X-Rays and γ-Rays from SN 1987A

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Theoretical light curves and spectra of X-rays and γ-rays from SN 1987A are calculated by the Monte Carlo method, based on a model built up from the early observations of neutrinos and optical light. Comparison of the predicted radiation with observational results obtained later confirms the radiation mechanism of supernovae: γ-rays are emitted in the decays of radioactive ^{56}Co and X-rays are generated by the Compton degradation of these γ-rays. It also suggests that large scale mixing occurred and clumpy structure was formed inside the ejecta. These findings lead us to construct the model with a new distribution of elements, which is determined through comparisons of observations of X-rays and γ-rays with numerical simulations based on the assumed distribution. Using this model, the subsequent X-ray and γ-ray emission is predicted: the light curves of X-rays and γ-rays as well as their spectral evolution are in very good agreement with that expected from the radioactive decays of ^{56}Co and ^{57}Co. The mass of newly synthesized ^{44}Ti and the emission from the neutron star will be determined by future satellite and balloon-borne observations.

1. Introduction

SN 1987A has given us an invaluable chance to examine supernova theory, which has predicted the emergence of X-ray and γ-ray radiation from supernovae. Several possible mechanisms for the X-ray and γ-ray emission have been discussed, such as collision of the ejecta with circumstellar matter, nonthermal radiation from a pulsar, and Compton degradation of the line γ-rays emitted by radioactive nuclei. The observed light curve clarified the energy source of the radiation. It started to show the exponential decline $\sim$ 120 days after the explosion with an e-folding time of 111.3 days (Catchpole *et al.* 1987; Hamuy *et al.* 1988). Since this time agrees with the lifetime for ^{56}Co to decay into ^{56}Fe, we infer that the dominant energy source of the optical radiation at this stage must be the decay of ^{56}Co. The ^{56}Co is believed to come from the 8.8d decay of ^{56}Ni, which is produced by the explosive nucleosynthesis and powers the light curve in the earlier stage. The actual mechanism of the X-ray and γ-ray emission from SN 1987A was found to be Compton degradation of line γ-rays emitted at the decays of ^{56}Co. During the first few hundred days after the explosion, the ejecta absorbs most of the energy released by the decay of ^{56}Co and emits it again in ultraviolet, optical and infrared bands (see McCray 1993). However, as the optical depth of the Compton scattering becomes small due to the expansion of the ejecta, (McCray *et al.* 1987) X-rays from SN 1987A were expected to become observable by *Ginga* and Kvant (M. Itoh *et al.* 1987). The line γ-rays were also predicted to be detectable by the satellite *MIR* and *Solar Maximum Mission* (Gehrels *et al.* 1987; Chan and Lingenfelter 1987). These results mandate a more detailed prediction of the light curves of X-rays and γ-rays based on a more realistic model of SN 1987A.

2. Hydrodynamical Model of the Ejecta

To predict the radiation from SN 1987A, a model of SN 1987A proposed by Shigeyama *et al.* (1988) and Nomoto *et al.* (1987a) is employed. The progenitor was a star with $\sim 20 M_\odot$ on the main sequence and developed a helium core of $\sim 6 M_\odot$ as inferred from the luminosity of SK-69° 202 (Woosley *et al.* 1988b).

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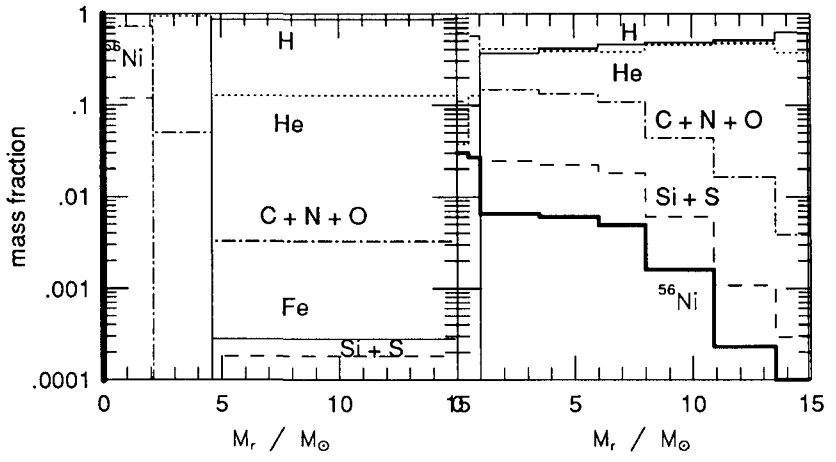

