The new possibility to explain the nature of the thermal X-ray composites (TXCs) as projection effect of 2- or 3-dimensional shell-like supernova remnants (SNRs) evolved in a nonuniform medium is proposed. X-ray and radio morphologies as well as basic theoretical features of such an SNR and surrounding medium are considered. It is shown that the theoretical properties of the shell-like SNR evolved at the edge of molecular cloud with gradient of ambient density along the line of sight correspond to observed properties of TXCs very well. So, at least a part of the objects from the class may be interpreted in the frame of the considered effect.

1 Introduction

Observations show that supernova remnants (SNRs) have an anisotropic distribution of surface brightness (Seward [1990]; Whiteoak & Green [1996]). There are four morphological classes of SNRs: shell-like, Crab-like (or plerionic), composite and thermal X-ray composites (TXCs) (or mixed-morphology, or centrally-influenced) (Jones et al. [1998]; Rho & Petre [1998], hereafter RP98). In past few years considerable interest rises to TXCs (e.g., Jones et al. [1998]; Cox et al. [1999]; Shelton et al. [1999]; Sun et al. [1999]). This is an SNR with the centrally concentrated thermal X-ray and limb brightened radio morphologies. Remnants W44, W28, 3C 400.2, Kes 27, 3C 391, CTB 1, MSH 11-61A and other represent the mixed-morphology class. RP98 introducing the class note that circumstances for creating the thermal X-ray centrally filled SNRs are not generally rare because the quantity of these SNRs is about 25% of the remnants detected in X-rays.

Two physical pictures are presented to explain the TXC (see RP98 for a review). One of them is enhanced interior X-ray emission from the evaporated material of numerous swept-up clouds which increase the density in the central region of SNR. This model is frequently used; sometimes its application is intrinsically inconsistent, e.g., as in MSH 11-61A where evaporation timescales exceed the age of SNR in 50-100 times (Jones et al. [1998]). In the second proposition the shock temperature are small due to essential cooling; very soft emission of the shell are absorbed in ISM and interior region only remains visible. In this model, thermal conduction may level the temperature profiles and increase the central density altering the interior structure (Cox et al. [1999]).

Mentioned models are used to obtain the centrally filled morphology in the frame of one-dimensional (1-D) hydrodynamical models. It is interesting that a simple projection effect may cause the shell-like SNR to fall into the another morphology class, namely, centrally influenced (Hnatyk & Petruk [1999]). The main feature of such an SNR is thermal X-ray emission emitted from the swept-up gas and peaked in the central part of the projection. So, getting out of one
dimension, we obtain the new possibility to try to explain the nature of TXC. Such a possibility is considered in this work.

SNRs are modelled with the hydrodynamic method for the description of an asymmetrical point explosion in an arbitrary large-scale nonuniform medium (Hnatyk & Petruk [1999]). Equilibrium thermal X-ray emission is calculated with the model of Raymond & Smith ([1977]).

2 Observed properties of the thermal X-ray composites

RP98 argue that mixed-morphology SNRs create a separate morphology class since their properties distinguish these remnants from another. Analysing the X-ray data on a number of such a SNRs authors found two their prominent morphological distinctions: a) X-ray emission is thermal, distribution of the X-ray surface brightness is centrally peaked or amorphous, fills the area within the radio shell and may reveal a weak evidence of X-ray shell, b) emission arises primarily from the swept-up ISM material, not from ejecta.

It is emphasized by RP98 that, besides a similar morphology, the sample has also similar physical properties. Namely, a) the same or higher central density comparing with the edge, b) complex interior optical nebulosity as in W28 and probably in 3C 400.2 (Long et al. [1991]); c) higher emission measure $n_e^2 l$ ($n_e$ is the electron number density, $l$ is length) in the central region as, e.g., in 3C 391 (Rho & Petre [1996]); d) X-ray surface brightness in the central region ($r < 0.2R_s$, $R_s$ is the average radius of the projection), in general, exceeds brightness near the edge ($r > 0.6R_s$) in 2-5 times, e) temperature profiles are close to uniform. Concerning the last properties, it is necessary to note that temperature may decrease toward the centre, as in 3C 391 (Rho & Petre [1996]); no strong evidences about increasing the temperature toward the centre are found for all TXCs but Cox et al. ([1999]) noted that the spectral hardness in W44 is greater in the centre, so temperature might nevertheless be higher in this region. Possible variation of temperature may be within the factor about 2 as, e.g., in the case of W44 (Rho et al. [1994]; Cox et al. [1999]) or in W28 (Long et al. [1991]).

