X–RAY EMISSION OF THE REMNANTS OF ASPHERICAL SUPERNOVA EXPLOSIONS

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Evolution of the adiabatic remnants of an aspherical supernova explosion in uniform medium is considered. Thermal X-ray emission of the remnants is investigated. It is shown that integral thermal X-ray characteristics (X-ray luminosity and spectrum) of the objects do not allow to reveal the asymmetry in the explosion of the progenitor because these characteristics are close to their Sedov counterparts. Surface distribution of the X-ray emission is sensitive to the anisotropy of the explosion and nonuniformity of interstellar medium.

INTRODUCTION

In some models of a supernova explosion the energy is realized anisotropically [1, 5]. Aspherical explosion of supernova (SN) may cause a barrel-like supernova remnant (SNR) [4]. Observations show that SN really may be aspherical, as, *e.g.*, in well-known case of SN1987A [12, 6, 7, 8]. High birth velocities of pulsars also suggest anisotropy in SN explosion [10]. In the past, the morphological evolution and instabilities of asymmetric SN explosion were investigated [3, 2, 16].

In present work we consider the properties of the thermal X-ray emission of adiabatic remnants of aspherical SN explosions. Hydrodynamics is modelled here with the approximate method for description of the adiabatic phase of a remnant of aspherical SN explosion in an arbitrary large-scale nonuniform medium [9]. Equilibrium thermal X-ray emission model is taken from [14] and approximation for the Gaunt factor from [11].

ASPHERICAL SN EXPLOSION IN A UNIFORM MEDIUM

Spherical adiabatic SNR in uniform medium is described by self-similar Sedov solutions [15] where the distributions of thermodynamic parameters are self-similar downstream: $\rho(r,t) = \rho_{\rm s} \cdot \overline{\rho}(\overline{r})$, $P(r,t) = P_{\rm s} \cdot \overline{P}(\overline{r})$, $T(r,t) = T_{\rm s} \cdot \overline{T}(\overline{r})$, where distance from the center $\overline{r}$, density $\overline{\rho}$, pressure $\overline{P}$, temperature $\overline{T}$ are normalized on the values at the shock: $R_{\rm s}$, $\rho_{\rm s}$, $P_{\rm s}$, $T_{\rm s}$.

Let us consider aspherical supernova explosion

$$E(\vartheta,\phi) = E_o\ \psi(\vartheta,\phi), \quad \text{where} \quad \int_0^{2\pi} d\phi \int_0^{\pi} \psi(\vartheta,\phi)\sin\vartheta d\vartheta = 4\pi. \tag{1}$$

As an example of aspherical energy distribution we will consider the function:

$$\psi(\vartheta,\phi) = \left(1-\frac{b}{2}\right) + b|\cos\vartheta|, \qquad 0 \le b < 2, \tag{2}$$

SNR 3C 58, which is probably on the free expansion phase of his evolution, has maximal axis ratio among known young SNRs: 1.67. So, possible anisotropy of explosion energy distribution is $E_{\max}/E_{\min} = (R_{\max}/R_{\min})^2 = 2.8$. Such anisotropy takes place for (2) if $b \approx 1$.

Let us consider uniform medium. Our hydrodynamic method works within the framework of sector approximation approach where the flows in sectors are independent. This causes essential simplification in modelling of the object. Namely, in such a case, we have only to re-normalize energy in each sector and distributions of parameters in each sectors remain to be self-similar since each sector may be described by the Sedov solution with a relevant value of explosion energy. Thus, the flow characteristics may be written as

$$\begin{aligned} &R_{\rm s}(\vartheta,\phi) = \tilde{R}_{\rm s}\ \psi(\vartheta,\phi)^{1/5}, \qquad D(\vartheta,\phi) = \tilde{D}\ \psi(\vartheta,\phi)^{1/5}, \\ &\rho_{\rm s}(\vartheta,\phi) = \rho_{\rm s}, \qquad P_{\rm s}(\vartheta,\phi) = \tilde{P}_{\rm s}\ \psi(\vartheta,\phi)^{2/5}, \qquad T_{\rm s}(\vartheta,\phi) = \tilde{T}_{\rm s}\ \psi(\vartheta,\phi)^{2/5}, \end{aligned} \tag{3}$$

where $\tilde{R}_{\rm s}$, $\tilde{D}$, $\tilde{P}_{\rm s}$, $\tilde{T}_{\rm s}$ coinside with the relevant values in case of Sedov SNR.

