NON-EQUILIBRIUM THERMAL X-RAY EMISSION IN THE EARLY PHASE OF SUPERNOVA REMNANT

Hitoshi HANAMI and Tatsuo YOSHIDA
Department of Physics, I.F.S., University of Texas
Austin, TX 78712-1060
Department of Physics, Hokkaido University, Sapporo 060, Japan

Abstract. The X-ray emission from the interaction of the ejecta with circumstellar matter (CSM) for SN1987A is investigated. The electron and the ion temperatures seem to be in non-equilibrium in the early phase of a SN remnant. We have studied the two-temperature model in the early phase of SNR and discuss the X-ray emission from SN1987A and its CSM.

1. Introduction

It is implied that the density of the CSM of SN1987A is lower than that of SN1979C and SN1980K from radio observations (Turtle *et al.*1987). The progenitors of SN1979C and SN1980K seem to be red supergiants which had formed the dense CSM by winds. Indeed, from the positional coincidence and the observation by IUE, the blue supergiant called Sanduleak 69 202 is identified as the progenitor of 1987A (Gilmozzi *et al.* 1987). Then it was predicted that Ginga Observatory could not detect the X-ray emission from SN1987A because the density of CSM estimated by radio observation is low. However, since day 130 after the explosion, the thermal emission has been observed by Ginga (Dotani *et al.* 1987). Itoh *et al.* (1987) and Masai *et al.* (1987) have expected that the X-ray emission is enhanced when the shock hits the dense CSM formed in the red giant stage.

In the present paper we give a simple analytic method of getting the information about the CSM density from the X-ray observations. We estimate the electron temperature and the X-ray luminosity, which depends on the electron temperature, in a wide range of the parameter of the CSM density $\dot{M}/V_W$. Our simple analytic methods consists of two parts which are self-similar analysis for the dynamical properties and two-temperature model for the thermal process.

2. Analytic Method for the Two Temperature Model in the Early Phase of SNR

2.1 Self-similar solutions for the interaction region.

In early phase ejecta collide with the CSM, and the interaction region

D. McNally (ed.), Highlights of Astronomy, Vol. 8, 217–221.

with shocked ejecta and shocked CSM, which are separated by the contact discontinuity, is formed between outer and inner shocks. Chevalier (1982) investigated the interaction of the expanding ejecta with CSM by similarity analysis. Following him, we assume that the expanding ejecta and the CSM have power law density profiles which are represented by the density index n and s respectively. From dimensional analysis, the radius of the contact discontinuity which separates shocked ejecta and shocked CSM shells is given by

$$Rc = (Ag^{n}/q)^{1/(n-s)} t^{1/L}, \quad L = (n-s)/(n-3), \qquad (1)$$

where g and q are constants related to the explosion energy E and mass M of ejecta and the density of the CSM. If the CSM is formed by steady mass loss with a constant terminal velocity, then s=2 and $q = \dot{M}/(4 V_w)$. A is a constant which can be determined from the result by this analysis. By using suitable similarity variables, we can get the structure of the density, the pressure and velocity in the shocked interaction region.

2.2 Two-temperature model

Itoh (1987) pointed out that the one-temperature model of SNRs cannot explain the observed X-ray temperature for young SNRs. He studied the two-temperature model that the electron temperature is not equilibrated with the ion temperature behind the shock front in the sedov phase. Here, in order to investigate the X-ray emission in the early phase, we extend the above one-temperature model to a two-temperature model.

We assume that the post-shock electrons are heated only through Coulomb collisions with the ions. The evolution of the normalized electron temperature $g_e = T_e/T$ for a fluid element represented in Lagrangian coordinate is given by

$$3/2 \ln((1+g_e^{1/2})/(1-g_e^{1/2})) - g_e^{1/2}(g_e+3) = \ln A/80\, n_i/T^{3/2}(t-t_o) = f(t) \qquad (2)$$

where we use cgs units. T_e is the electron temperature; T is the mean temperature. Eq. (2) means that the electron temperature is determined by heating time $t-t_o$ and the postshock conditions. We can derive a useful form of the function f(t) rewritten by a temporal function with R_c and a function of similarity variables. Furthermore, in order to obtain g_e from f(t), Eq. (2) must be inverted. We can use the convenient explicit form with f(t) for g_e found by Cox and Anderson (1982),

$$g_e = 1 - \exp[-(5/3f)^{0.4}\{1+0.3(5/3f)^{0.6}\}] \qquad (3)$$

Then we obtain the spatial distribution of the electron temperature in the interaction region at any time in the early phase. As an example, we show in Fig. 1 the spatial distribution of the electron and the mean temperature by the solid line and the dashed curve for the case s=2 and n=7. The labelling numbers indicate $\dot{M}/V_w$ normalized with $10^{-6}\ M_\odot/yr$

