A HYDRODYNAMICAL MODEL OF KEPLER's SUPERNOVA REMNANT CONSTRAINED BY X-RAY SPECTRA

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Abstract: We present NEI hydrodynamical models of Kepler's SNR compared with the EXOSAT and EINSTEIN X-ray spectra.

I-INTRODUCTION

The remnant of the historical supernova observed by Kepler in 1604 was recently observed in X-rays by the EXOSAT satellite up to 10 keV. A strong Fe K emission line around 6.5 keV is readily apparent in the spectrum (Smith et al, 1987). From an analysis of the light curve of the SN, reconstructed from historical descriptions, Baade (1943) proposed to classify it as type I. Standard models of SN I based on carbon deflagration of a white dwarf predict the synthesis of about 0.5 $M_\odot$ of iron in the ejecta. Observing the iron line is a crucial check for such models.

Alternatively Dogget and Branch (1985) argue that the light curve of SN II-L is very similar to that of SN I and that the original observations are compatible with either type. In view of this uncertainty we have run a hydrodynamics-ionization code for both SN II and SN I remnants.

II-HYDRODYNAMICAL MODEL

The detailed comparison between theory and observation is far from straightforward: the hydrodynamical evolution of the shocked interstellar medium and of the 'reverse shocked' ejecta, together with the ionization structure throughout the SNR, must be computed in order to be able to construct synthetic spectra to be compared to the observations (e.g. Itoh, 1977; Nugent et al, 1984).

Here we use a 1-D lagrangian hydrodynamical code. A detailed description is given in a forthcoming paper (Ballet et al, 1987). Our model assumes an initially constant density in the ejecta, spherical symmetry, a uniform ambient medium and temperature equipartition between electrons and ions. The ionization structure is followed using the ionization and recombination rates of Arnaud and Rothenflug (1985). The emission model is from Mewe et al (1985). Synthetic spectra are computed separately for each element, allowing their abundances to vary.

Indeed we always assume that heavy elements are trace elements:

- For an SN II remnant we assume homogeneous ejecta with 90% hydrogen + 10% helium in number.
- On the other hand current SN I models predict pure heavy elements in the ejecta with a stratified structure (e.g. Nomoto et al, 1984). Hamilton et al

(1985a,b), using an analytical approximation for the hydrodynamics, already worked on such a picture and compared it favorably with the two other presumably type I historical supernovae remnants (SN 1006 and Tycho). In this preliminary work we consider 1.4 $M_\odot$ of pure Helium ejecta. This assumption simplifies the computations (no feedback between the ionization structure and the density and temperature) and ensures a nearly correct A/Z ratio. A more sophisticated model is in progress.

III-OBSERVATIONAL CONSTRAINTS

The age of the Kepler SNR is evidently known (380 years). Its angular radius is measured from X-ray and radio maps: about 100". We fixed the interstellar column density to 2.8 10^{21} Hcm^{-2} (Danziger and Goss, 1980).

The observed X-ray spectra are depicted in figures 1a and 1b: the spectrum obtained by the SSS on board the EINSTEIN observatory (Becker et al, 1980) and the spectrum obtained with the Medium Energy proportional counter of EXOSAT (Smith et al, 1987). The two low energy points on figure 1b correspond to the fluxes obtained with the LE+CMA experiment, with the Lexan 3000 and Boron filters. The EXOSAT instrument response we adopted is depicted in Smith et al (1987) and the SSS one in Ballet et al (1987): in particular we let as a free parameter the amount of ice on the SSS.

The main features of these spectra are:

1-the Fe L lines below 1.3 keV, main component in the CMA energy range.
2-the Si and S lines around 1.85 and 2.4 keV, whose centroids and strengths are well determined due to the good resolution of the SSS.
3-a cool continuum
4-a hard continuum (essentially free-free emission for a standard medium)
5-the Fe K lines (around 6.5 keV)

Only these last two components are important above 4 keV and the shape and strength of this continuum together with the centroid and intensity of the line are determined by the EXOSAT observation.

Therefore the quality of the fit will be very sensitive to the following model outputs: temperature and density of the hottest component (the main shock), the ionization structure of Si,S,Fe and their abundances.

This combined analysis can of course constrain the model better than previous ones based on the SSS data alone (Hughes and Helfand, 1985).

III-2 MAIN RESULTS

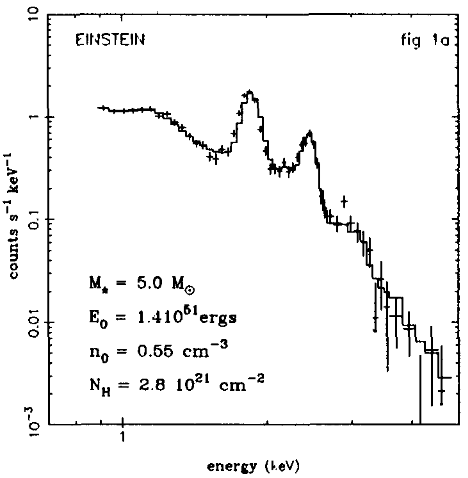
SNII model: We adopted the ejecta mass: $M_*= 5$ $M_\odot$.

