The H-R diagram for supernova remnants

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Abstract. This paper introduces a sort of "H-R diagram" i.e. $L_{\mathrm{X}}-kT$ diagram for supernova remnants (SNRs). Although the example given in this paper is only illustrative and the models discussed too simplistic, further investigation of this topic may hold some promise for better understanding of the evolution of SNRs.
Key words: ISM: supernova remnants; X-rays: ISM; methods: statistical.

Introduction

Supernovae (SNe) are probably the strongest explosions in the universe which mark the endpoint of life for some stars. They release about $E_o \approx 10^{51}$ ergs in the form of kinetic (and thermal) energy. While supernova events happen quite suddenly and last for a relatively short time, in astronomical standards, supernova remnants (SNRs) – the material ejected in an explosion continues its life in the interstellar medium (ISM) for thousands, and in extreme cases even for a million years.

Supernova remnants are generally characterized by the interaction of supernova ejecta with the surrounding ISM. In some cases the ejected material primarily interacts with the dense circumstellar medium in the vicinity of the star, during the phase known as the radio supernova (see e.g. Weiler & Sramek 1988). The main features of SNRs are strong shock waves, amplified magnetic field, ultra-relativistic particle (cosmic rays) acceleration and associated synchrotron radiation. Synchrotron radiation is dominant at radio frequencies so the most of SNRs are identified in radio domain (for Galactic SNRs check Green's catalogue (Green 2009), while for extragalactic SNRs see e.g. Urošević et al. 2005).

However, due to the increasing number of space observatories in recent decades (ROSAT, ASCA, Chandra, XMM-Newton), many SNRs have been observed in X-rays as well. A large number of SNRs emit "soft" X-rays ($\lesssim 10$ keV) thermal *bremsstrahlung* radiation (free-free emission). Older remnants evolving in dense environment (with hydrogen number density $n_{\mathrm{H}} \sim 300$ cm^{-3}) may also emit thermal bremsstrahlung in radio domain (Urošević & Pannuti 2005). On the other hand, there are considerable efforts nowadays in detecting and analyzing non-thermal X-rays in younger remnants (see an excellent review by Vink 2012).[1] Morphologically, SNRs in X-rays resemble their radio counterparts and have a visible emitting shell. There is, however, a special class of SNRs, not completely understood, the so-called *mixed-morphology* SNRs with a radio shell with flat radio spectra and thermal X-rays emitting interior (see Onić 2013).

[1] Non-thermal X-rays are likely synchrotron or non-thermal bremsstrahlung emission (see Zeković et al. 2013), while thermal emission may be bremsstrahlung, recombination continuum (free-bound emission), and two-photon emission (Vink 2012).

Relation of SNRs to their SNe is not easily established, especially for remnants in the adiabatic or Sedov (1959) phase (and later phases) when the mass of ejecta is much less than the mass of the swept-up ISM. Mathewson et al. (1983) classified SNRs into four categories based on their optical features: Balmer-dominated (B), oxygen-rich (O), plerionic/composite, and evolved SNRs. It has been suggested by van den Bergh (1988) that Balmer-dominated SNRs are connected to type Ia SNe – deflagration of a CO white dwarf, and are remnants with high velocity, nonradiative, collisionless shock interacting with ISM, while oxygen-rich SNRs originate in the type Ib/c event – explosion following the core-collapse of a massive star stripped of their H/He envelope, if isolated progenitor scenario is correct (Arbutina 2007).

X-ray emission lines diagnostics has been a valuable tool in performing this task. In the following section we will discuss the relation between X-ray luminosity $L_{\rm X}$ and electron temperature (or kT) – a sort of "H-R diagram" for SNRs, that may also provide some insight into SNRs properties and progenitors.

