Three Supernova remnants observed by BeppoSAX

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We present the results of three observations of shell-type supernova remnants observed by BeppoSAX. Two of the remnants (N132D and Cas A) are oxygen rich supernova remnants. They were observed during the PV phase. SN1006 was observed during A01. For SN1006 we present preliminary results on the abundance measurements based on the emission from the center of the remnant.

1. Introduction

Supernova remnants (SNRs) are of astrophysical interest for a number of reasons. Especially young remnants can reveal important information about the last stages of stellar evolution; both about the nucleosynthesis as about the the impact that stellar winds have on the circumstellar medium. In case of remnants of type Ia supernovae they might help to clarify their origin: are they the result of the carbon deflagration or detonation of a white dwarf? From a more physical point of view SNRs are important cosmic laboratories; displaying phenomena as collisionless shocks, shock acceleration of particles (the formation of cosmic rays) and the physics associated with tenuous hot plasmas.

For our understanding of SNRs X-ray emission plays an important role; the bulk of the shock heated plasma can only be seen in X-rays. In that respect the narrow field instruments of BeppoSAX [1] (i.e. LECS, MECS, HP, PDS) can play an important role. As we shall show, especially the broad energy range and the good sensitivity around 6 keV have already resulted in important findings.

In this paper we will give a review of the analysis of BeppoSAX data of two oxygen rich supernova remnants (N132D and Cas A) and some preliminary results for SN1006.

2. N132D in the LMC

Oxygen rich remnants constitute a small but important subclass of SNRs. The amount of oxygen present (often detected first with optical spectroscopy) makes it very likely that these SNRs are the result of the core collapse of a massive early type star (an O star or a Wolf-Rayet star). Important examples of this subclass are Cas A, Puppis and N132D. The latter is the brightest remnant in the Large Magellanic Cloud (LMC). In fact it is intrinsically brighter than Cas A. N132D has a size of 1.8′, so it can not be resolved with the LECS or MECS. From kinematic and spectroscopic studies of the remnant we know that its age is about ∼ 2500 yrs [2].

2.1. Abundances

Although optical studies indicate that N132D is an oxygen rich remnant, a detailed analysis of data from various instruments of the Einstein mission [3] indicated underabundances for all major elements with respect to LMC abundances. However, an analysis of PV phase data of BeppoSAX of N132D [4] resulted in abundance estimates which were in accordance with respect to

Table 1

| Element | N132D | LMC |
|---------|-------|-----|
| O       | 1.2   | 0.32|
| Ne      | 1.1   | 0.42|
| Mg      | 0.85  | 0.74|
| Si      | 0.62  | 1.7 |
| S       | 0.75  | 0.27|
| Ar      | 0.73  | 0.49|
| Fe      | 0.52  | 0.50|
LMC abundances and even indicated overabundance of O, Ne and Mg as can be expected for an oxygen rich remnant (see Table 1).

Another result was that the LECS and MECS indicated the presence of Fe K emission (around 6.6 keV). As a consequence there must be plasma present with a substantially hotter electron temperature than the 0.7 keV found for N132D. Indeed a spectral fit to the BeppoSAX data using the SPEX spectral code [6] gave \( kT_e = 0.8 \text{ keV} \) and 2.7 keV. The emission measure for the hot plasma is almost a factor ten lower than the cooler plasma, but the hot plasma gives nevertheless a measurable effect. A significant difference with the Einstein result was that the LECS indicated an absorption towards N132D of \( N_H = 3 \times 10^{21} \text{ cm}^{-2} \), whereas in [3] a value of \( N_H = 6 \times 10^{20} \text{ cm}^{-2} \) was listed. It may well be this difference which led to the lower abundances found for the Einstein data.

2.2. A hardness map

Now that we had found that part of the emission comes from a hot plasma, we were naturally interested where the hot plasma might be located. As mentioned before, the MECS does not allow to resolve N132D. We therefore used archival ROSAT PSPC data to see if there is any spectral variation over the remnant. Note however that the PSPC band is still rather soft (up to 2.1 keV), so that the spectral variations may not be the same as the one that gives rise to the hot plasma found in the BeppoSAX spectrum. Nevertheless, Fig. 1 clearly shows that there is spectral variation over the remnant, which may be caused by the interaction of the blast wave with an inhomogeneous interstellar medium.