7 objects from the list of 11 TXCs reveal the observational evidences about the interaction with the molecular clouds (RP98). So, ambient media in the regions of their localisation are nonuniform and lend to nonsphericity of the SNRs. There are evidences of cloud localization on the line of sight for some of these SNRs (e.g., Rho et al. [1994]).
3 Theoretical properties of the ”projected composites”

Sedov ([1959]) model does not give a centrally concentrated morphology due to the geometrical properties of the self-similar solutions for explosion in the medium with density $\rho(r) \propto r^{-m}$, $m$ is a constant. Solutions are 1-D and give the specific internal profile of the flow density: most of mass is concentrated near the shock front. These and the cumulation of emission along the line of sight give the shell-like morphology. When we take into account more complicated nonuniform ISM, we get out from the one dimension and need to consider additional parameters responsible for the nonuniformity of the medium and orientation of a 3-D object.

Projection effects hide a real anisotropy of the shock front shape and contrasts in the surface brightness distribution of the nonspherical SNR and may essentially change the morphology of the object (Hnatyk & Petruk [1999]). Density over the surface of the nonspherical SNR may essentially differs in various regions. If ambient density distribution is enough to provide high density in one of the SNR shell region and this density exceeds the internal column density near the edge of the projection, we will see the centrally filled projection of a real shell-like SNR. Such a density distribution may be ensured, e.g., by a molecular cloud located near the SNR.

What is a real shell-like 3-D SNR? We suggest that such a remnant has an internal density profiles like to the profiles in Sedov ([1959]) solutions. So, we separate a shell-like SNR (as intrinsic property of the 3-D object) and limb brightened projection (as morphological property of the projection). Let us call in this paper shell-like SNRs with centrally filled projections ”projected composites”.

Let us consider the case of a 2-D SNR and take the basic characteristics of the SNR and surrounding medium could happen at the smoothed boundary of a molecular cloud. So, SNR evolves in the ambient medium with the hydrogen number density $n$ distributed according to the law

$$n(\tilde{r}) = n_o + n_c \exp(-\tilde{r}/h), \tag{1}$$

where $n_o$ is the density of the intercloud medium, the second term represents the density distribution into the boundary region and cloud, $h$ is the scale-height, $\tilde{r}$ is the distance from the centre of the symmetry of the density distribution. Let us take the explosion site to be at the point $\tilde{r}_o$ where $n(\tilde{r}_o) = 2n_o$. It is assumed the other parameters to be $n_o = 0.1 \text{ cm}^{-3}$, $n_c = 100 \text{ cm}^{-3}$ (such $n_c$ is taken to ensure the shock front moving toward the centre of symmetry $1$ to do not reach the centre; if this is the case, model characteristics are insensitive to the value of $n_c$). Energy of supernova explosion is $E_o = 1 \cdot 10^{51} \text{ erg}$. We consider three basic evolutionary cases of the SNR models which cover practically whole adiabatic phase (models a-c, Table 1) and then we vary parameter $h$ (models d-f), in
Table 1: Characteristics of SNRs in the media (1). \( R \) and \( D \) are the radius and velocity of the shock front, \( T_s \) and \( n_s \) are the temperature and number density of the swept-up gas on the shock front, \( L_x \) is the X-ray luminosity and \( \alpha_x \) is the spectral index of the thermal X-ray emission from whole SNR. \( T_{\text{ef}} \) is the effective temperature of the nonspherical SNR defined as \( T_{\text{ef}} \propto M^{-1} \), where \( M \) is swept-up mass (Hnatyk & Petruk [1999]). The contrasts in the distribution of the X-ray surface brightness \( S \) and spectral index \( \alpha \) are presented for the case then the angle between the plan of the sky and SNR’s axis of symmetry \( \delta = 90^\circ \). \( \alpha_{0.95} \) is value of the index at 0.95R_s.