1. Analysis and results

Volume emissivity of thermal bremsstrahlung is given by (Shu 1991):

$$\varepsilon_\nu = \sum_i n(Z_i) n_{\rm e} \Big(\frac{2m_e}{3\pi kT}\Big)^{1/2} \Big(\frac{32\pi^2 Z_i^2 e^6}{3m_e^2 c^3}\Big) \bar{g}_\nu e^{-h\nu/kT} \tag{1}$$

The above formula includes contributions to emission from all ions with charge number Z_i and number density $n(Z_i)$. $n_{\rm e}$ is electron number density, $m_{\rm e}$ electron mass and c speed of light. Gaunt factor $\bar{g}_\nu \lesssim 1$ introduces quantum mechanical correction.

In radio domain $\bar{g}_\nu \propto \nu^{-0.1}$ and since $h\nu \ll kT$ for radio luminosity of a source at given frequency we have $L_\nu = 4\pi d^2 S_\nu = \int \varepsilon_\nu {\rm d}V \propto \nu^{-\alpha} \propto \nu^{-0.1}$, where S_ν is flux density, d is the distance and V the volume of a source. Spectral index $\alpha = 0.1$ at lower frequencies is characteristic for HII regions if medium is optically thin.

In X-rays $e^{-h\nu/kT} \neq 1$ (Shu 1991) so we must keep the whole term in equation (1). For total (frequency integrated) luminosity here we approximately have

$$L = \int_{\nu_L}^{\infty} L_\nu {\rm d}\nu \propto n_{\rm H} n_{\rm e} (kT)^{1/2} e^{-E_L/kT} V, \tag{2}$$

where $E_{\rm L} = h\nu_L$ is lower energy limit for the detector. Nevertheless, significant part of thermal emission also comes from emission lines.

Let us consider "total" X-ray luminosity of a SNR in more detail. According to Magnier et al. (1997) equation (2) can be written as:

$$L_{\rm X} = \bar{\Lambda} n_o^2 \bar{V}, \tag{3}$$

where $\bar{V} = f\pi D^3/6$ is effective volume of an SNR in units cm^3, f is the volume filling factor, n_o [cm^{-3}] number density of the surrounding ISM and

Table 1. X-ray data for supernova remnants in Large (LMC) and Small Magelanic Cloud, taken from Hughes et al. (1998) and van der Heyden et al. (2004).

Name	Other name	Temperature kT [keV]^a	Luminosity L_{X} [10^{36} erg/s]^{a,c}	Diameter D [pc]^b	SNR Type
LMC 0453-68.5		0.51	0.98	30	
LMC 0505-67.9	DEM L71	0.82	3.4	21	B
LMC 0506-68.0	N 23	0.53	2.5	13	
LMC 0525-66.0	N 49B	0.41	3.2	34	
LMC 0525-66.1	N 49	0.58	6.3	16	
LMC 0525-69.6	N 132D	0.68	30	24	O
LMC 0535-66.0	N 63A	0.62	20	17	
SMC 0044-73.4	DEM S32	1.29	0.16	40	
SMC 0045-73.4	IKT 2	0.39	0.2	19	
SMC 0046-73.4	HFPK 419	0.28	0.57	26	
SMC 0046-73.5	IKT 4	3.50	0.18	24	
SMC 0047-73.5	IKT 5	0.71	0.096	34	Ia
SMC 0049-73.6	IKT 6	0.54	0.66	43	Ib/c (II)
SMC 0056-72.5	IKT 16	1.76	0.39	58	
SMC 0057-72.2	IKT 18	0.51	0.39	46	
SMC 0101-72.4	IKT 21	0.58	0.58	18	
SMC 0102-72.3	IKT 22	0.78	13	14	O
SMC 0103-72.6	IKT 23	0.68	1.5	58	O
SMC 0103-72.4	DEM S128	0.61	0.078	36	Ia
SMC 0104-72.3	IKT 25	0.60	0.45	32	Ia

[a]Data for IKT 4, 5, 6, 21, 23, 25 and DEM S128 are obtained from non-dynamical model, while for the rest of SNRs Sedov dynamical model was applied.
[b]Measured X-ray diameters.
[c]Luminosities L_{X} for LMC SNRs are for energy range 0.5–5 keV, while for SMC SNRs they are for 0.5–2 keV range. The difference is not that important, for this initial study, because of the exponential tail of spectral energy distribution.