FIGURE 1. The distribution of chemical abundance of model 14E1 before mixing (left; Hashimoto *et al* 1989) and after mixing (right).

A neutron star with mass $1.4M_\odot$ was formed at the explosion, which is inferred from the observed neutrino flux. the chemical composition of the ejecta after the explosive nucleosynthesis is shown in Fig. 1 (left). The ejecta consist of a heavy element core of $2.4M_\odot$ (composed of $0.073M_\odot$ ^{56}Ni, $0.26M_\odot$ Ar-S-Si and $2.07M_\odot$ Mg-Ne-O-C), a $2.2M_\odot$ He-rich layer (4% carbon and 1% oxygen in mass fraction) and a H-rich envelope of mass $10.3M_\odot$ (including heavy elements of 1/4 times the solar abundance). Using the model of the ejecta 14E1 (Nomoto *et al.* 1987a; Shigeyama *et al.* 1988), Monte Carlo simulations are performed to follow the trails of photons inside the ejecta. In evaluating the flux at Earth, we assume the distance to the supernova to be 55 kpc.

3. X-Ray and γ-Ray Light Curves

3.1. *The effects of mixing*

Comparison of the resulting X-ray light curve (dotted curve in Fig. 2) with the early *Ginga* observations (*crosses*; Dotani *et al.* 1987), suggests large scale mixing in the ejecta (M. Itoh *et al.* 1988; Kumagai *et al.* 1988a, 1992; Nomoto *et al.* 1991a, 1991b). Monte Carlo simulations are conducted assuming the region of mixing, and the results show that the model with mixing at $M_r < 13.5M_\odot$ most consistently reproduces the light curve (dashed curve in Fig. 2) with the *Ginga* observation till 300^d after the explosion. The resulting chemical composition is shown in Fig. 1 (right). After mixing, ^{56}Ni is mixed up to $M_r = 13.5M_\odot$ where the expansion velocity of the material amounts to 4200 km s^{-1}. The column depth to this layer is 2.4 g cm^{-2} at $t = 200^d$. At early times, the emergent X-rays originate from ^{56}Co at the outermost layers. Later, the γ-rays and X-rays from ^{56}Co in the deeper layer contribute. Though the mass fraction of original ^{56}Co is much larger in the core than in the envelope, the emergent flux does not increase so steeply because most of the ^{56}Co has already decayed and the absorption by the core material is larger. Thus, the X-ray light curve shows a relatively broad peak. Accordingly, the dashed curve is in good agreement with the *Ginga* observations up to $\sim 300^d$.

Fig. 3 shows the calculated line γ-ray light curves based on the above chemical distribution. They are all consistent with *SMM* and balloon borne observations. The early emergence of γ-rays in the model is due to the mixing of ^{56}Co out to $M_r \sim 13.5M_\odot$.

