NON- EQUILIBRIUM IONISATION IN SUPERNOVA REMNANTS
- A case like Tycho -

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Abstract: X-ray observations of young supernova remnants (SNR) provide the most direct tool to study their evolution, their chemical composition, and their interaction with the interstellar medium. We will show for a SNR with the characteristics of Tycho that great care has to be taken in interpreting spectral data obtained with X-ray detectors with low spatial resolution.

I. Introduction

Observations of historical SNR of known age, especially those of type I explosions with well defined circular appearance should allow direct conclusions about the explosion itself and the structure of both the star and the surrounding interstellar medium. Although much progress has been made in recent years, particularly by observations with the Einstein, EXOSAT and Tenma satellites, there are still rather large discrepancies in the interpretation of the data. This is due to insufficient theoretical modelling of the SNR as well as to deficiencies in current observational techniques. The purpose of this paper is to demonstrate that high spectrally and spatially resolved observations are necessary to get reliable information about the remnant's properties.

As an example we use parameters for a SNR with the characteristic properties of Tycho, well studied by Gorenstein et al. (1983), Hamilton et al. (1986), and Tsumeni et al. (1986). We follow the hydrodynamic evolution of the remnant using a 1-D Lagrangean hydrocode with a mixed artificial viscosity given by Wilkins (1980). The initial profile is that of an exploding white dwarf, analytically approximated by Chevalier (1982), expanding into a uniform ambient medium. The physical parameters were taken similar to those of the above papers on Tycho, i.e., $E_o = 7\ 10^{50}$ ergs, $n_o = 0.5\ cm^{-3}$ and a mass of the ejecta of $M = 1.4 M_\odot$.

For both the ejecta and the interstellar medium we use solar abundances for the 13 elements H, He, C, N, O, Ne, Mg, Si, S, Ar, Ca, Fe, and Ni and assume temperature equilibrium between electrons and ions throughout the calculation. For SNR of type I explosions, i.e. Carbon deflagration of white dwarfs, ejecta material composed of mainly heavier elements is expected (Nomoto et al., 1984). A proper modelling of the Tycho SNR would require the use of ejecta material with greatly non solar abundances, which is currently under way. However, in this case a different hydrodynamical structure of the remnant is expected as the electron pressure becomes strongly dependent on the ionisation structure.

The ionisation structure was calculated with an implicit method at every time step for every zone in the hydrocode (for details see Brinkmann and Fink, 1987) using the rate coefficients given by Arnaud and Rothenflug (1985). The hydrocode was run until the age of Tycho (~410 years) was reached.

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II. Equilibrium Ionisation

In a first step we assumed that the matter was everywhere in ionisation equilibrium at the corresponding temperature. The photon spectrum integrated over the whole remnant is shown in Figure 1a for the energy range from 1 to 10 keV.

A best fit to this spectrum (excluding the line regions) with a thermal bremsstrahlungs law would result in a temperature of kT ≃ 14 keV. Fitting a thermal ionisation equilibrium spectrum to the data would result in a temperature of kT ≃ 9 keV. In both cases there is some excess at higher energies, which would be naturally interpreted as an additional hard component.

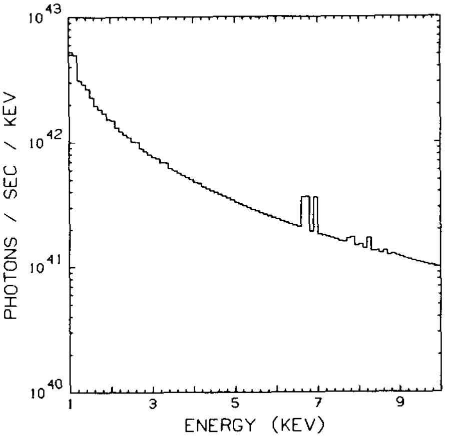

Fig.1a: Integrated equilibrium spectrum

Assume now that we have an X-ray detector with high spatial resolution and sufficient spectral resolution. Then line-of-sight spectra as given in Fig. 1b, c taken at the remnant's centre and near the rim, on the shock, could be obtained.

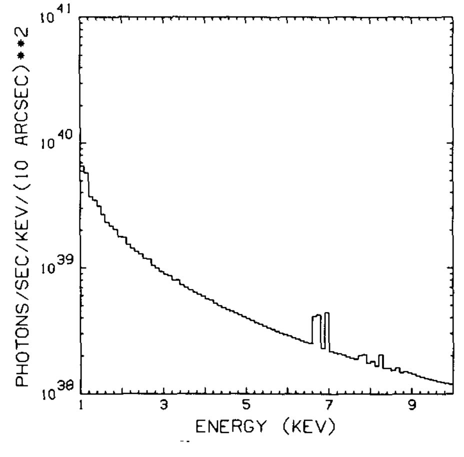

Fig.1b: Line-of-sight equilibrium spectrum near remnant's centre

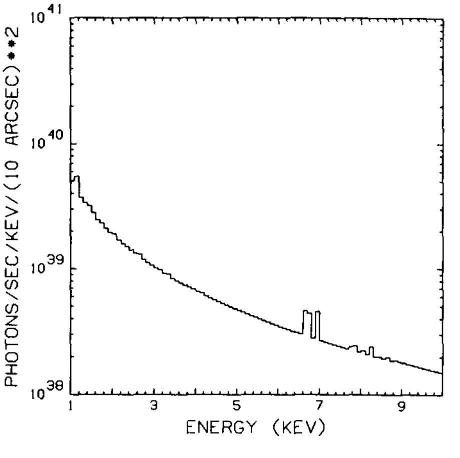

Fig.1c: Line-of-sight equilibrium spectrum on shock

The differences in the spectra are evident and bremsstrahlung fits would result in temperatures of T ≃ 5 keV at centre and of T $\geq$ 20 keV on the

