NON–EQUILIBRIUM IONISATION IN TYCHO'S SUPERNOVA REMNANT

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ABSTRACT: We present a detailed numerical study of the X–ray emission of Tycho's supernova remnant. Using Nomoto's W7 model of an exploding white dwarf as intial condition we follow the hydrodynamical and ionisation evolution for different densities of the interstellar medium and compare the emitted spectra with EXOSAT GSPC observations. The results indicate that the density of the ambient medium is $0.5 \lesssim n_0 \lesssim 1.0\ \mathrm{cm}^{-3}$, the distance to Tycho is about 3 kpc.

1. Introduction

Observations and modelling of the thermal X–ray emission of young supernova remnants provide the most direct tool to study their evolution, their chemical composition, and their interaction with the interstellar medium. Using a nuclear explosion model for the actual supernova event as initial condition in a hydrodynamical – ionisation modelling of a remnant the only free parameters in the calculation are the chemical composition and the density of the interstellar medium swept up by the outgoing shock wave. Matching the shape and intensity of the emitted spectrum with the observed X–ray flux as well as the comparison of the of the measured size of the remnant with the calculated size should result in a selfconsistent determination of the interstellar gas density and the distance of the remnant.

The ideal object for this type of study is the remnant of SN 1572, Tycho. The obtained optical light curves indicate that the event was a type I explosion which are thought to be caused by exploding white dwarfs where a deflagration front, starting at the centre of the white dwarf disrupts the whole star (Nomoto et al., 1984). Detailed numerical modelling of this kind of explosion resulted in well determined spatial profiles for the chemical composition, density and velocity (Thielemann et al., 1986). The X–ray shape of the remnant is nearly perfectly spherical symmetric, indicating that the explosion went off in a largely homogeneous medium and no signs for the existence of a central pulsar have been found. An analysis of the Einstein data (Gorenstein et al., 1983) roughly confirms the "standard" picture, although the mass derived for the progenitor star is larger than the $\simeq 1.4 M_{\odot}$ expected from the deflagration of a white dwarf (Nomoto et al., 1984).

Recently, detailed spectral observations in the harder X–ray band of ~ 1.6 – 10 keV have been made with the GSPC detectors onboard EXOSAT (Smith et al., 1988) and Tenma (Tsunemi et al., 1986). These instruments cover the vital energy range of the higher excited Si, S, Ar, Ca, and Fe lines and provide a good estimate for the temperature of the underlying continuum.

Itoh, Masai and Nomoto (1988) recently compared the Tenma results with hydrodynamical–ionisation calculations using Nomoto's W7 model as intial conditions. As the Tenma data indicate a rather soft X–ray continuum they assumed throughout their calculations that the electrons are heated by Coulomb collisions with the ions only, resulting in a considerably lower electron temperature compared with the ion temperature and, therefore, in a relatively soft X–ray continuum.

We present the results of a detailed numerical modelling of the X–ray emission of Tycho and compare them with the EXOSAT GSPC data. We assume temperature equilibrium between electrons and ions obtained by non–linear plasma processes, as postulated by McKee (1974). The details of the numerical calculations are given in Brinkmann et al. (1988). We are able to fit the observed spectrum quite well, although some marked differences between the simulated and observed spectra pertain indicating that some of the basic underlying model assumptions need readjustment.

2. Results

First we calculated models with the intial abundance distributions as given by Thielemann et al. (1986) and could not reproduce the observed spectra at all. At lower densities of the interstellar medium ($n_0 \lesssim 1$ cm^{-3}) we could not match the enormeous flux of the S – Ar – line complex at energies $\lesssim 3$ keV and the iron line at ~ 6.5 keV. Increasing the density of the interstellar material yielded better, but still unacceptable agreement between the measured and calculated spectra and at densities $n_0 > 2$ cm^{-3} the calculated total X–ray emissivity exceeds the observed value.

This problem to model the emission lines is not unexpected. It was encountered by Itoh et al (1988) as well and modelling of the early optical spectra of type I supernovae (Branch et al., 1985) could only be achieved by mixing the material of the ejecta. The physical reason for this mixing is, that in the deflagration models the burning front is convective due to the density inversion across the front and the hydrodynamics has, in principle, to be simulated by a more dimensional hydrocode which would then be able to handle the convective burning and mixing process properly.

Lacking this information we tried to reproduce the measurements by artificially mixing the elemental abundances of several outer zones homogenously over the region considered. As a first result it turned out, that a mixing of the material burned during the passage of the deflagration wave only is insufficient: a mixing of burned matter into the outer, unburned zones of the model is required. This implies, that mixing does not only occur in the convectively burning zones but that, eventually during the later expansion, unburned material is mixed into these zones, perhaps by Rayleigh – Taylor instabilities. Secondly, surprisingly little ^{56}Fe has to be mixed into the outer zones to match the measured iron line at ~ 6.5 keV.