and 1000 km/s ($E=10^{51}$ erg and $M=1M_\odot$). The average electron temperature in inner shell and outer shell of the interaction region is also obtained. In the almost phase of non-equilibrium state, $f(t)\ll 1$. Then g_e is nearly equal to $(5/3f)^{0.4}$ which can be shown as the asymptotic form of Eq.(3) in the limit $f(t)\ll 1$. Then the time evolution of T_e is given by

$$\langle T_e\rangle_{s=2} \propto t^{-0.4} \quad . \tag{4}$$

By the use of the average electron temperature obtained above, we can estimate the X-ray luminosities of the outer and inner shells. Here we use the following approximate expressions: When $0.01\text{keV} < T_e < 1\text{kev}$ bound-bound transitions dominant the X-ray radiation process; then the cooling function is given by

$$A_L(T_e) = 9.26 * 10^{-24} T_e^{-1} \quad \text{erg cm}^{-3}\ \text{s}^{-1} , \tag{5.1}$$

where T_e is in units of 1 keV and coronal ionization equilibrium is assumed. When T_e is higher than 1 keV, thermal bremsstrahlung dominates and the cooling function is represented by

$$A_L(T_e) = 5.9 * 10^{-24} T_e^{-1} \quad \text{erg cm}^{-3}\ \text{s}^{-1} . \tag{5.2}$$

We obtain the luminosities by putting $\langle T_e\rangle$ into Eqns.(5.1) and (5.2). Then we compare them with the observed one.

3. Discussion of the CSM of SN1987A and Conclusions

As an example of the application of our analysis we mainly discuss the X-ray emission from 4 keV to 12 keV observed in the region of SN1987A by the X-ray astronomy satellite Ginga. [The hard X-ray (12-200 keV) emission observed by Ginga and Kvant is not discussed here. It can be explained by Compton scattering process of γ-rays from ^{56}Co decay (Sunyaev *et al.* 1987; Itoh *et al.* 1987)]. The observed spectrum on 3 September 1987 can be fitted by a composite of a thermal bremsstrahlung spectrum with temperature of 4 keV and a flat spectrum. If the X-ray emission above 12 keV is from Compton degradation of γ-rays, the observed spectrum between 4-12 keV is fitted by only a thermal bremsstrahlung spectrum with electron temperature of 10-12 keV. The luminosity in the range 4-12 keV was about $7 * 10^{36}$ erg/s.

If X-rays in the above range are emitted by the collision of the ejecta with the CSM, we can estimate $\dot{M}/V_W$ by comparing the observed luminosity with the estimated luminosity and compare the temperature expected from the observed spectrum with the average temperature derived here.

For the density profile of the outer region of the ejecta, Colgate and McKee (1987) have found that the explosion of a star with polytropic index results in the outer density distribution of the ejecta whose density profile index n is approximately 7. For the CSM the index of the density profile is 2, assuming a steady mass loss rate and a constant terminal velocity. Therefore, we mainly discuss the case s=2 and n=7. In this case the X-ray luminosities due to thermal bremsstrahlung are written for the outer and inner shells as

$$L_{ff\,out} = 1.1 * 10^{30}(E^2/M)^{-1/5}(\dot{M}/V_W)^{12/5} \quad ty^{-1} \quad erg/s$$

and

$$L_{ff\,in} = 6.0 * 10^{30}(E^2/M)^{-1/5}(\dot{M}/V_W)^{18/5} \quad ty^{-1} \quad erg/s.$$

In the detector range of Ginga, the bremsstrahlung emission is dominant. The luminosity in the inner shell is larger than that in the outer shell because the density on the shocked ejecta is higher. The outer and inner average electron temperatures are given by

$$\langle T_e\rangle_{out} = 1.3(\dot{M}/V_W)^{-2/5} \text{ keV, and } \langle T_e\rangle_{in} = 0.49(\dot{M}/V_W)^{-2/5} \text{ keV.}$$

In Fig.2 the total luminosity L_x and the average electron temperature are expressed as a function of $\dot{M}/V_W$ where we take $ty=0.5$, $E_{51}=1$, and $M_1=1$. $ty=0.5$ is the time from the explosion to 3 Sept. 1987; L_x hardly depends on E and M. As shown in Fig.2, the value of $\dot{M}/V_W$ which corresponds to the luminosity observed by Ginga is 240. Then the outer shock radius is 0.02 pc. The average electron temperatures in the outer and inner shells are 16 keV and 5.7 keV respectively. We may say that these temperatures are in good agreement with the spectrum observed by Ginga.