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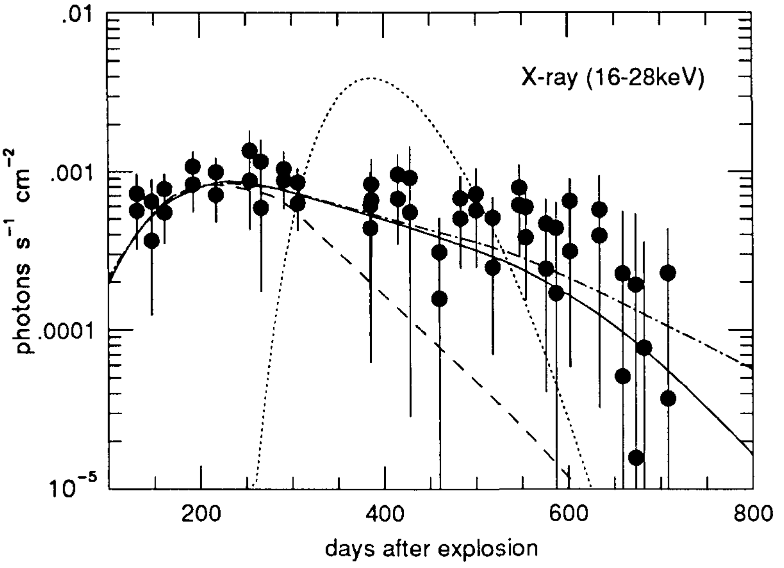

FIGURE 2. X-ray light curves calculated by Monte Carlo simulation based on the model 14E1 (Nomoto *et al.* 1987a: Shigeyama *et al.* 1988) The dotted curve is in the case without mixing and the dashed curve corresponds to spherical mixing at $M_r < 13.5 M_\odot$. The solid curve is for the model with the reduction of the photo-electric opacity by a factor 10 at $M_r < 8 M_\odot$ in addition to mixing and the dash-dotted curve is obtained by taking account of the effect of ^{57}Co, comparing the *Ginga* observation (Inoue 1991).

The flux ratio between 847 keV and 1238 keV line γ-rays is close to unity at early stages because of the smaller cross section for 1238 keV than for 847 keV. It approaches the experimental value of 0.68 as the column depth decreases.

The predicted light curves of line γ-rays from the decays of ^{57}Co and ^{44}Ti are shown in Fig. 4 (Kumagai et *al.* 1992). Recently, the Compton Gamma Ray Observatory detected the 122 keV line originating from ^{57}Co (Kurfess *et al.* 1992). These observations imply that the isotope ratio of ^{57}Ni and ^{56}Ni synthesized at the explosion 1.5 ± 0.5 times the solar ratio, which is consistent with the velue 1.7 from nucleosynthesis theory. Future observations of these lines should confirm the amount of radioactive nuclei and, hence, the nucleosynthesis theory.

3.2. *The effects of clumps*

At later times, $t > 300^d$, the 16 – 28 keV X-ray flux observed by *Ginga* (Inoue 1991) declines very slowly, while the calculated X-ray flux (the dashed curve in Fig. 2) decreases significantly faster than the observation. To be more realistic, we should take account of the effect of clumps on the X-ray absorption in the core, though the above calculation assumes homogeneous and spherically symmetric mixing, which maximizes the absorption.

If the heavy elements are localized in particular clumps, a large fraction of the X-rays could be transported through the hydrogen and helium-rich regions without suffering much photoelectric absorption; this would effectively reduce the opacity. A calculation assuming the photoelectric opacity to be reduced by a factor 10 in $M_r < 8 M_\odot$ gives the X-ray light curve most consistent with the *Ginga* observation (solid curve in Fig. 2). The most probable mechanism to mix the supernova ejecta is the Rayleigh-Taylor instability. Numerical simulations of such mixing have been carried out by Arnett *et al.* (1989b), Hachisu *et al.* (1989). For example, Hachisu *et al.* (1989) shows that the materials of Si

