Stellar spectroscopy methods for study of supernova remnants

Yu. V. Pakhomov[1], *N. N. Chugai*[1], *A. F. Iyudin*[2]

[1]Institute of Astronomy of RAS, 119017 Pyatnitskaya st. 48, Moscow, Russia
[2]Skobeltsyn Institute of Nuclear Physics, Moscow State University, 119991 Vorobevy gory, GSP-1, Moscow, Russia
`pakhomov@inasan.ru`

We present the method for study of the characteristics of the supernova remnants using their absorption properties. The background radiation sources are several stars with wide range of distances. Main task is accurate extraction of stellar spectra from observations. For Vela Jr. supernova remnant we found the absence of typical broad absorption in the spectral lines of Ca II doublet. Using modeles of supernovae remnants and data on radiation in ^{44}Ti γ-ray line we estimated the age and the distance to Vela Jr. We showed that a hypernova may be a probable candidate for Vela Jr. protogenitor.

Introduction

Most of the information about supernovae remnants (SNR) comes from UV, X-ray and γ-ray radiation, that is avalable for observations only from space. In optical light we can see the interaction of shock wave with interstellar clouds, but the main part of SNR is invisible. However, physical conditions inside SNR provide appearance of the absorption lines. These lines should be broadened due to high velocities of the SNR expansion. Study of such lines give us an information about physical characteristics of SNR. And presence or absence of these lines in stellar spectra can be used for estimation of the distance to SNR.

We used this method for study of the very young SNR — Vela Jr. This SNR is invisible in optical light and was discovered in 1998 by Aschenbach [1] in hard X-ray and Iyudin [4] in 1.16 MeV γ-ray line ^{44}Ti.

The method

The method consists of the following steps: selection of the stars with wide range of distances on the background of SNR; spectral observations of these stars; processing of the spectra; determination of stellar parameters (effective temperature T_{eff}, gravity log g, rotation velocity $v \sin i$); estimation of the interstellar reddening and distances to the stars; extraction of the interstellar spectra; searching for the broad absorption lines in interstellar spectra; estimation of the distances to SNR and its physical characteristics.

The spectra were obtained on the ESO 3.6-m telescope NTT (program 080.D-0012(A) PI: A. F. Iyudin) using the spectrograph EMMI in blue middle dispersion mode. The dispersion is 0.15Å/pix, the resolving power is $\lambda/\Delta\lambda = 9000$. The signal-to-noise ratio is between 90 and 350. For each star there are two overlapped spectra in the range of 3740–4021 Å. This spectral region encompasses resonance spectral lines of Fe I (3860 Å) and Ca II (3933 Å, 3968 Å).

Preliminary processing of the spectral CCD images were made with EMMI original `emmi_quickred` script for `MIDAS` software; the atmosphere and interstellar extinction were taken into account for each individual star. The spectra are flux calibrated with the help of spectra of the standard star HD 60753 obtained during the same set of observations. The derived response function was used to produce flux calibrated stellar spectra.

Results and conclusions

The stellar parameters were estimated using the method of the stellar athmospheres moddeling and found by fitting the synthesized profiles to six Balmer lines (H7–H12). The spectra were synthesized applying `Kurucz ATLAS9` code [5] and `SynthVb` package [7]. Obtained parameters are presented in Table 1. Interstellar reddening was calculated using observed and normal color indexes $(B-V)_0$ [3] which were estimated using stellar parameters.

Table 1: Parameters of the stars and distances calculated by spectral method and from Hipparcos parallaxes