3. The historical remnant of SN1006

3.1. Two different kinds of spectra

For a long time the apparent lack of line features in the X-ray spectrum of SN1006 was quite puzzling. There is always the possibility that
the spectrum was dominated by synchrotron radiation, but SN1006 does not contain a pulsar like the Crab SNR. The discovery by ASCA and ROSAT that the spectrum from the center was thermal (i.e. dominated by line emission and bremsstrahlung), but that the bright rims had a non-thermal spectrum, was a step forward. It was proposed that the emission from the rims was synchrotron radiation, caused by shock-accelerated electrons with energies in excess of TeVs. However, one should be careful with immediately adapting this point of view, the arguments are valid, but not conclusive. On the other hand, if one assumes, as was done in the past, that some kind of process suppresses the line emission, one might rightly ask why such a model does not apply to the emission from the center. In it was reported that a deprojection of the ROSAT PSPC image indicates that the bright rim are not just the result of limb-brightening, but instead that they are concentrated in caps. Such a geometry is not easily explained by simple models for synchrotron emission. See also the discussion below about the hard X-ray emission of Cas A.

Another problem associated with SN1006 is that, although it is thought to be the remnant of a type Ia supernova, there is no sign of the presence of $0.5M_\odot$ of iron as expected for a type Ia supernova.

### Table 2

Element mass abundance with respect to oxygen. A comparison between the solar values, a white dwarf deflagration model and our best fit model for the center of SN1006.

| Element | Solar | Nomoto | SN1006 |
|---------|-------|--------|--------|
| C       | 0.32  | 0.38   | 0.8    |
| N       | 0.12  | -      | 0.04   |
| O       | 1     | 1      | 1      |
| Ne      | 0.18  | 0.03   | 0.12   |
| Mg      | 0.067 | 0.06   | 0.14   |
| Si      | 0.073 | 1.067  | 1.27   |
| S       | 0.038 | 0.60   | 0.85   |
| Fe      | 0.19  | 5.2    | 1.3    |

### 3.2. Abundances measurements of the central region

SN1006 was observed by BeppoSAX in April 1997. The remnant was covered by three pointings, one at the relatively bright Southeast and two pointings at the rims. As Fig. 2 shows the thermal spectrum of the center can be clearly distinguished from the power law spectrum of the rims. Preliminary results from an analysis of the spectrum from the center are presented in table 2. The analysis was made with the spectral fitting program SPEX and is based on a two compo-
nant non-equilibrium ionization model. The ionization parameter found, \( \log(n_e t) = 9.6 \), was in accordance with the age and density (\( \sim 0.1 \text{ cm}^{-3} \)) of the remnant. In the table we compare our spectral fit with the predicted abundances for a carbon deflagration model and we see that the amount of iron may not be as high as predicted, but is certainly not far off. Note that our future analysis should include a proper handling of the spatial behaviour of the LECS and the MECS, such as the contamination of the spectrum of the center by scattered emission from the rims.

An interesting result was that the spectrum of the center shows evidence for Iron K-shell emission at a 2\( \sigma \) level with a measured equivalent width of \( (0.6 \pm 0.3) \text{ keV} \) (Fig. 3).

4. Cassiopeia A

4.1. An oxygen rich remnant with little Ne and Mg

Cassiopeia A (Cas A) is as far as we know the youngest (about 310 yrs) remnant in our galaxy. Given its distance of 3.4 kpc it should have been an historical remnant, but no record exist of a bright supernova in the second half of the 17th century, although it may have been observed as a 6th magnitude star by Flamsteed in 1680 \[1\]. Cas A is the best studied example of an oxygen rich remnant and it has by now become clear that the progenitor was probably a Wolf-Rayet star (WN7 \[2\]) with very few hydrogen left in its envelope. As a consequence, part of the hot plasma may be hydrogen poor which leads to a lower mass estimate for the ejecta, namely around \( 4M_\odot \) \[3\]. The reason is that the most abundant element in the ejecta, oxygen, is a more efficient bremsstrahlung emitter than Hydrogen. The mass estimate is based on the assumption that the ejecta, shocked by the reverse shock, are associated with the low temperature component (\( \sim 0.7 \text{ keV} \)), whereas the shocked circumstellar medium has a temperature of \( \sim 4 \text{ keV} \).

Although well studied there are some unanswered questions with respect to Cas A. One is about the nature of the stellar remnant that the core-collapse must have left behind. Despite several attempts at various wavelength no stellar remnant has been discovered. So can we conclude that Cas A contains a black hole? Possibly, but this seems at odds with the recent discovery of emission from radio-active \( ^{44}\text{Ti} \) by the CGRO/Comptel experiment \[4,13\], as we will explain below. A puzzling fact is also the rather small amount of neon and magnesium \[3\], which...
is not expected for an oxygen rich remnant. The lack of Ne and Mg was confirmed by the BeppoSAX data [16].