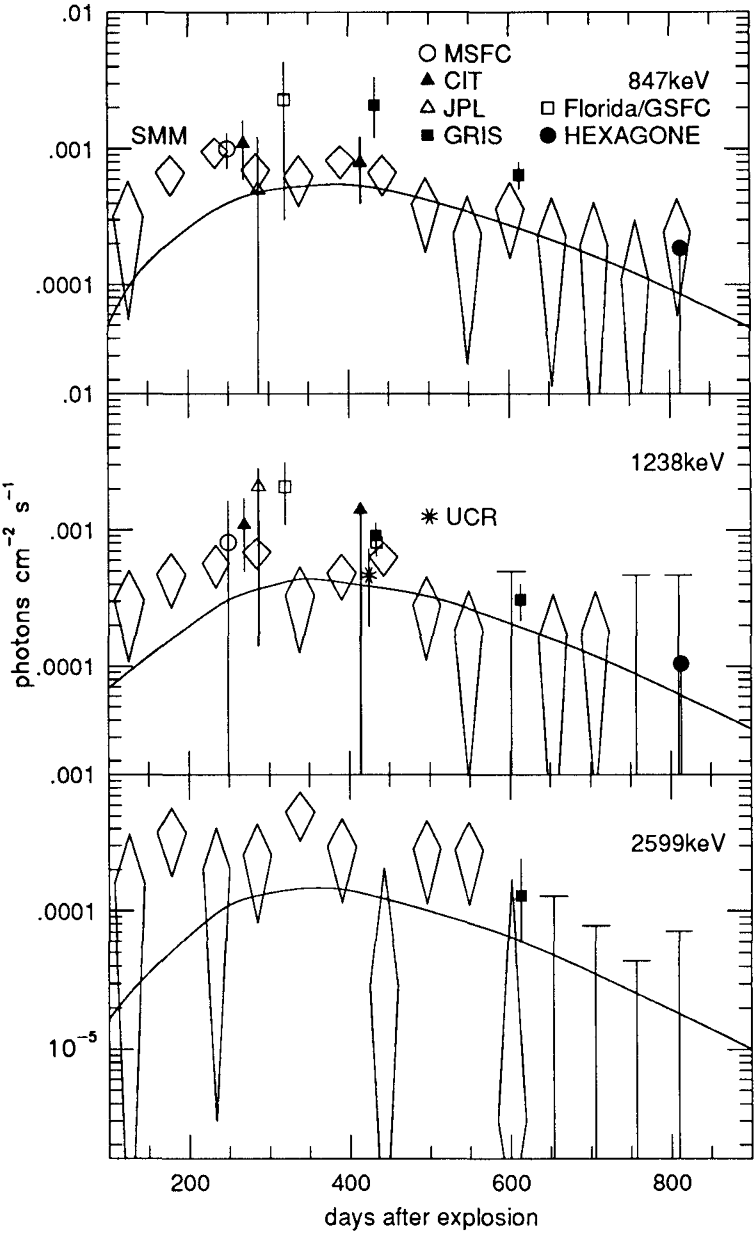

FIGURE 3. The calculated and observed line γ-ray light curves of 847 keV (upper), 1238 keV (middle), and 2599 keV (lower) of model 14E1 comparing with the observation of *SMM* (*diamonds*: Gehrels *et al.* 1987) and balloons (*crosses*: Sandie *et al.* 1988; Cook *et al.* 1988; Mahoney *et al.* 1988; Rester *et al.* 1989).

and O-rich layer are mixed up to $M_r = 8M_\odot$, where the expansion velocity is ~ 2200 km s^{-1}, and that hydrogen is mixed down to $M_r = 1M_\odot$ at the same time. These results can explain the occurrence of mixing in the ejecta, but cannot completely reproduce the extent of ^{56}Co mixing to outer layers presented by the X-ray, γ-ray, and infrared observations.