$\bar{\Lambda}$ is a function of temperature:

$$\bar{\Lambda}(T) = 3(kT)^{1/2} e^{-E_{\mathrm{L}}/kT}, \tag{4}$$

in units 10^{-23} erg s^{-1} cm^3. Temperature kT is given in keV. Line emission is included with correction $\log\bar{\Lambda} \rightarrow \log\bar{\Lambda} + \Delta\log\bar{\Lambda}$, where

$$\Delta\log\bar{\Lambda} = -\frac{0.2 n_o}{1 + 1.5(\log kT - 0.5)^2} \tag{5}$$

The last expression is an analytical approximation to numerical model that calculates the contribution of emission lines of an SNR in adiabatic phase, with explosion energy in units 10^{51} ergs, $E_{51} = 1$. Temperature behind the blast wave is given by (Shu 1992)

$$kT = \bar{\mu} m_{\mathrm{H}}\ p/\rho = 3/16\ \bar{\mu} m_{\mathrm{H}} v^2, \tag{6}$$

from which, by using Sedov solution, one finds $D^3 = 4900 E_{51} n_o^{-1} (kT)^{-1}$ [pc^3]. In equation (6), p and ρ are the pressure and the density behind the shock, v

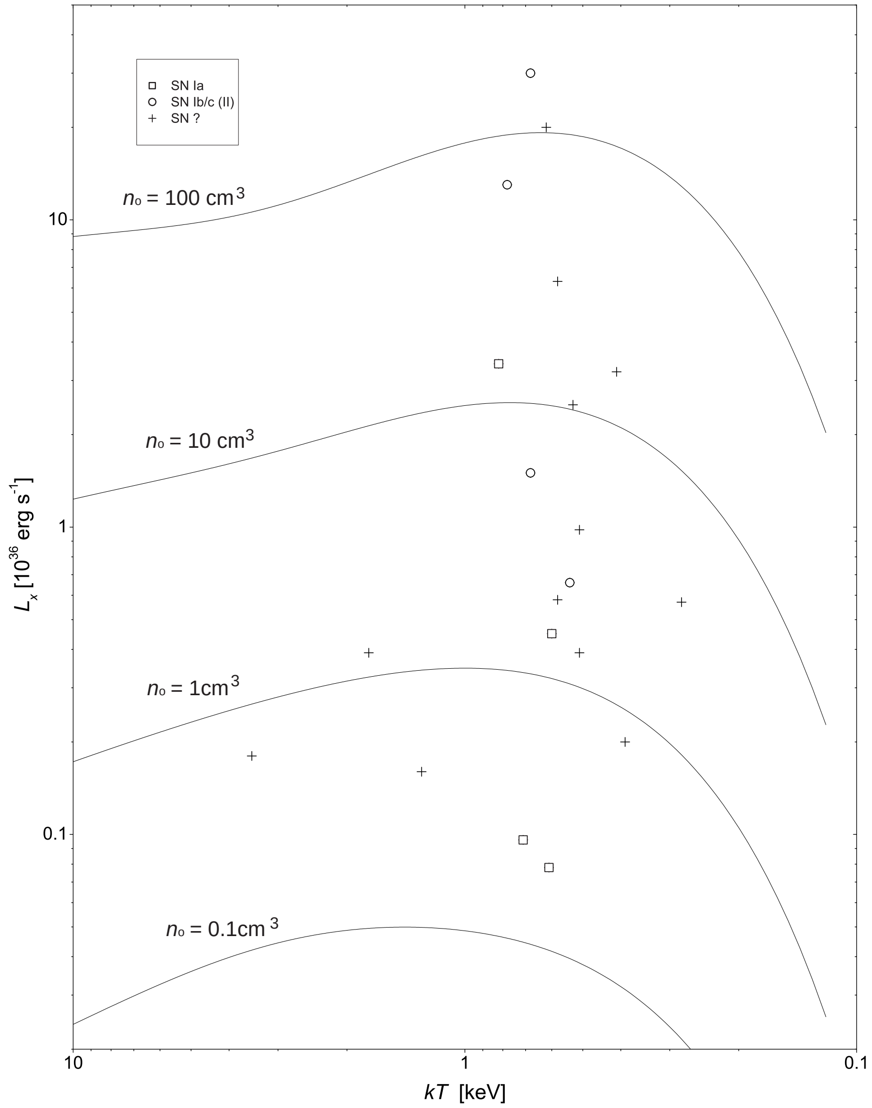

Fig. 1. $L_\mathrm{X} - kT$ diagram, i.e. a sort of "H-R diagram" for supernova remnants.