4.2. The hard tail

Cas A was observed by the BeppoSAX narrow field instruments during the PV phase. The most remarkable finding was the existence of a hard tail to the spectrum up to 60 keV [16]. This was not quite unexpected, since it was already detected by HEAO-2 [17] and confirmed by the CGRO/OSSE experiment [18]. The hard tail was also detected by RossiXTE [19,23]. These studies indicate that the hard-tail is best fitted with a power law spectrum with a photon index close to 3.

So there is agreement that such a hard tail exist; however, there is no agreement yet on the nature of the emission. There are several possible emission mechanism, the most likely ones being (non-thermal) bremsstrahlung and synchrotron emission. The synchrotron emission was already discussed in connection to SN1006. In the case of Cas A, with its magnetic field in the order of 1 mG, it would indicate the presence of shock accelerated electrons with energies up to 40 TeV [19]. On the other hand, a bremsstrahlung model needs only energies of several tens to hundreds of keV. Such electron energies may be the signature of electrons that have just been accelerated by shocks or they may arise from electrons interacting with plasma waves. Note that we can be sure that Cas A should emit bremsstrahlung in the PDS band, simply because we know from the synchrotron emission observed at radiowave-length that there exists a population of electrons with energies in the MeV to GeV range. Since electrons are continuously accelerated from thermal energies there must also exist a population of electrons emitting bremsstrahlung at intermediate energies. The reason that some discard this explanation for the hard tail is that a simple calculation of this so-called electron injection spectrum predicts a photon-index of 2.26 [20]. However, things are not so easy; the injection of electrons in a shock are poorly understood and the actual energy spectrum may vary well be consistent with the observed photon index [21]. Finally, a preliminary analysis of the MECS data indicates that the iron K-shell emission has a different distribution than the high energy continuum [22]. This may favour the synchrotron model, but it may also indicate that the iron emission does not completely trace the hot plasma, simply because the iron is not present everywhere with equal abundances.

4.3. Abundances

The nature of the hard tail is important for the modeling of the overall X-ray spectrum of Cas A. If the hard tail is mainly the result of bremsstrahlung, we can trust the abundances derived from the line intensities below 10 keV. However, if the mechanism is synchrotron we are dealing with a very different continuum, also at lower energies. The line to bremsstrahlung continuum ratio is then much higher than in the former case, resulting in higher abundance estimates and lower inferred densities and plasma mass. A comparison between abundances listed in [16] reveals that treating the continuum to be partly synchrotron radiation gives abundances a factor 3 higher and a mass estimate which is 40% lower (∼2 M⊙ instead of ∼4 M⊙ of shocked ejecta).

4.4. Titanium 44

During the core collapse of a star heavy elements are formed, some of them are radio-active such as 56Ni (6.1 days half-life). Another important radio-active isotope is 44Ti, which has a half-life time of about 50 yrs and decays in 44Sc (6hrs half-life), which decays into 44Ca. The decay of 44Sc was detected by CGRO/Comptel at 1.157 MeV [14,15]. During its decay to 44Sc 44Ti emits two photons at 67.9 keV and 78.4 keV. The flux in these lines should correspond to the flux at 1.157 MeV of (3.4±0.9)×10⁻⁵cm⁻²s⁻¹ reported for Comptel [15]. Attempts to measure these lines with RossiXTE [23] and CGRO/OSSE [18] are not yet successful, although the results are not inconsistent with the Comptel results.

The importance of 44Ti is that it is directly linked with processes during the core-collapse. A substantial amount of the 44Ti is therefore inconsistent with the presence of a massive black-hole in Cas A. For the same reason the lack of iron 56 (a product of nickel 56) is an indicator for the
presence of a black hole, so this seems at odds with the presence $^{44}$Ti. However, a solid detection of $^{44}$Ti may provide an opportunity to fine-tune the current models and give us new insights in the details of the explosion or even allow to obtain a mass estimate for the black-hole that may be present in Cas A [24].

We also made an attempt to measure the line flux with the PDS, but up to now we can only come with an upper limit of $5 \times 10^{-5} \text{cm}^{-2} \text{s}^{-1}$ (99% confidence) for 35ksec of data. In the near future when more data will be available we hope to come with a more substantial result.

5. Concluding remarks

We have shown the potential of the BeppoSAX narrow field instruments. The broad energy range allows for the detection of hard energy tails (such as in Cas A) and a better determination of the absorption at low energies (as in SN1006). Both are essential for a better understanding of the X-ray spectra of SNRs. Furthermore the MECS sensitivity around 6.5 keV resulted in the detection of Fe K complexes not yet seen with other missions (SN1006 and N132D). The Fe K complex is an important diagnostic tool for determining hot plasma parameters such as temperature and ionization stage. Note that the sensitivity is as much due to a reasonable effective area as to a low background; the latter being the result of a telescope mirror of good quality.

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