The dash-dotted curve in Fig. 2 adds a contribution from the decay of ^{57}Co to the

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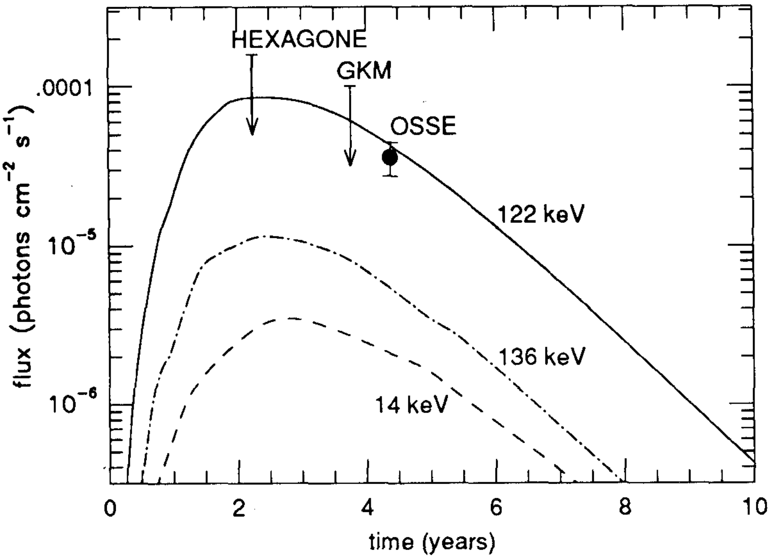

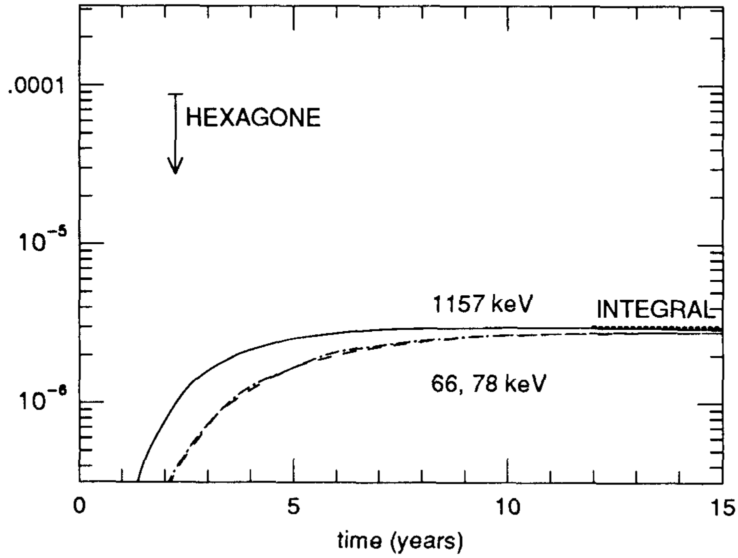

FIGURE 4. (*top*) The calculated line γ-ray light curves of 122 keV (solid curve) from ^{57}Co decay is compared with the upper limits obtained from the balloon experiments (GKM: Gunji *et al.* 1992; HEXAGONE: Chapuis *et al.* 1993) and the flux translated from the OSSE experiments (Kurfess *et al.* 1992). The light curves of 136 keV (dash-dotted curve), and 14 keV (dashed curve) are also shown. (*bottom*) The calculated line γ-ray light curves of 1154 keV (solid curve), 511 keV (dash-dotted curve), 67.9 keV and 78.4 keV (dotted curves) from ^{44}Ti, compared with the upper limit obtained with HEXAGONE (Chapuis *et al.* 1993).

solid curve, which corresponds to ^{56}Co only. This additional X-ray flux exceeds that from the ^{56}Co decay at $t > 600^d$ and slows down the decline of the X-ray light curve. However, the effect is not sufficiently large and a reduction of the photo-electric opacity is still necessary to account for the observations for $t > 300^d$.

Calculated X-ray light curves of higher energy bands adding the effect of ^{57}Co, based on the mixing model obtained above are shown In Fig. 5. They also agree very well with the *MIR* observations (Sunyaev *et al.* 1988).

