THE X-RAY EMISSION FROM SN 1987A AND THE REMNANT OF SN 1572 (TYCHO)

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Abstract: The thermal X-ray emission from SN 1987A may be enhanced to a detectable level when the blast shock hits the circumstellar medium which has formed in the red-supergiant stage of the progenitor.

The X-ray spectrum of Tycho observed with the satellite Tenma can be explained approximately within the context of a carbon deflagration model for Type Ia supernovae, if the ejecta are assumed to be mixed partially.

SN 1987A: A theoretical analysis of the light curve of SN 1987A indicates that the supernova progenitor had a fairly small radius of the order of 10^{12} cm (Shigeyama et al. 1987). It is likely that the progenitor once evolved to a red supergiant, lost a substantial fraction of its envelope material, and contracted. We have calculated the dynamical evolution and nonequilibrium X-ray emission of a supernova remnant (SNR) in such an environment, using a spherically symmetric hydrodynamic code (Itoh 1977). We assume that SN 1987A has exploded in a cavity, which is bounded at a radius R_c by the wind material coasting radially with a speed, v_w, of 10 km s^{-1} and a mass loss rate, $\dot{M}_w$, of 5×10^{-5} $M_\odot$ yr^{-1}. By assuming that the explosion occurred at a time t_c since the end of the intense mass loss, R_c is written as $v_w t_c$. The value of t_c is very uncertain, and tentatively set equal to 10^3 yr in the present calculation. The ejecta are assumed to have a mass of 5 $M_\odot$ and an initial kinetic energy of 2×10^{51} erg. The density distribution in the outer regions of the initial ejecta is taken to be proportional to r^{-7}, where r is the distance from the centre of the star, and is truncated at a point where the expansion speed reaches (v_{ex} =) 2×10^4 km s^{-1}. The initial expansion of the ejecta is assumed to be homologous. Nonequilibrium ionization and X-ray emission are calculated for H, He, C, N, O, Ne, Na, Mg, Al, Si, S, Ar, Ca, Fe, and Ni. The rate coefficients are taken mainly from Arnaud and Rothenflug (1985) and Mewe et al. (1985). Only ions are assumed to be heated substantially across the shock front and electrons are assumed to be heated through Coulomb collisions with the ions.

The calculated time evolution of the 2-20 keV luminosity is shown in figure 1. The blast shock reaches R_c at a time, $t = t_h \sim (v_w/v_{ex})t_c$, since the explosion. It can be shown that the volume emission measure of the shocked wind attains a maximum of about $(\dot{M}_w/mv_w)^2/4\pi R_c$ with m being the mean atomic mass, when the blast-shock

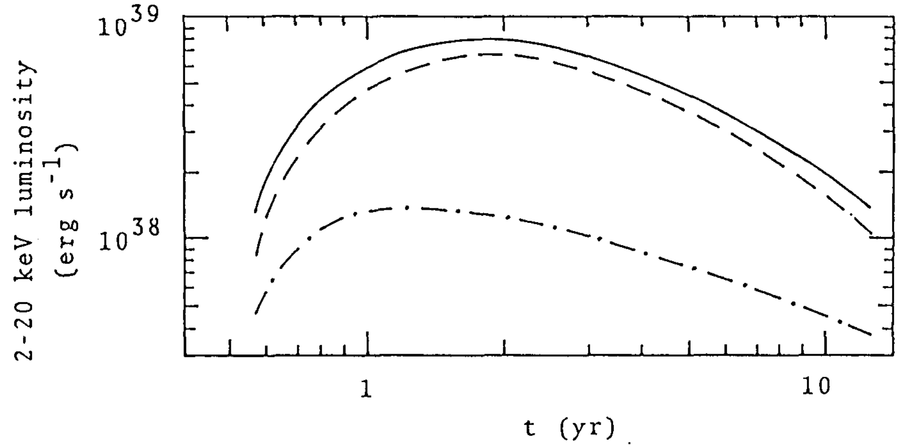

Figure 1: Time evolution of the 2-20 keV luminosities of the whole remnant (————), the ejecta (— — . —), and the wind material (— · — · —).