However, Chevalier and Fransson (1987) have deduced $\dot{M}/V_W=16$ from the radio observation of SN1987A on days 2.1 and 3.1 after the explosion. If the ejecta continue to interact with the CSM of this low value, X-ray emission could not be detected by Ginga. Therefore, the above difference between values $\dot{M}/V_W$ estimated by X-ray and radio observations seems to mean that the CSM of SN1987A consists of two CSM formed by the winds of different phase. As one possibility the dense outer CSM was forced by the wind from the red supergiant. After the red stage is over, the star contracts and becomes a blue supergiant. Then the low density CSM is formed by the high velocity wind. As another possibility, the outer was formed by the couldlet-evaporating wind from the blue supergiant. In this case, a hot wind-blown bubble, trapped by the cloudlets around the progenitor, might be formed like nebulae around the WR stars (Hanami and Sakashita 1987). Then we conclude that when the outer shock passed the boundary of the two CSM of different densities and reached the outer CSM, the X-ray emission was detected by Ginga.

4. References

Chevalier, R.A. 1982, *Astrophys.J.* **258**, 790.
Chevalier, R.A. and Fransson, C. 1987, *Nature* **328, 44**.
Colgate, S.A. and McKee, C. 1969, *Astrophys.J.* **157**, 623.
Cox, D.P. and Anderson, P.R. 1982, *Astrophys.J.* **253**, 263.
Dotani, T. *et al.* 1987, *Nature* **330**, 230.
Gilmozzi, R. *et al.* 1987, *Nature* **328**, 318.
Hanami, H. and Sakashita, S. 1987, *Astron. Astrophys.* 181, 343.
Itoh, H. 1978, *Publ.Astron.Soc.Japan* **30**, 489.
Itoh, H. 1979, *Publ.Astron.Soc.Japan* **31**, 429E.

https://doi.org/10.1017/S1539299600007814 Published online by Cambridge University Press

Itoh, H., Hayakawa, S., Masai, K., and Nomoto, K. 1987, *Publ.Astr.Soc. Japan* 39, 529.
Itoh, H. *et al.* 1987, *Nature*, 330, 233.
Masai, S., Hayakawa, S., Itoh, H. and Nomoto, K. 1987, *Nature* 330, 233.
Turtle, A.J. *et al.* 1987, *Nature*, 329, 38.

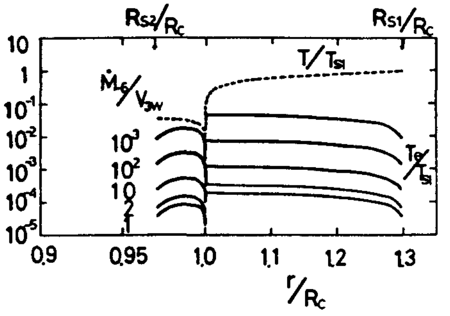

Fig.1. The spatial distributions of the electron normalized to the outer shock temperature, T_e/T_s are plotted (solid curves) against the radial distance. The normalized mean temperature T/T_s is also shown for the case s=2, n=7 (dotted curve).

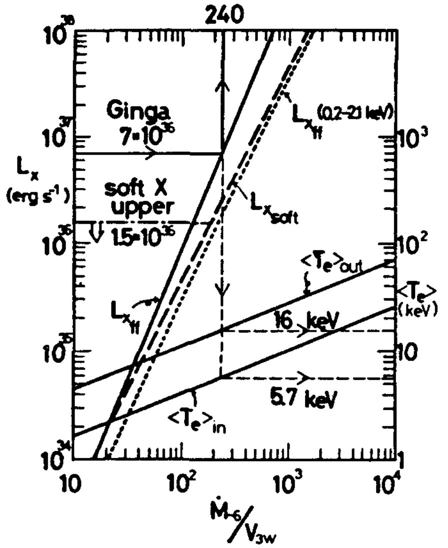

Fig.2. For the case s=2, n=7, ty=0.5, E_{51}=1, and M_1=1, the dependence of the X-ray luminosities on $\dot{M}/V_w$ is shown. The solid line represents the luminosity due to thermal bremsstrahlung between 0.2-2.1 keV. The dashed line shows the total soft X-ray luminosity with that due to bound-bound transitions. The outer and the inner average electron temperatures are also plotted as a function of $\dot{M}/V_w$.

https://doi.org/10.1017/S1539299600007814 Published online by Cambridge University Press