THERMAL X-RAYS DUE TO EJECTA/CSM INTERACTION IN SN 1987A

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The X-ray spectrum observed by Ginga[1)] is characterized by a component below 10 *keV* which decreases with increasing photon energy, and a component above 10 *keV* which is nearly flat. This unusual X-ray spectrum may be understood as follows; X-rays below 10 *keV* is likely to be due to thermal emission coming from the shock-heated ejecta, and X-rays above 10 *keV* to be due to γ-ray degradation inside the ejecta. If thermal emission due to the collision of the ejecta with circumstellar matter (CSM)[2)-4)] is responsible for X-rays below 10 *keV*, the epoch of the collision can be estimated to be $\sim 0.2\,yr$ after the explosion if $\sim 0.5\,yr$ is the time when the X-ray flux at $\sim 10\,keV$ reaches its maximum. The X-ray light curve then requires the inner radius of CSM to be $\sim 1\times10^{16}\,cm$ for an expansion velocity, $V_{ex} \simeq 2\times10^{9}\,cm\,s^{-1}$.

X-rays emitted from the reverse-shocked ejecta dominate those from the blast-shocked CSM because of much higher density in the ejecta[3)]. The electron temperature of the shocked ejecta is raised to $> 10\,keV$ and then decreases with time to $\sim 10\,keV$ at $\sim t_{max}$, at which the flux at $\sim 10\,keV$ reaches its maximum. Free-free emission dominates the thermal spectrum except for a contribution of iron K-line emission around 7 *keV*. If CSM concerned is the remnant of a stellar wind, the mass loss rate $\dot{M}_w$ can be estimated from the observed thermal flux at 10 *keV* as[4)],

$$\dot{M}_w \sim 3\times10^{-6}\,(v_w/10^{6}\,cm\,s^{-1})^{3/4}(I_{10keV}/10^{-4}\,photons\,cm^{-2}\,keV^{-1}\,s^{-1})^{1/2}$$
$$\times(V_{ex}/2\times10^{9}\,cm\,s^{-1})^{3/4}(t_{max}/0.5\,yr)^{3/4}\ M_{\odot}\,yr^{-1}, \qquad (1)$$

where v_w and τ are the wind velocity and the time elapsed after the progenitor left the mass loss phase, respectively, and the distance to SN 1987A is assumed to be 55 *kpc*. We performed a numerical calculation of the dynamical evolution and non-equilibrium X-ray emission for the collision at $1.1\times10^{16}\,cm$, which is the inner radius of CSM. The density of CSM was assumed to be $\simeq 5.1\times10^{4}\,(r/1.1\times10^{16}\,cm)^{-2}\,H\,cm^{-3}$ at a distance r from SN 1987A, corresponding to $\dot{M}_w/v_w \simeq 2.8\times10^{-6}\,M_{\odot}\,yr^{-1}/10\,km\,s^{-1}$. The calculated X-ray spectrum at $t_{max} \sim 0.5\,yr$ is compared with the spectrum observed by Ginga in Fig. 1, where the residual flux above the thermal spectrum is also shown. Because of strong absorption below 20 *keV*, the residual spectrum may be ascribed to X-rays coming from the optically thick ejecta through the Compton degradation of γ-rays[5)].

For a blue supergiant with a typical wind velocity $v_w \simeq 100\text{-}1000\,km\,s^{-1}$, the value of $\dot{M}_w$ given by eq. (1) is too large. On the other hand, for $v_w \simeq 30\,km\,s^{-1}$, the mass loss rate is estimated to be $\dot{M}_w \sim 7\times10^{-6}\,M_{\odot}\,yr^{-1}$, which is not inconsistent with that for a red supergiant. This result implies that the CSM may be attributed to the stellar wind in the latest phase of a red supergiant or in the transition phase to a blue supergiant. Then, the time which has passed since the stellar wind ceased is estimated as, $\tau \sim 1\times10^{2}\,(v_w/3\times10^{6}\,cm\,s^{-1})^{-1}\,yr$. In any case, the lifetime in the blue supergiant phase would be of the order of $10^{2}\,yr$ if X-rays below 10 *keV* arise from the interaction between the ejecta and the wind remnant.

The material related with the secondary light source $\sim 4\times10^{16}$ *cm* away from the primary (IAU Circ. No. 4382) can be one of the candidates responsible for thermal X-ray emission. If the outermost envelope of the ejecta expands with the velocity $(3\text{-}4)\times10^{9}$ *cm* s^{-1}, it has reached this material 0.3-0.4 *yr* after the explosion. Also molecular clouds in the vicinity of SN 1987A can be candidates to interact with the ejecta. Fig. 2 shows 6-10 *keV* light curve expected from the wind remnant model adopted here. The light curve of thermal X-rays depends on the density structure of the colliding material. Therefore, continual watching can provide information on CSM. Recent near-infrared speckle data (IAU Circ. No. 4481) may suggest the existence of shell-like dusty CSM at $(1\text{-}2)\times10^{17}$ *cm* from SN 1987A. This CSM may be a remnant of the stellar wind in the red supergiant phase. The expanding ejecta will collide with this material and emit thermal X-rays 3-6 years hence. These X-rays will be an important diagnostic tool for the study of environments of Sk -69 202 and of chemical composition and the stellar evolution of similar blue supergiants in LMC. It is desired to make a future plan of X-ray observatory succeeding to active instruments.

References
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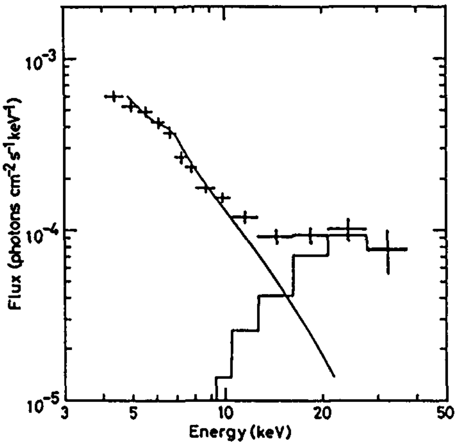

Fig. 1 Thermal spectrum (solid line) calculated with an energy resolution of $0.49(E/keV)^{1/2}$ *keV* (FWHM) is overlaid on the observed spectrum with Ginga$^{1)}$ (crosses). The residual flux over the thermal emission is represented by the histogram.

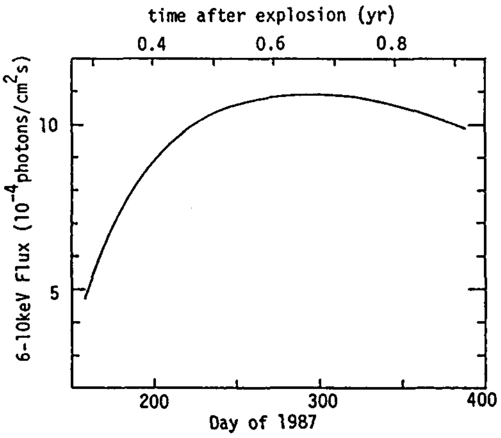

Fig. 2 6-10 *keV* light curve of thermal X-rays expected from a wind remnant model (see text). $Z = 1/3\,Z_\odot$, the hydrogen column density of 4×10^{21} cm^{-2} and the distance of 55 *kpc* to SN 1987A are assumed in Figs. 1 and 2.