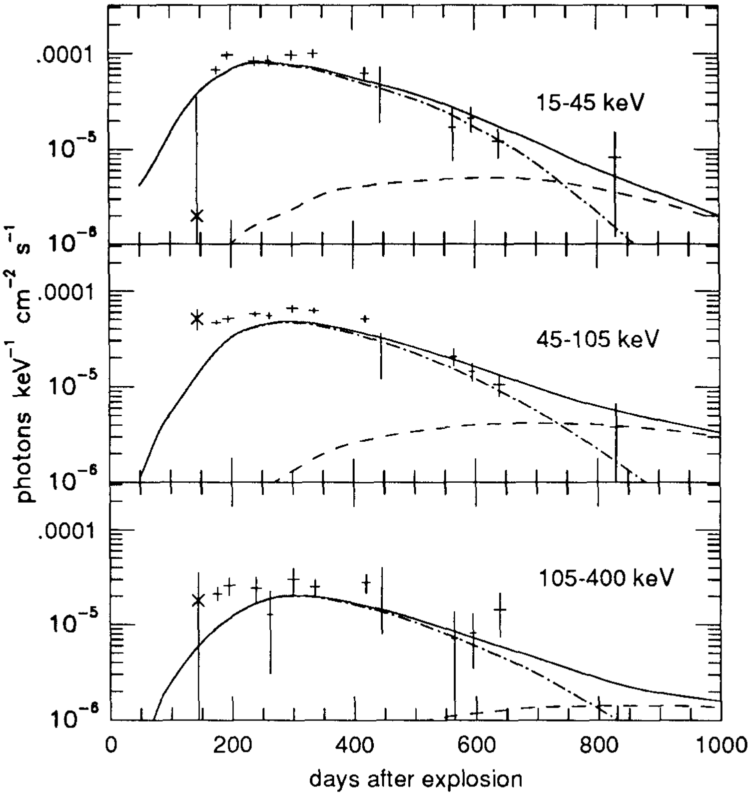

FIGURE 5. Calculated and observed light curves of 15 – 45 keV (upper), 45 – 105 keV (middle) and 105 – 400 keV (lower). Dash-dotted lines and dashed lines are the contributions of ^{56}Co and ^{57}Co, respectively, and the solid lines are their sum. The *MIR* observations are also shown for comparison (Sunyaev *et al.* 1988, 1989).

4. X-Ray and γ-Ray Spectra

It is also important to compare theoretical calculations of the hard X-ray and γ-ray spectra from the decays of ^{56}Co and ^{57}Co with observations. Fig. 6 shows this comparison. The calculated spectra for $E \gtrsim 15$ keV are in good agreement with the observations, which implies that the down-scatterings of γ-rays and hard X-rays in SN 1987A are well modeled by our calculation. The theoretical spectrum does not appreciably change until $t \sim 400^{\rm d}$ and becomes harder as the ejecta expands and the number of Compton scattering decreases.

The dash-dotted curves in Fig. 6 show the emergent spectra due to the degraded line γ-rays from the ^{57}Co decay. Because ^{57}Co has a longer half life ($271^{\rm d}$) than ^{56}Co ($78^{\rm d}$), the X-rays below 122 keV are dominated by the ^{57}Co component for $t > 600^{\rm d}$. This fact is evident in the dash-dotted and solid curves in Fig. 2. It is interesting to compare the predicted hard X-ray spectrum at $t = 600^{\rm d}$ with HEXE observations (Fig. 6; Sunyaev *et al.* 1989). Without a contribution from ^{57}Co decay, the theoretical flux below 100 keV is about a factor of 2 smaller than the observed flux. With the adopted abundance of ^{57}Ni, the contributions from the decays of ^{56}Co and ^{57}Co are comparable at $t \sim 600^{\rm d}$; this choice gives excellent agreement between the predicted and the observed flux, as seen in Fig. 6. This suggests that the abundance ratio of ^{57}Ni/^{56}Ni may be about twice as large as the solar ratio as calculated by Hashimoto *et al.* (1989) (see also Sunyaev *et al.* 1989).