<table>
<thead>
<tr>
<th>Parameters Model</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n_s, ; \text{pc} )</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>5</td>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>( r, ; 10^4 ; \text{yrs} )</td>
<td>1.0</td>
<td>6.8</td>
<td>17.7</td>
<td>6.8</td>
<td>6.8</td>
<td>6.8</td>
</tr>
<tr>
<td>( \log T_{\text{ef}}, ; \text{K} )</td>
<td>8</td>
<td>7</td>
<td>6.5</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>( M, ; M_\odot )</td>
<td>9.5</td>
<td>94</td>
<td>280</td>
<td>98</td>
<td>95</td>
<td>94</td>
</tr>
<tr>
<td>( R_{\text{max}}/R_{\text{min}} )</td>
<td>1.4</td>
<td>1.8</td>
<td>2.1</td>
<td>1.4</td>
<td>1.2</td>
<td>1.1</td>
</tr>
<tr>
<td>( D_{\text{max}}/D_{\text{min}} )</td>
<td>1.9</td>
<td>2.8</td>
<td>3.1</td>
<td>1.9</td>
<td>1.5</td>
<td>1.1</td>
</tr>
<tr>
<td>( T_{s, \text{max}}/T_{s, \text{min}} )</td>
<td>3.5</td>
<td>7.9</td>
<td>9.8</td>
<td>3.7</td>
<td>2.2</td>
<td>1.2</td>
</tr>
<tr>
<td>( n_{s, \text{max}}/n_{s, \text{min}} )</td>
<td>9.5</td>
<td>45</td>
<td>84</td>
<td>11</td>
<td>3.9</td>
<td>1.4</td>
</tr>
<tr>
<td>( \log L_x^{0.1} ; \text{keV} )</td>
<td>34.1</td>
<td>36.7</td>
<td>37.3</td>
<td>36.4</td>
<td>36.2</td>
<td>36.1</td>
</tr>
<tr>
<td>( \alpha_x ; \text{keV} )</td>
<td>0.98</td>
<td>3.2</td>
<td>3.1</td>
<td>3.9</td>
<td>4.1</td>
<td>4.2</td>
</tr>
<tr>
<td>( \log (S/c/S_{\text{max}}) ; 2 )</td>
<td>0.43</td>
<td>2.1</td>
<td>2.3</td>
<td>0.72</td>
<td>-0.10</td>
<td>-0.54</td>
</tr>
<tr>
<td>( \alpha_{0.95}/\alpha_c )</td>
<td>1.6</td>
<td>1.8</td>
<td>3.6</td>
<td>1.3</td>
<td>1.2</td>
<td>1.3</td>
</tr>
</tbody>
</table>

order to see how gradient of ambient density affects the X-ray characteristic of the SNRs.