Figure 1 show a spectrum with mixing of matter in the region of incomplete Silicon burning in Nomoto's W7–model which gave in general the best fits to the observed spectra and a density of the interstellar medium, $n_0 = 0.5$ cm^{-3} (for details see Brinkmann et al., 1988). For this amount of mixing only a fraction of $\lesssim 0.05\ M_\odot$ of the total ^{56}Fe content of the ejecta participates in the emission which means, that the vast majority of the produced iron remains cold, inside the remnant.

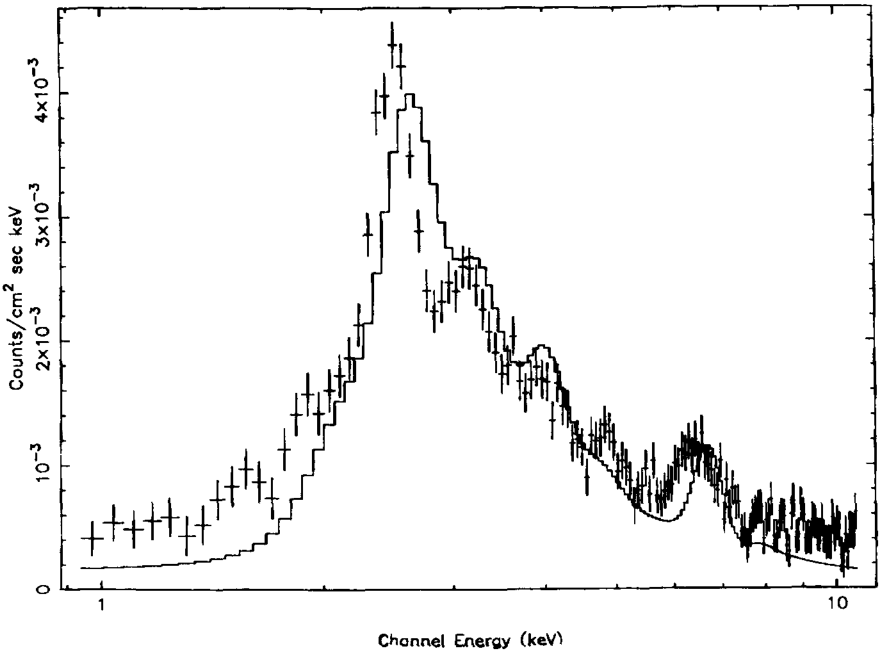

Figure 1: Calculated X–ray spectrum (solid line) convolved with the EXOSAT GSPC detector response in comparison with the observed fluxes (crosses)

Models with densities of the interstellar material in the range of $0.5 \lesssim n_0 \lesssim 1.0\ \mathrm{cm}^{-3}$ seem to be in best agreement with the experimental results: For higher densities the continuum flux gets too high putting the remnant too far away. Further, as the material is heated much longer, the slope of the continuum get too flat indicating a higher temperature than obtained by EXOSAT. (It should be noted that for our models the continuum is consistent with the value of ~ 6 keV claimed for the EXOSAT data, not with Tenma's ~ 3 keV). At lower external densities, the total flux as well as the strength of the emission lines is, in general, too low.

A detailed inspection of the modelled spectra shows that the majority of the emission originates from a localized region near the hydrodynamical contact discontinuity. This is a peculiarity of the employed chemical composition of the ejecta: Further out, in the outer shock, the temperature of the gas is too high, only bremsstrahlung is emitted. Near the contact discontinuity temperature and ionisational status are just ideal for line emission and further in, the ionisation time $n_e t$ is still too small to populate the higher ionisation stages effectively. In particular, most of the line emission originates from this region while the high temperature continuum flux is produced in the outer shock. This shows, that both spectral components are mainly produced independently in spatially and physically distinct regions. It further shows that the radius of the remnant, as seen by Einstein in the enegy band ≤ 4 keV, has to be identified with the position of the contact discontinuity and **not** with the position of the outer shock!

An estimate for the distance of the remnant can be obtained by comparing the emitted spectral power in the model calculations with the flux actually observed with EXOSAT. A second, independent measure for the distance is found from comparing the X–ray images of Tycho, taken with the Einstein HRI detector, with the radial brightness distribution resulting from our numerical models. In both cases the distance to Tycho is found selfconsistently to be $\gtrsim 3$ kpc.

3. Conclusions

A modelling of the X–ray emission of Tycho's supernova remnant using Nomoto's W7 model as initial condition results in a total X–ray spectrum which is in reasonable agreement with the observed EXOSAT GSPC spectrum of Tycho. The most severe difference between the observed and modelled spectra is that the centroids of the calculated emission lines of Fe and S are systematically shifted to higher energies, indicating that these elements are over-ionized in the calculations. Possible reasons for this can be our lack of the knowledge of actual microphysical processes involved (state of the electron gas, effects of magnetic fields and relativistic particles) as well as uncertainties in the astrophysical modelling (nuclear explosion model, clumpiness of the matter, global deviations from spherical symmetry, plasma instabilities).

Better, i.e. at least two dimensional explosion models and X-ray spectra with high spectral and spatial resolution together with a detailed hydrodynamic simulation seem to be the only way to get insight into the different physical processes involved and to obtain "physically reliable" parameters for these objects.

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