On the other hand, the Compton-degraded γ-rays cannot account for the X-rays below

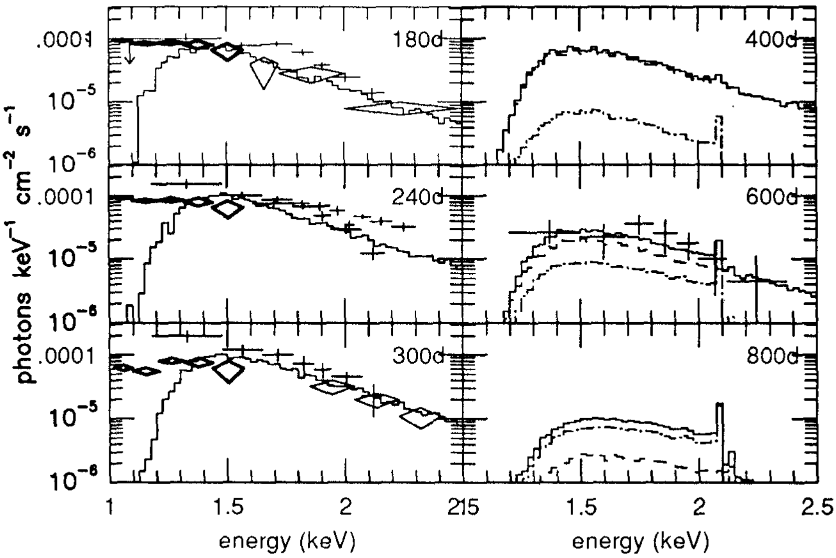

FIGURE 6. Calculated hard X-ray and γ-ray spectra due to the decays of ^{56}Co (solid curve) and ^{57}Co (dash-dotted curve) for model 14E1 with the photoelectric opacity reduced by a factor 10 for $M_r < 8M_\odot$. The thin diamonds show the spectra observed by *Ginga* (Inoue 1991); the thick diamonds and the thick crosses are observations with Pulsar X-1 and HEXE on *Kvant* (Sunyaev *et al.* 1987, 1989); and the thin crosses are balloon-borne observations (Wilson *et al.* 1988). For the figures of $t = 400^{\rm d}, 600^{\rm d}$, and $800^{\rm d}$, the ^{56}Co and ^{57}Co components are shown by the dashed and dash-dotted curves, respectively, and the solid curve is their sum.

16 keV observed by *Ginga*, which show the time variations of the intensity and spectrum. Instead, thermal emission from the ejecta heated by collision with preexisting circumstellar matter reproduces them very well (see H. Itoh *et al.* 1987; Masai *et al.* 1987, 1988).

5. Conclusions

Through the comparison of the theoretical light curves and spectra of X-rays and γ-rays from SN 1987A with observational results obtained later, we reach the following conclusions: **(1)** The high energy radiation mechanism of supernovae is confirmed: γ-rays are emitted at the decays of radioactive ^{56}Co and X-rays are generated as Compton degraded γ-rays. **(2)** A new model of supernova ejecta is constructed, in which a large scale mixing occurs and clumpy structure is formed. This model reproduces very well the optical and infrared observation. **(3)** The theoretical UV-IR light curve based on the above model is predicted to decay faster than exponential decline of ^{56}Co at ~ 300 days after the explosion, because a larger fraction of X-rays and γ-rays escape from the ejecta in this stage. This was confirmed later by the observations at SAAO, ESO, and CTIO.

With the new model described above, future X-rays and γ-rays originating from other radioactive nuclei with longer half lives, such as ^{57}Co and ^{44}Ti, and a buried neutron star are predicted. The 122 keV line γ-ray from ^{57}Co has been detected by the Compton Gamma Ray Observatory and its intensity is consistent with the prediction. The intensities of line γ-rays from ^{44}Ti should become almost constant for post-explosion times greater than 5 years and should be observable with future satellites. If a pulsar

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with a luminosity of 10^{37} erg s^{-1} exists, the X-ray flux will become intense enough to be observable with *ASCA* in $\sim$ 1995 and with *ASTRO-E* in $\sim$ 2000.

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