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shock. This shows that fits to a spectrum integrated over the whole remnant (see above) give only limited information on the remnant's nature. However, none of these temperatures is representative for the remnant. The hydrodynamical simulations show that the shock- and reverse shock temperatures are different, the fitted values are just "weighted" temperature averages. In particular, the various line ratios in the spectrum could be interpreted as being due to non-equilibrium effects. Therefore, it seems hard to draw clear physical conclusions from X-ray observations with low spatial resolution, even for the idealized case where the emitted spectrum is locally an equilibrium spectrum.

III. Non-equilibrium Ionisation

In a second run we evolved the hydrodynamic structure simultaneously with the ionisation structure. As we used solar abundances, where H and He were always completely ionized, the local electron density is close to the equilibrium case and the dynamical evolution of the two models is nearly identical.
At the age of 410 years the ionisation structure in the outer regions of the remnant is in a very strong non-equilibrium state as can be seen from the total spectrum in Fig. 2a.

Bremsstrahlungs or thermal equilibrium fits with temperatures of kT ≈ 10 keV would represent the continuum of the spectrum above ≥ 4 keV reasonably well, but the line strengths do not match such temperatures at all: the iron line at 6.7 keV is much stronger in equilibrium models, whereas the large equivalent widths of the S, Si, and Ar lines seem to indicate the presence of a much cooler gas with a temperature of kT ≈ 1 keV.

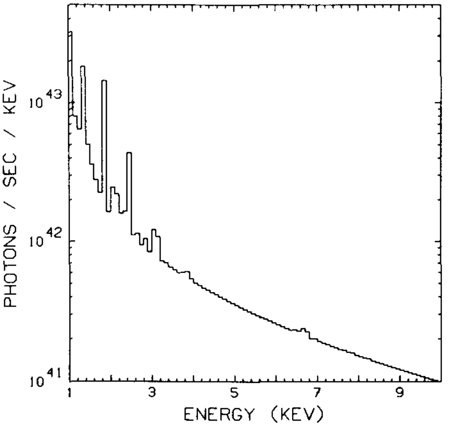

Fig.2a: Integrated non-equilibrium spectrum

The best way of getting a better insight into the physical parameters of the remnant would be to take spatially well resolved spectra at different radii from the remnant's centre. Figure 2b and 2c show two line-of-sight spectra, one taken at the centre (b), the other on the shock (c).

The continuum slopes are very complex and would require more component fits, which do not allow reliable conclusions on the remnant's temperature structure. A good diagnostic tool represents the iron line at about 6.7 keV as it is the dominant line for plasma temperatures above ~ 1 keV. Fig. 2b shows that, although the gas temperature at the shock is ≥ 10^8 K, the iron line has not formed yet. In appears only further in, i.e. at times much

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later than the crossing time of the shock. Its maximum equivalent width is reached near the position of the reverse shock. Near the centre (fig. 2c) its equivalent width is smaller again due to averaging effects. As the radial variations of the equivalent widths of the lines correspond to their temporal evolution, i.e. their ionisation time $n_e t$, their measurement together with a well defined continuum flux give strong model constraints on the temperature-density-structure of the remnant.

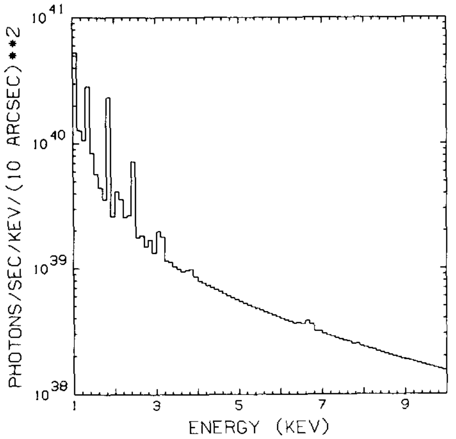

Fig.2b: Line-of-sight non-equilibrium spectrum near remnant's centre

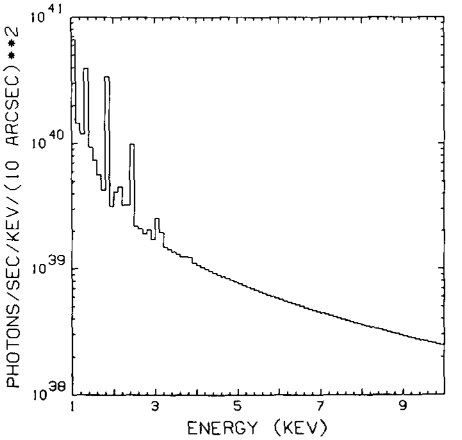

Fig.2c: Line-of-sight non-equilibrium spectrum on shock

IV. Conclusions

We have demonstrated that X-ray spectra integrated over the whole remnant do not reveal with the required accuracy the physical parameters of a SNR. Radially resolved spectra, together with a detailed hydrodynamic simulation and a simultaneous calculation of the ionisation structure seems to be the only way to obtain "physically reliable" parameters for the supernova remnants.

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