In general, model for synchrotron emission from SNRs is not wholly clear (Reynolds [1998], hereafter R98). However, a simple estimation on the radio morphology of SNR in nonuniform medium is possible. Volume emissivity in radio band \( S_{\nu} \propto KB^{s+1/2} \), \( K \) is the the normalization of electron distribution \( N(E)dE = KE^{-s}dE \), \( B_\perp \) is tangential component of magnetic field (relative to electron velocity or normal to the shock). Power \( s \) is constant downstream and over the surface of SNR because of strong shock. Ambient field is assumed to be uniform, so, \( B_\parallel \) and \( B_\perp \) rise everywhere in a shock by factors of 1 and \( \rho_s/\rho_o^s = 4 \) (for \( \gamma = 5/3 \); index ”s” refers to values at the shock and ”o” to surrounding medium; no further amplification is assumed) and evolve differently behind the shock front (Reynolds & Chevalier [1981]; R98). Since magnetic field is flux-frozen \( B_\parallel(r)rdr = \text{const} \), the tangential component in each 1-D sector of 2-D disturbed region is \( B_\perp(r) = B_\perp(a)(\rho(r)/\rho(a))(r/a) \), where \( a \) is the Lagrangian coordinate. Radial component \( B_\parallel(r) = B_\parallel(a)(a/r)^2 \) due to
Figure 1: **a-d.** Distribution of the thermal X-ray surface brightness $S$ (erg s$^{-1}$ cm$^{-2}$ st$^{-1}$) for photon energy $\varepsilon > 0.1$ keV (**a**, **b**), and radio surface brightness $S_\nu$ at some frequency in relative units (**c**, **d**). SNR model is b. X-rays: $\log S_{\text{max}} = -3.1$, logarithmic interval $\Delta \log S = 0.3$ and $\delta = 0^\circ$ (**a**) or $\delta = 90^\circ$ (**b**). Radio: $s = 2$, $\delta = 90^\circ$ and $c \phi = 0^\circ$, $\log (S_\nu^{\text{max}}/S_\nu^{\text{min}}) = 2.7$, $\Delta \log S_\nu = 0.3$; d $\phi = 90^\circ$, $\log (S_\nu^{\text{max}}/S_\nu^{\text{min}}) = 1.3$, $\Delta \log S_\nu = 0.1$.

magnetic flux conservation $B_\parallel d\sigma = \text{const}$. Energy density $\omega$ of relativistic particles in each fluid element is proportional to the energy density of magnetic field

$$\omega \equiv \int_{E_{\text{min}}}^{E_{\text{max}}} EN(E) dE = K \int_{E_{\text{min}}}^{E_{\text{max}}} E^{1-s} dE \propto B^2,$$

that yields $K \propto B^2 \left(E_{\text{max}}^{2-s} - E_{\text{min}}^{2-s}\right)^{-1}$. We have to expect the variation of $E_{\text{max}}$ and $E_{\text{min}}$ over the surface of nonspherical SNR and downstream. However, maximum energy to which particles can be accelerated varies only in few times during whole adiabatic phase (R98). ISM nonuniformity does not affect the evolution of SNR on the free expansion stage. So, as the first approach, we assume that no variation of $E_{\text{max}}$ and $E_{\text{min}}$ is caused by the nonuniform medium and both energies are constant over the surface$^1$. Individual electron energy

$^1$Since $\omega_s \propto P_s$ (Reynolds & Chevalier [1981]) and shock velocity $D \propto (\rho_s R^3)^{-1/2}$ in
losses due to adiabatic expansion are $\dot{E} = E \dot{\alpha}/3\alpha$, where $\alpha(r) = \rho(r)/\rho_s$ (R98), and therefore $E(r) \propto \alpha(r)^{1/3}$. Thus, $K(r) \propto B(r)^2 \alpha(r)^{(s-2)/3}$. Radio morphology depends also on the aspect angle $\phi$ between the line of sight and ambient magnetic field (R98) as well as on the inclination angle $\delta$.

Fig. 1 demonstrates the influence of the projection on the observed X-ray morphology of SNR. Radio images are also presented for $\phi = 0^\circ$ and $\phi = 90^\circ$. (It is interesting that radio limb brightened morphology is most prominent for $\phi = 0^\circ$ and radio surface brightness is uniform within $\Delta \log S_v = 0.2$ under $\phi = 90^\circ$.) So, morphological properties match the basic features of TXC class: centrally peaked distribution of the thermal X-ray surface brightness within the area of radio shell; emission raises from the swept-up ISM material.

Concerning the physical properties. a) Column number density increases from the edge toward the centre of the projection (e.g., for model b from $10^{18.9}$ cm$^{-2}$ to $10^{19.4}$ cm$^{-2}$). b) Diffuse optical nebulosity over the internal region of the projection may naturally have place in such a model. c) Emission measure in X-ray peak is highest because both $n_e$ and $\ell$ are maximal there.

