above $\simeq 3$ keV, the extra soft emission needed to compensate the higher absorption has to come from line emission of mainly O VIII and Fe-L.

At a distance of the LMC of $\simeq 50$ kpc the diameter of N132D ($\simeq 110$ arcsec) corresponds to a radius of 13.5 pc, implying an emitting volume $V = f \cdot 2.9 \times 10^{59}$ cm^3, where f is the filling factor. A total emission measure at 50 kpc of 175×10^{58} cm^{-3} implies then a mass $M = f^{0.5} \cdot 760 \, M_\odot$. The canonical filling factor for a strong shock is 0.25, although the "clumping" of the soft X-ray emission seen in the ROSAT HRI images (Morse et al. 1996a) would indicate a smaller filling factor. On the other hand, Dickel & Milne (1995) claim, based on the shell thickness at radio wavelength, that a filling factor of 0.5 may be a more appropriate value, although the relevance of the radio-determined filling factor to the X-ray emission is not obvious. If we thus assume a possible range of 0.1 to 0.5 for the filling factor (with an extra 15% uncertainty for the size of the remnant) the derived total mass for the N132D X-ray emitting material is between 250 and 600 $M_\odot$, a large value which confirms that the X-ray emission is mostly associated with swept-up CSM/ISM and not with stellar ejecta. The pre-shock density inferred is close to 1 cm^{-3}. The $\simeq 450 \, M_\odot$ of shocked CSM/ISM contain, assuming that the matter has the canonical LMC abundances of Russell & Dopita (1992), about 6 $M_\odot$ of O; at the same time the high O abundance of the X-ray spectrum (significantly higher than the LMC ambient O abundance) implies a total O content for the X-ray emitting plasma a few $M_\odot$ higher, consistent

Table 1. The best-fit parameters for the two-temperature NEI model fit to the LECS/MECS X-ray spectrum of N132D. Also shown, for each parameter, the formal 90% range (i.e. $\Delta\chi = 2.71$). All the parameters are derived assuming a distance to the SNR of 50 kpc. All abundances are relative to the solar value. The mean values for the LMC abundances are from Russell & Dopita (1992).

Parameter	Best-fit	90% range	LMC
N_H (10^{21} cm^{-2})	3.0	0.9 – 6.5	
component 1			
kT (keV)	0.8	0.55–0.85	
$n_e \, n_H \, V$ (10^{58} cm^{-3})	158	107 – 240	
$n_e \, t$ (10^3 cm^{-3} yr)	2.3	0.5 – 4.8	
component 2			
kT (keV)	2.7	1.8 – 6.0	
$n_e \, n_H \, V$ (10^{58} cm^{-3})	17	10 – 32	
$n_e \, t$ (10^3 cm^{-3} yr)	5.3	1.9 – ∞	
[O/H]	1.2	0.8 – 5.0	0.32
[Ne/H]	1.1	0.5 – 3.5	0.42
[Mg/H]	0.85	0.8 – 1.8	0.74
[Si/H]	0.62	0.4 – 1.1	1.7
[S/H]	0.75	0.5 – 2.0	0.27
[Ar/H]	0.73	0.0 – 2.5	0.49
[Fe/H]	0.52	0.35 – 0.75	0.50

with the X-ray emitting material containing a small amount of mixed ejecta, and with N132D being an O-rich remnant, having its origin in a core collapse supernova.

The discovery of a hot plasma component in the X-ray spectrum of N132D raises the question of the origin of this temperature structure. The usual interpretation of a two-component NEI model, i.e. that the low-temperature component corresponds to the reverse shock going through the ejecta and that the hot component corresponds to the shock-heated swept-up circumstellar mass, does not apply here, as shown both by the HRI/HST comparison discussed above and by the high implied X-ray emitting mass, higher than any plausible stellar mass. Even associating the hot component only with pure ejecta would still result in too high a mass, given also the predominance of non-X-ray emitting ejecta in the remnant. It is thus not possible to separately derive a mass for the ejecta from the X-ray spectrum.

The high mass of this remnant suggests that it is in, or entering the Sedov phase of its evolution. Models for the temperature structure of a pure Sedov shock model show that there is a gradient in the temperature, i.e. a hot tenuous medium is present inside the swept-up shell. The Sedov model (as implemented in SPEX) produces an acceptable fit to the data, but with a lower best-fit interstellar column density and a lower O abundance than implied by the two-component NEI model. The derived size and age of the remnant and the density of the ISM (Kaastra & Jansen 1993) appear however to be an order of magnitude larger than the actual values, casting doubts on the actual applicability of a pure Sedov model.

A more promising explanation for the presence of the hot component (which has significantly lower emission measure

than the cool component) involves the inhomogeneity of the CSM/ISM. A shock propagating through an inhomogenuous medium will have different shock velocities in different regions. Where the density is higher the shock decelerates more rapidly, resulting in a cooler post-shock temperature, proportional to the square of the velocity. The temperature of the cool component corresponds to a shock velocity close to $600\,\mathrm{km\,s^{-1}}$, whereas the temperature of the hot component indicates velocities around $1100\,\mathrm{km\,s^{-1}}$. The latter value is still slower than the velocity of the presumably freely expanding O-rich knots (Morse et al. 1996a). The above velocities are computed assuming that ion and electron temperatures are in equilibrium; if this assumption is not valid, the actual velocities can be higher.

If the hot component is due to the inhomogeneity of the CSM/ISM, can this be localized? Given the relatively small size of the N132D remnant when compared with the spatial resolution of the LECS and MECS instruments, and the variation of the point spread function of the detectors with energy, an investigation of the presence of possible spectral variations with position requires a detailed analysis, which will be the subject of a future paper. We have however performed a preliminary analysis of the ROSAT PSPC data for N132D (the higher on-axis spatial resolution and smaller spectral band of the PSPC make such an analysis more straightforward), obtained from the public archive, extracting two separate images, one in the 0.5–1.0 keV band and the other in the 1.3–2.1 keV band, and calculating a hardness-ratio image. The hardness-ratio map shows the presence of a hard feature in the south-east region of the remnant, which could be the seat of the hot plasma seen in the LECS/MECS spectra. This X-ray hard region has approximately the same location as a radio-bright region in the 3.5 cm map of Dickel & Milne (1995), again suggestive of its possible association with the hotter plasma component.

4. Conclusions

The good spectral resolution of the LECS and MECS detectors over a broad spectral range (here 0.3–8.5 keV) allows a good determination of the temperature structure and the interstellar column density for the X-ray spectra of N132D, both of which are important for determining abundances. The most relevant result obtained from the analysis of the SVP X-ray BeppoSAX spectra of N132D is the detection of a plasma component at hotter temperature than previously reported for this remnant. The presence of the hotter plasma, which is evident in the spectrum through its well-resolved Fe K line emission, makes it necessary to use two NEI components to properly fit the data; given the association of both components with the swept-up CSM (with some ejecta mixed in) the abundances in the two components have been coupled together. The best-fit parameters for the two-component model imply abundances similar to (or in some cases higher than) the canonical LMC abundances, thus showing that the puzzling under-abundances reported by H93 on the basis of the *Einstein* SSS data are likely to be the result of the neglect of the hotter component. Our analysis confirms the high X-ray emitting mass of N132D, indicating a SNR in or entering the

Sedov phase of its evolution. In a future paper we will perform a detailed comparative spatial analysis of the LECS, MECS and ROSAT PCPS data.

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