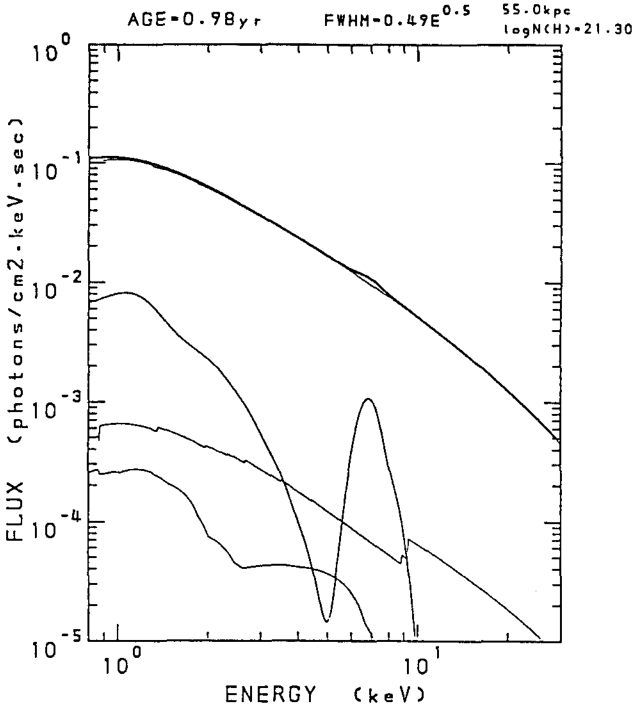

Figure 2: The spectrum at t = 0.98 yr. The total, bremsstrahlung, recombination, two-photon, and line emissions are shown. The total and line spectra are convolved with a Gaussian to a resolution of 0.49 $E^{0.5}$ keV (FWHM), where E is the photon energy in keV. The distance and interstellar hydrogen column density to the supernova are assumed to be 55 kpc and 2 x 10^{21} cm^{-2}, respectively.

radius is about $2R_c$. If the expansion is nearly free, this occurs at t $\sim 2t_h$. The reverse-shocked ejecta are several times as luminous in this energy range as the blast-shocked wind, owing to the relatively high densities. Figure 2 shows the X-ray spectrum at t = 0.98 yr. The bremsstrahlung dominates the spectrum. The line emission is generally weak, because abundant metal elements are ionized nearly completely. The Fe K-line blend is an exception, and can be used for plasma diagnostics. The thermal X-ray emission can be distinguished from emissions of interior origins (e.g., ^{56}Co decay or a pulsar), because the spectrum of the former is less affected by photoelectric absorption than those of the latter. The enhanced X-ray emission may be detectable by the satellite Ginga if the maximum volume emission measure mentioned above is large enough. More detailed discussion will be presented elsewhere (Itoh et al. 1987).

The Remnant of SN 1572 (Tycho): Type Ia supernovae are likely to be due to the deflagration of a C/O white dwarf. However, this has not been fully confirmed by the observations, in particular at X-ray wavelengths, of SNRs. Using the numerical code described above, we have calculated the dynamical evolution and nonequilibrium X-ray emission of an SNR on the basis of model W7 constructed by Nomoto et al. (1984) and Thielemann et al. (1986). The results have been compared with the observations of the remnant of SN 1572 (Tycho).

The observed outer radius and thickness of the reverse shock wave (Seward et al. 1983) and the observed continuum spectrum (Tsunemi et al. 1986) are reproduced approximately for an age of 411 yr, by assuming an ambient density of 1.3 amu cm^{-3}. Then the distance to Tycho is obtained as 2.43 kpc. It is found that the calculated equivalent width of the Fe K-line blend is sensitive to the mixing of the ejecta. Since the reverse shock has not propagated deep into the iron-dominated inner regions of the ejecta, transport of iron atoms into the outer regions by mixing results in a significant increase in the Fe line emission. We assume that the composition of the ejecta with the initial velocities less than 1.33 x 10^4 km s^{-1} is homogenized by mixing. The upper boundary of the velocity range corresponds approximately to the location at which the convective deflagration front freezes. As shown in figure 3, the resultant spectrum agrees well with the spectrum observed with the satellite Tenma (Tsunemi et al. 1986), if the interstellar hydrogen column density, N_H, to Tycho is taken to be about 1 x 10^{22} cm^{-2}. For a conventional value of N_H=3 x10^{21} cm^{-2}, the calculated photon fluxes below 2.5 keV are larger than the observed fluxes by up to a factor of 1.8. In either case, the carbon deflagration model is indicated to apply to Tycho's supernova. The numerical results will be discussed in more detail elsewhere.

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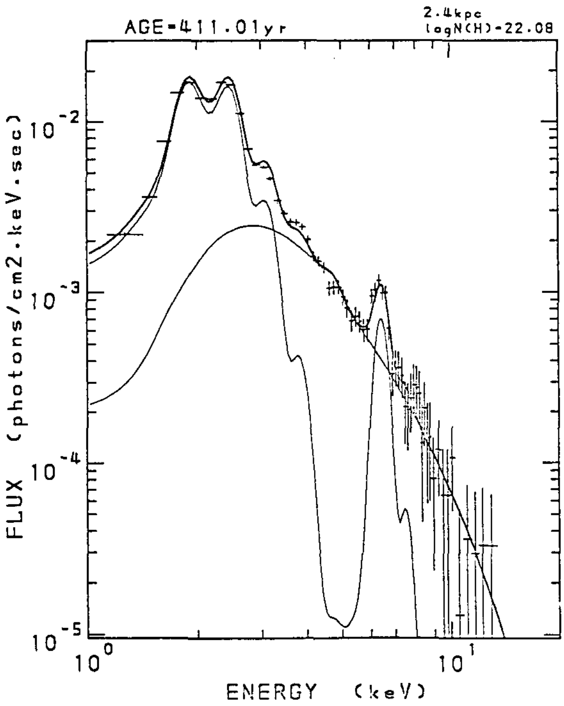

Figure 3: A model spectrum for Tycho. The total, continuum, and line emissions are convolved with the efficiency and response function of the GSPC aboard Tenma. The distance and interstellar hydrogen column density to Tycho are assumed to be 2.43 kpc and 1.2 x 10^{22} cm^{-2}, respectively. The crosses denote the spectrum observed with Tenma (Tsunemi et al. 1986).

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