Luminosity of an SNR

$$L_{\rm x}=\int\limits_0^{2\pi}d\phi\int\limits_0^{\pi}\sin\vartheta d\vartheta\int\limits_0^{R_{\rm s}(\vartheta,\phi)}\Lambda(T)n_{\rm e}n_{\rm H}r^2dr, \qquad (4)$$

where emissivity $\Lambda(T)=\int\big(\Lambda_{\rm c}(T,\varepsilon)+\Lambda_{\rm l}(T,\varepsilon)\big)d\varepsilon$, subscript "c" refer to continuum and "l" to line emission, in the case of the Sedov SNR is

$$L_{\rm x}=C(\gamma,\mu)\cdot E_{51}\ n_{\rm H}\ T_{\rm s}^{-1}\cdot I_o(T_{\rm s})\quad {\rm erg/s}, \qquad (5)$$

where

$$I_o(T_{\rm s})=4\pi\int\limits_0^1\Lambda\big(T_{\rm s}\cdot\overline{T}(r)\big)\ \overline{n}^2(r)\ r^2\ dr, \qquad (6)$$

and $C=3.65\times10^{66}$ for $\gamma=5/3$, $\mu=0.609$. Thermal X-ray spectral index

$$\alpha=-\frac{\partial\ln}{\partial\ln\varepsilon}\int\limits_V\Lambda_{\rm c}(T,\epsilon)n_{\rm e}n_{\rm H}dV \qquad (7)$$

is, in the case of the Sedov SNR,

$$\alpha_o=-\frac{\partial}{\partial\ln\varepsilon}\ \ln I_{o,{\rm c}}(T_{\rm s}), \qquad (8)$$

where

$$I_{o,{\rm c}}(T_{\rm s})=\int\limits_0^1\Lambda_{\rm c}\big(T_{\rm s}\cdot\overline{T}(r)\big)\ \overline{n}^2(r)\ r^2\ dr. \qquad (9)$$

Luminosity of the remnant of aspherical supernova explosion $E(\vartheta,\phi)=E_o\ \psi(\vartheta,\phi)$ in uniform medium is

$$L_{\rm x}=C(\gamma,\mu)\cdot E_{51}\ n_{\rm H}\ \tilde{T}_{\rm s}^{-1}\cdot I(\tilde{T}_{\rm s})\quad {\rm erg/s}, \qquad (10)$$

where the integral

$$I(\tilde{T}_{\rm s})=\int\limits_0^{2\pi}d\phi\int\limits_0^{\pi}\psi(\vartheta,\phi)^{3/5}\ \sin\vartheta d\vartheta\int\limits_0^1\Lambda(\tilde{T}_{\rm s}\ \psi(\vartheta,\phi)^{2/5}\ \overline{T}(r))\ \overline{n}^2(r)\ r^2\ dr. \qquad (11)$$

Thermal X-ray spectral index of such SNR is

$$\alpha=-\frac{\partial}{\partial\ln\varepsilon}\ \ln I_c(\tilde{T}_{\rm s}), \qquad (12)$$

where $I_c(\tilde{T}_{\rm s})$ is the same integral as (11) with Λ_c instead of Λ. In general case, the temperature $\tilde{T}_{\rm s}$ in (10)–(12) is a characteristic parameter, the value of $\tilde{T}_{\rm s}$ coincides with real temperature $T_{\rm s}$ on the shock front in the case of Sedov SNR.

Since volume, mass and effective temperature of a remnant of aspherical SN explosion differ from spherical SNR within 1% only [13], we may expect that luminosity L_x and spectral index α of such SNR will be close to their Sedov counterparts because these characteristics essentially depend on emission measure $EM\simeq n_{\rm e}^2V\simeq M^2V^{-1}$. Really, Fig. 1a shows integrals $I_o(T_{\rm s})$ and $I(\tilde{T}_{\rm s})$ and Fig. 1b demonstrates variation of thermal X-ray spectral indexes $\alpha_o(T_{\rm s})$ and $\alpha(\tilde{T}_{\rm s})$. We see that luminosity in the band $\varepsilon>0.1$ KeV has maximal differences of order 2% for $b=0.5$ and 5% for $b=1.5$; they are 2% and 17% in the band $\varepsilon>4.5$ KeV. Relative differences in spectral index are less then 1% for $b=0.5$ and 5% for $b=1.5$.

So, summarizing, we cannot distinguish the cases of spherical and aspherical supernova explosions in uniform ISM having characteristics of SNR as a whole object, because such characteristics are very close to their Sedov counterparts.

It is easy to show that surface brightness along the radius of the projection of Sedov SNR distributes as

$$S_o(x)={\rm const}\cdot E_{51}^{1/3}n_{\rm H}^{5/3}T_{\rm s}^{-1/3}\int\limits_x^1\Lambda(T_{\rm s}\overline{T}(r))\ \frac{\overline{n}^2(r)\ dr}{\sqrt{r^2-x^2}}, \qquad (13)$$

