X-RAY EMISSION FROM SUPERNOVA REMNANTS

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ABSTRACT. A brief review of the observations of X-ray emission from supernova remnants is presented including the results from the Einstein, EXOSAT and TENMA satellites. The status of the interpretation of the spectra and images is highlighted and the need for broad band, spectrally resolved imaging measurements is emphasized.

INTRODUCTION

X-ray emission from supernova remnants is a research field almost as old as X-ray astronomy itself. It effectively started in 1964 with the detection of X-rays from the Crab Nebula with an experiment on a sounding rocket. Since then many rocket experiments have been carried out but a real break-through came along with the advent of imaging telescopes, the first one being the Einstein observatory and later-on the EXOSAT observatory. These instruments have provided us with plenty of information, including arcsec resolution images, energy spectra of medium and high resolution, and broad band energy coverage. Nevertheless, even better instruments are required to take us one step further towards our aim of a deeper understanding of supernova remnants, including the aspects related to: the nature of the progenitor, the physics of the explosion and subsequent expansion and the interaction with the multi-component interstellar medium.

Today, we know of 33 galactic X-ray remnants, 25 sources in the LMC, 10 in the SMC, 2 sources in M31 and 1 source in M33 are very likely candidates for supernova remnants; and finally there is one in NGC4449.

CLASSIFICATION

Supernova remnants are left-overs from a stellar explosion and one can in principle have or have not two possible relicts of this catastrophic event: an extended remnant and a stellar object:

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1) There is neither an extended object nor a stellar one, at least not visible. It is noted that this possibility should be considered for statistical counting e. g. of supernova rates. The number of these apparently missing objects is connected with the explosion energy as well as with the ambient interstellar density, both required to be sufficiently low for the event to escape X-ray detection.
2) There is no extended remnant but a stellar one. These are the cases of isolated neutron stars and radio pulsars.
3) There is no stellar object left but an extended remnant. These are the so-called classical supernova remnants with a shell-like radio and X-ray brightness appearance. They make up the overwhelming majority of all galactic supernova-remnants. Einstein images as well as the EXOSAT images of Cas-A, Tycho, Kepler and SN1006, for example, demonstrate their roughly circular appearance, the limb brightening, the more or less pronounced clumpyness and the brightness asymmetry. These are young remnants. Old remnants are dominated in their X-ray appearence by the matter distribution in the interstellar medium, across which the shock wave of the explosion has passed. Puppis-A is a very good example.
4) Finally, there may be an extended remnant as well as a stellar component. This group can be subdivided according to the nature of the compact source. Each of these sources shows an extended remnant, which has been identified as a synchrotron nebula for most cases, but clearly with one exception: the RCW103 shell type remnant has a thermal spectrum. Three sources contain an X-ray pulsar (Crab, MSH15-52, 0540-693). MSH15-52 may be embedded in a larger shell-like remnant (RCW 89), the association of which is, however, uncertain. The Vela remnant includes a large thermal and an arcminute synchrotron nebula centred on the radio pulsar, which does not exhibit X-ray pulsations. RCW 103 is a shell-like remnant within which a non-pulsating neutron star emits thermal surface radiation. Although no stellar-like object has been detected so far, 3C58, CTB180 and G27.4+0 have been included in this category because of their centrally peaked brightness distribution. The presence of the X-ray pulsar in MSH15-52 and 0540-693 and the non-thermal X-ray spectrum of the surrounding nebula clearly identifies these sources as Crab-like supernova remnants, in which the central pulsar continuously powers the nebula emission. For Vela this classification is not that straightforward despite the presence of the synchrotron nebula and the radio pulsar. In fact, the details of the energy production are less understood than for the classical Crab-like remnants.

THERMAL SUPERNOVA REMNANTS

It is well established through the observation of emission lines that the X-ray spectrum of shell-type remnants has a thermal origin. The outwards propagating blast wave heats the interstellar medium to X-ray temperatures which in the early life of a remnant is as high as a few keV. In a later stage an inwards propagating, or reverse shock will heat the stellar ejecta again to X-ray temperatures, but presumably to lower values than the blast wave heating the interstellar medium. In principle one would expect a two temperature spectrum if the remnant is not spatially resolved. Responsible for the X-ray emission are the electrons and a long standing question is how the electrons are being heated. The most simple process is via Coulomb collisions between the hot ion gas and the electrons, but time scale arguments demonstrate that this process is by far too slow to produce X-ray temperatures in at least the young remnants. Plasma instabilities and plasma turbulence have both been proposed as a way out but no details have been worked out so far. To my knowledge the heating problem is still standing. Because of lack of better knowledge almost all measured spectra have been interpreted assuming thermal equilibrium between the ions and electrons.

Earlier models have started even from an additional assumption which is related to the ionization states of the heavy elements. They assumed that the plasma is in collisional ionization equilibrium (CIE). The results obtained with the Einstein FPCS however demonstrate that even in a remnant as old as Puppis-A ionization equilibrium has not yet been reached (Winkler et al., 1983). The degree of ionization changes with the plasma density and with the time which has elapsed since the plasma has been shock heated. Since the line intensity depends on both the ionization state and the element abundance it is necessary to know the ionization state rather precisely to determine element abundances to the same level of accuracy. In recent years non-ionization equilibrium models (NIE) have been worked out and both CIE and NIE models are now applied to the measurements. To illustrate the impact of the model on abundance determinations the results for Cas-A and Tycho are discussed in the following.