is shock velocity, m_H is the atomic mass unit and $\bar{\mu}$ mean molecular weight. By combining the last equation with the previous two we finally obtain

$$L_\mathrm{X} \propto f\ \delta\bar{\Lambda}\ n_o (kT)^{-1/2} e^{-E_\mathrm{L}/kT}, \tag{7}$$

where $\delta\bar{\Lambda}(T, n_o) = 10^{\Delta \log \bar{\Lambda}}$.

If we measure X-ray luminosities and electron temperatures, we can construct a sort of "H-R diagram" for SNRs and compare the distribution of remnants on the plot with assumed evolutionary tracks. These data from X-ray studies of SNRs in Large (Hughes et al. 1998, Nishiuchi 2001) and Small Magelanic Cloud (van der Heyden et al. 2004) are given in Table 1. We have chosen LMC and SMC SNRs, rather than Galactic, because we can assume that all SNRs in LMC and in SMC are practically at the same distance (equal to the LMC i.e. SMC distance).

Figure 1 represents H–R, i.e. $L_{\rm X} - kT$ diagram for supernova remnants. Besides different types of SNRs, figure also shows evolutionary tracks of decreasing temperature for given densities, for the simplified model (7) assuming $E_{51} = 1$, $f = 0.25$ (which are the typical values for SNRs) and $E_{\rm L} = 0.5$ keV.

2. Discussion and conclusions

As in the case of the so-called $\Sigma - D$ (surface brightness to diameter) relation in radio domain (Arbutina et al. 2004), one can see a considerable scatter of data in Fig. 1. Given the spectral and spatial resolution of X-ray observations and fitting procedures, the data points may be pretty uncertain. Also, it is not by any way certain that all remnants emit thermal rather than non-thermal radiation, or perhaps a combination of the two.

The model itself is also too simple. Concerning the model parameters, we have neglected variation in energy, the filling factor f may be larger, etc. But more importantly, electron temperature is not expected to be equal to ion temperature, the plasma in SNRs is far from equilibrium - one usually considers non-ionization equlibrium (NEI) models and their modifications. All SNRs may not be (and most probably are not) in the Sedov phase. For some remnants we may also observe emission coming from the ejecta.

Despite all these shortcomings, one can notice on H-R diagram in Fig. 1 that for the same temperature, known SN Ia remnants, on average have smaller luminosity than SN Ib/c (II) remnants, probably as a consequence of the fact that they evolve in a less dense environment. Namely, we know from stellar evolution theory that massive stars mainly occur and remain in denser environment owing to their shorter lifetimes, where the longer-lived lower-mass stars have enough time to abandon their birthplace and explode as SN Ia in low density environment. The situation thus may resemble that with the $\Sigma - D$ relation in radio (Arbutina & Urošević 2005). Based on the above, we can speculate that three remnants with low luminosity and $kT > 1$ keV, IKT 4, 16 and DEM S32, may be SN Ia candidates. Of course, each object needs to be checked individually. IKT 16 is associated with a compact source (which may also be a background/foreground object). Owen et al. (2011) suggest that the X-ray and radio properties of this source strongly favour a pulsar wind nebula (PWN) origin in which case IKT 16 can not be SN Ia remnant and could be massive star explosion inside a wind blown bubble.

Example of H–R diagram given in this paper is only illustrative, as something that should be worked on in the future. However, even in this simple picture, it seems to emphasize the importance of environment density and the environment itself for the evolution of different types of SNRs (Arbutina 2005).

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