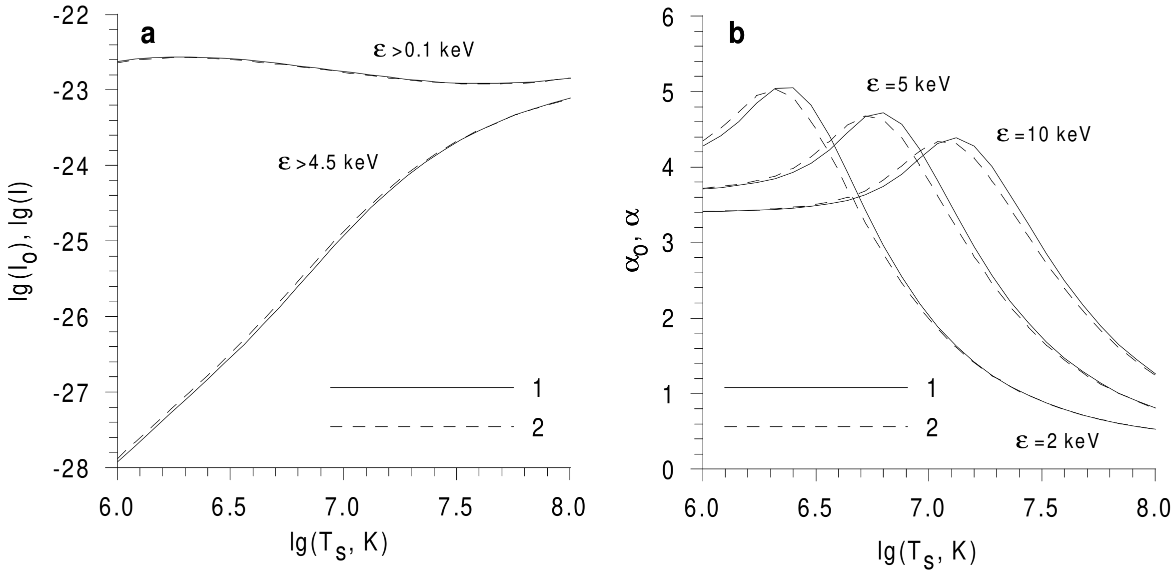

Figure 1: **a** Integrals $I_o(T_s)$ and $I(T_{ch})$ for various emission band and different distribution of supernova explosion energy. 1 – $I_o(T_s)$, 2 – $I(T_{ch})$ for $b = 1.5$. **b** Spectral indexes $\alpha_o(T_s)$ and $\alpha(T_{ch})$ at different photon energy. 1 – $\alpha_o(T_s)$, 2 – $\alpha(T_{ch})$ for $b = 1.5$

where x is the position along the SNR radius of the projection in the units of the radius ($0 \leq x \leq 1$), const $= 1.1\times10^{21}$ for $\gamma = 5/3$ and $\mu = 0.609$.

If explosion is axially-symmetrical $E(\vartheta, \phi) = E_o\psi(\vartheta)$ ($\partial E/\partial\phi = 0$) then the shape of the shock front is a circulation figure with profile $R(\vartheta) = \tilde{R}_s\psi(\vartheta)^{1/5}$. If, additionally, the symmetry axis of the distribution $\psi(\vartheta)$ lies in the plan of projection (inclination angle $\delta = 0°$), the surface brightness distribution of such an SNR is given by

$$S(x,\ z) = S_o\psi(\vartheta)^{1/5}\sin\vartheta, \tag{14}$$

where $z = R(\vartheta)\cos\vartheta$ is the coordinate along the symmetry axis of the distribution $\psi(\vartheta)$, x is the coordinate perpendicular to z in the plane of projection. This indicates that the surface brightness distribution profiles parallel to axis x are re-normalized profiles of the surface brightness distribution in Sedov SNR. This fact may be used to test the orientation of the axis-symmetrical SNRs in uniform medium. Distribution of the spectral index has a similar behaviour in case of $\delta = 0°$: profiles parallel to axis x are like to profile of the Sedov SNR when $\delta = 0°$. Cases $\delta \neq 0°$ are considered in [13].

Evolution of an adiabatic remnant of aspherical SN explosion in nonuniform medium is investigated in a further paper [13] where integral characteristics as well as spatial distributions of thermal X-ray and synchrotron emission are considered.

CONCLUSIONS

The aspherical supernova explosion causes only small differences in thermal X-ray luminosity and spectral index of adiabatic SNR comparing to a spherical explosion case. Such a behaviour takes place in different X-ray bands and for a spectral index at different frequencies in X-rays. Thus, the thermal X-ray spectrum of a remnant of aspherical explosion is close to the spectrum of Sedov SNR.

These facts do not allow us to distinguish between the cases of spherical and aspherical SN explosion, if we consider only the integral characteristics of X-ray emission of an adiabatic SNR.

X-ray properties of an SNR essentially depend on features of a disturbed plasma flow behind the shock because the emission depend on density squared and temperature on velocity squared. Therefore, surface distributions of the X-ray emission characteristics are a sensitive test on the conditions in which the object evolves. Asphericity of explosion reveals in the surface distributions of thermal X-ray characteristics. In the case of an axially-symmetrical explosion in uniform medium and when the axis of symmetry lies in the plan of projection, the profiles of X-ray surface brightness and spectral index along the lines perpendicular to the axis are re-normalized profiles of relevant distributions of the Sedov SNR.

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