EXOSAT has taken the broad band spectrum of Cas-A from 0.1 - 10 keV (Jansen et al., 1985). Above the continuum line emission is clearly present from the He-like ions of S, Ar and Ca as well as Fe-K_α and Fe-K_β emission. Similar results have been obtained with the experiment onboard of TENMA (Tsunemi et al., 1985), and earlier with the Einstein SSS, which, however, was restricted to energies below $\lesssim$ 4 keV. There is acceptable agreement for the line energies and equivalent widths thus that the results are completely consistent within the errors quoted. Taking the Einstein data, there seems to be no major difference in the abundance values derived from CIE and NIE models, and furthermore the EXOSAT results agree quite well with those. Except the Fe-abundance, there is a general overabundance of heavy elements compared with solar values. In contrast the TENMA results provide values which are very close to solar values, and disagree with the other two experiments. For Tycho, analogue measurements have been made: again the line energies are completely consistent, but the abunances are not. There is agreement for S and Ca, which are overabundant by a factor of 10 and 15, respectively. But the TENMA results indicate an Fe abundance of 6 times solar, whereas the EXOSAT results are consistent with a solar value (Davelaar et al., 1985). It remains to be seen, how this discrepancy will be solved, possibly only by future experiments and a comparison of the underlying emission models.

The observations presented so far are not spatially resolved but they have been analysed assuming a single spectrum for the total emission integrated over the whole remnant. It is, however, very likely that density and temperature variations across a remnant do exist which would require spatially resolved spectroscopy to derive proper abundances. A few spatially resolved energy spectra have meanwhile become available. Various fields within Puppis-A have been observed with the FPCS and the SSS, and in particular the latter show quite a change in the energy spectrum, above all, the spectrum is hardest at the rim positions, which one is inclined to interpret as the hotter blast wave region. A complete temperature map of Puppis-A with a resolution of 1 arcmin has become available with EXOSAT using low energy filter spectroscopy (Aschenbach, 1985). There is quite a variation in temperature of an order of magnitude. Future experiments with simultaneous spatial and spectral resolution as well as broad band coverage to include the Fe-K line complex are mandatory. A more detailed review on galactic thermal supernova remnants can be found in the paper by Aschenbach, 1985.

THE CRAB NEBULA

It is in some sense obvious that the morphology of extended supernova remnants bears clues to the origin of the energy production and transport mechanism, but only a few ideas have emerged so far for thermal remnants. For the Crab-like remnants the situation is apparently simple, as the rotating neutron star is known as the energy source. But a fully consistent picture of the physics is also still lacking. The first high resolution X-ray image of the Crab Nebula was taken with the Einstein HRI resolving the nebula and the central pulsar. This image has recently been re-analysed to eliminate the effects of the point spread function of the telescope (Brinkmann et al., 1985). The result shows that the emission is confined to a toroidal volume which is tilted in the plane of the sky, giving the image an elliptical appearance with an almost vanishing flux in the middle. Furthermore, there seems to be a jet extending to the southeast. Now, this image can be explained in the following way, as proposed by Aschenbach and Brinkmann in 1975: the electrons leaving the pulsar are accelerated by the Gunn-Ostriker mechanism. They are phase locked to the 30 Hz electro-magnetic wave of the Crab pulsar and therefore do not radiate. This explains the central emission hole. Furthermore the electrons are not accelerated spherically symmetric but they are confined to the rotational equator of the spinning neutron star. The electrons get out of phase where the nebula pressure overcomes the ram pressure of the outflowing 30 Hz wave and the particle pressure. From there on they start to radiate synchrotron radiation, filling the equatorial region which appears as a torus of emission. By tilting the equatorial plane in the plane of the sky the ratio of the major and minor axis of the inner radiation free region is given. This elliptical hole agrees with the hole observed in the optical image which was already noted by Scargle in 1969. The direction of the neutron star's spin axis is also completely determined by the same tilt angles, and as a matter of fact it points exactly along the jet seen in the deconvolved image, which underlines that this jet emission originates in the pulsars spin axis.

FUTURE MISSIONS

The next X-ray astronomy mission will be ROSAT. It will be launched end of 1987 and its prime objective is to perform the first all-sky survey with an imaging X-ray telescope followed by a pointing programme lasting at least one year. It is in this pointing period where deep and high resolution exposures of supernova remnants will be made. Energy spectra with $E/\Delta E > 2$ will be measured in each spatial resolution element. There is another focal plane instrument on ROSAT which has a resolution capability of 5 arcsec which is 2 times better than the resolution achieved on the Einstein observatory. This will give us the highest resolution X-ray images for at least a period of 8 years. In addition this instrument is 9 times more sensitive than the Einstein instrument, so that we will shift the observation horizon farther out by a factor of 3 with improved resolution. So far I have referred to thermal sources. However, given its sensitivity, spectral and spatial resolution, ROSAT will also help to establish the non-thermal origin of the spectrum of Crab-like supernova remnants.

A feature of particular diagnostic value is the iron K line complex at ~ 6.7 keV which has been detected so far only with non-imaging instruments. Spatially resolved images up to ~ 10 keV will become available from the NASA AXAF and the ESA XMM, but which, I am afraid, will not be in operation before the mid nineties.

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