As Fig. 2 demonstrates, the distribution of the X-ray surface brightness has a strong maximum $S_c$ around the centre and slighter shell with a second maximum $S_{\text{max}, 2}$. Essentially, that such a morphology is in different X-ray bands (lines 2, 4, 5). Contrasts in X-ray surface brightness $S_c/S_{\text{max}, 2}$ may lie within a wide range, as in our models do from 3 to 250 (Table 1). X-ray flux from the centre normal medium (Hnatyk [1988]), possible variation of $\omega_b \propto R^{-3}$ lies within the factors 3 to 9 for models a-c.
region $R < 0.2R_s$ exceeds flux out of $R > 0.6R_s$ in 0.16, 5.4 and 16 times in models a, b and c respectively. Thus, observational property d of TXCs have place just in the adiabatic stage.

Surface distribution of the spectral index $\alpha$ of the thermal X-ray emission gives us the profiles of effective temperature $T$ of the column of emitting gas ($\alpha \propto T^{-1}$ then Gaunt factor is assumed to be constant). Fig. 2 shows that the temperature may as increases as decreases toward the centre. Decreasing have place early in the adiabatic phase. Variation of the index lies within the factor 1.6 to 3.6 during the adiabatic stage (Table 1), contrast increases with the age. Such a values correlates to the possible diapason of variation of the temperature over the projection of the thermal X-ray composites.

In order to reveal the dependence of the distributions of $S$ and $\alpha$ on the density gradient of ISM a number of models with different $h$ were calculated (Fig. 3 and Table 1). Surface brightness distribution has stronger peak for stronger gradient. With increasing $h$, outer shell becomes more prominent in the projection. Only a scale-height of order $h < 10$ pc could cause a "projected composites". Less strong gradient of ambient density makes temperature $T$ more uniformly distributed in the internal region of projection. Decreasing the temperature toward the central X-ray peak does not happened with variation of $h$; character of temperature distribution depends mainly on the age of the object.

In addition, the distinctions of the physical models for TXC in comparison with the projection model are noted below. 1) Strong cooling have place in the radiative SNR, not in adiabatic. 2) Thermal conduction makes a spectrum of the central region softer due to reducing the temperature (Jones et al. [1998]). 3) Thermal conduction or evaporation model increase the density in the central region of the SNR. Projection model does not require modification of the internal density distribution; these profiles are like to those in the Sedov (1959) solution. 4) Small-scale inhomogeneous ISM is required for the model with evaporation. Projected composites are a consequence of a large-scale nonuniformity of the ISM with scale-height of order $< 10$ pc. 5) Other possibilities to create a centrally filled morphology, as differential absorption\(^2\) or emission from an ejecta, modify specifically the spectra of the object.

### 4 Conclusions

Considering the 2-D or 3-D models of SNRs it is necessary to take into consideration the effects of projection. When ambient density gradient is oriented close to the line of sight and is enough strong, then the visible X-ray morphology of SNR will be centrally filled while radio morphology will remains limb

\(^2\)Long et al. (1991) conclude that a centrally peaked X-ray morphology within a radio shell is unlikely a result of the absorption alone because the distributions of the X-ray and radio emitting plasmas have to be different in this case.
Figure 3: **a and b.** Distribution of the thermal X-ray **a** surface brightness $S$ for $\varepsilon > 0.1$ keV and **b** spectral index $\alpha$ at 5 keV. 1 – model b, 2 – model d, 3 – model e, 4 – model f.

brightened. All observational properties of the thermal X-ray composites coincide with the theoretical properties of the ”projected composites”. Considered sets of parameters of ”projected composites” and ISM are not exclusive among the possible. Thus, circumstances when such an SNR will project as a centrally filled X-ray object have to have place. Majority of the members of the mixed-morphology class is really located near the molecular clouds. So, at least a part of them may be a real result of a simple projection effect of the adiabatic SNR evolved in the nonuniform medium, e.g., at the edge of a molecular cloud.

References