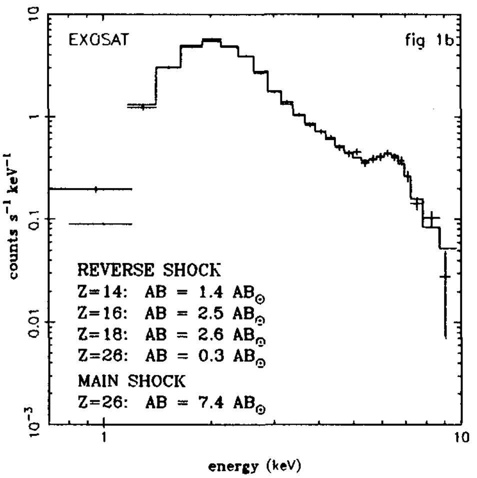
The continuum at 6.5 keV is essentially due to bremsstrahlung on fully stripped hydrogen and helium and can be computed by means of a pure hydro code. It depends on 2 free parameters: n_0 (outside density) and E_0 (explosion energy),the age and angular radius of the SNR being independently 'known'. Thus a relation between n_0 and E_0 is rapidly obtained by comparing such computations with the observed value. Then we made full hydro - ionization computations for 3 cases consistent with that first constraint: ($0.7cm^{-3}$,7.10^{50}ergs); ($0.7cm^{-3}$,10^{51}ergs); ($0.55cm^{-3}$,1.4 10^{51}ergs).

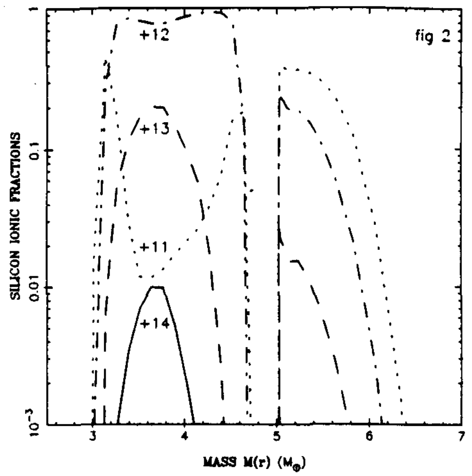
Our main conclusions are:

-The explosion energy must be high enough ($E_0>10^{51}$ergs) to supply a reverse shock hot enough to produce a sufficient continuum at low energy (below 4 keV).

- Si and S are rapidly ionized in the ejecta for such high values of E_0, the temperatures increasing with the explosion energy. The centroids of the Si and S K lines originating in this medium are higher than observed. This is illustrated in figure 1a, which depicts the best fit obtained for the $E_0=1.4\ 10^{51}$ ergs model, assuming normal abundances in the ambient medium and letting free the ejecta ones. Figure 2 shows the silicon ionic profile obtained. Notice that Si (and S) is less ionized in the main shock due to a higher ionization delay (lower density). Therefore a better fit is obtained if we allow an overabundance of Si and S in the outside medium, but values as high as 8 and 10 times solar are required. An alternative is that the lines are redshifted. A redshift of .75% (v= 2250 km s^{-1}, consistent with the shock velocity) is required.





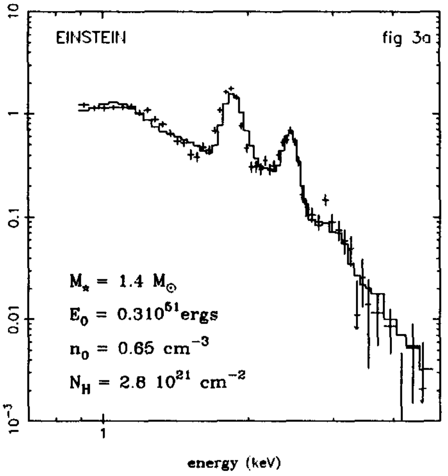


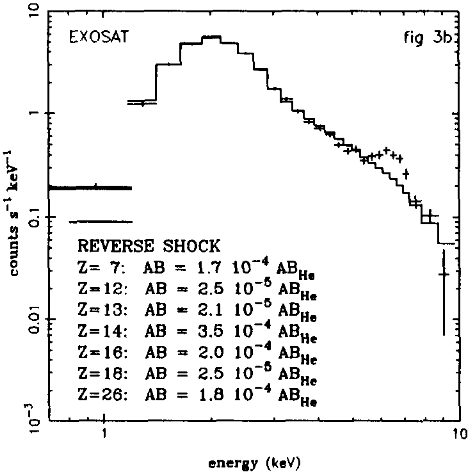
- The ratio FeK/FeL is very low, Fe being underionized in most layers. A correct ratio is only obtained if iron is overabundant in the main shock (see figure 1). Indeed, in spite of a stronger ionization delay, the main shock temperature is so high that the FeK/FeL ratio is larger there than in the reverse shock.

SNI model: The conclusions are essentially the same. We checked the 4 following cases consistent with the continuum flux at 6.5 keV: $n_0=0.5cm^{-3}$, $E_0=0.5,0.8,1.4\ 10^{51}$ergs and $n_0=0.65cm^{-3}$, $E_0=0.3\ 10^{51}$ergs.

-The reverse shock continuum is stronger for this helium plasma and always accounts for the continuum observed at low energy.

-Si and S are more ionized than in the SNII model, excluding models with $E_0>5.10^{50}$ergs. Figure 3 shows the best fit spectrum for $E_0= 3.10^{50}$ergs assuming normal abundances in the ambient medium and letting free the ejecta ones. Notice that the energy centroids of the Si and S lines are still too high. No reasonable redshift can lower their centroids enough.





- A very faint FeK line is produced in that case (see figure 3b). As above, an overabundance of Fe (~10 times the solar value) is required in the outside medium to match the observation.

IV- CONCLUDING REMARKS

The mean ionization of a given element depends on its spatial distribution, as each shell has a different ionization history. In the present models, iron was uniformly distributed inside the ejecta. In this case, the observed FeK/FeL ratio implies unrealistic ambient overabundances. Relaxing this assumption, we presently study models in which iron is confined in the inner shells. Preliminary results are encouraging.

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