Star	T_{eff} (K)	log g	$V \sin i$ (km s^{-1})	$(B-V)_0$ (mag)	A_V (mag)	M ($M_\odot$)	d_{sp} (pc)	d_{HIP} (pc)
HD75309	26500±400	3.60±0.10	210	-0.25	0.8	16	1900±300	
HD75820	11400±200	4.00±0.10	200	-0.10	0.2	3.2	470±100	505±184
HD75873	8900±200	2.50±0.05	15	0.01	1.2	6	1400±200	
HD75955	10400±200	3.85±0.10	190	-0.07	0.2	3.0	320± 70	262± 35
HD75968	12250±150	3.86±0.05	80	-0.11	0.0	3.8	570±140	719±254
HD76060	13400±200	4.10±0.10	240	-0.13	0.1	3.6	390± 90	335± 63
HD76589	11800±200	4.10±0.10	95	-0.10	0.1	3.2	390± 90	240± 76
HD76649	13300±150	3.65±0.05	33	-0.13	0.8	4.5	640±110	
HD76744	10500±200	4.20±0.10	150	-0.08	0.5	2.4	270± 50	
CD-454590	22400±400	3.60±0.10	140	-0.22	1.3	11	2400±300	
CD-454606	29500±500	3.80±0.10	240	-0.27	2.0	17	1670±160	
CD-454645	8400±200	4.35±0.10	80	0.08	0.4	1.8	330± 70	
CD-454676	29000±500	3.70±0.10	125	-0.27	3.2	18	1080±150	
CD-464666	10500±200	2.05±0.05	30	-0.08	2.1	12	5700±500	

To determine the distances we used a modified method of spectral parallaxes in which the stellar luminosity is derived from stellar evolutionary tracks as follows. Using stellar parameters (T_{eff} and log g) and evolutionary tracks [6] we estimate the stellar mass and thus derive the bolometric luminosity. The absolute magnitude M_V is then determined using the bolometric correction. The distance was determined from formula:

$$\log d_{sp} = 0.2\,[\{4.69 - 2.5\,(-10.607 + \log{(M/M_\odot)} + 4\log\,T_{eff} - \log\,g) - BC_V\} - m_V - 5 + A_V]\,, \quad (1)$$

where BC_V is the bolometric correction, A_V is the interstellar absorption in V Johnson band and m_V is the apparent magnitude in V Johnson band.

Excluding modelled stellar spectra from observation gives the residual spectrum:

$$r = \frac{C(\lambda)\cdot F_l^{obs} - F_l^{syn}}{F_c^{syn}}, \quad (2)$$

where r is the relative residual spectrum, F_c^{syn} and F_l^{syn} are the flux in continuum and in lines of the synthetic spectrum, F_l^{obs} is the flux in lines of the observed spectrum, and $C(\lambda)$ is the smooth fitting factor which is defined as linear approximation of the ratio of synthetic to observed spectrum F_l^{syn}/F_l^{obs}.

The relative residual spectra for all the stars are shown in Fig. 1. Also 3σ levels (equals to 1.5–4 %) are indicated for each star. The spectra do not reveal broad absorption resonance lines of Ca II 3933 Å, 3968 Å or Fe I 3860 Å. Specifically, the relative depth of the broad Ca II absorption (if any) produced by Vela Jr. is less than 0.04 at the level of 3σ. Note, that weak absorption features at 3819 Å and 4009 Å in the hottest stars of our sample are related to helium which generally shows non-local thermodynamic equilibrium excitation effects and cannot be modelled reliably within the LTE approximation.

With the exception of two stars (HD 75873 and CD-454645) all the spectra show narrow unresolved interstellar Ca II lines. The interstellar absorptions can be divided into two major groups: low-velocity $|V| <$50 km s^{-1}, and high-velocity $|V| >$100 km s^{-1}. Most stars have one component with positive radial velocity of ∼22-48 km s^{-1}. Three stars show high-velocity components: HD 75309 (+153 km s^{-1}, −92 km s^{-1}), HD 76060 (−92 km s^{-1}), and CD-454676 (−150 km s^{-1}). These velocities are typical for high-velocity interstellar Ca II absorptions found earlier in the direction of old Vela SNR [2]. At least one star, CD-454676, shows conspicuous CN absorption of electronic transitions $R(0)$, $R(1)$, and $P(1)$ with the wavelengths of 3873.994 Å, 3874.602 Å, and 3875.759 Å correspondingly. The heliocentric radial velocity of these lines is +23 km s^{-1} (V_{LSR} = +10 km s^{-1}), that is consistent with the radial velocity of Ca II interstellar lines of the same star.

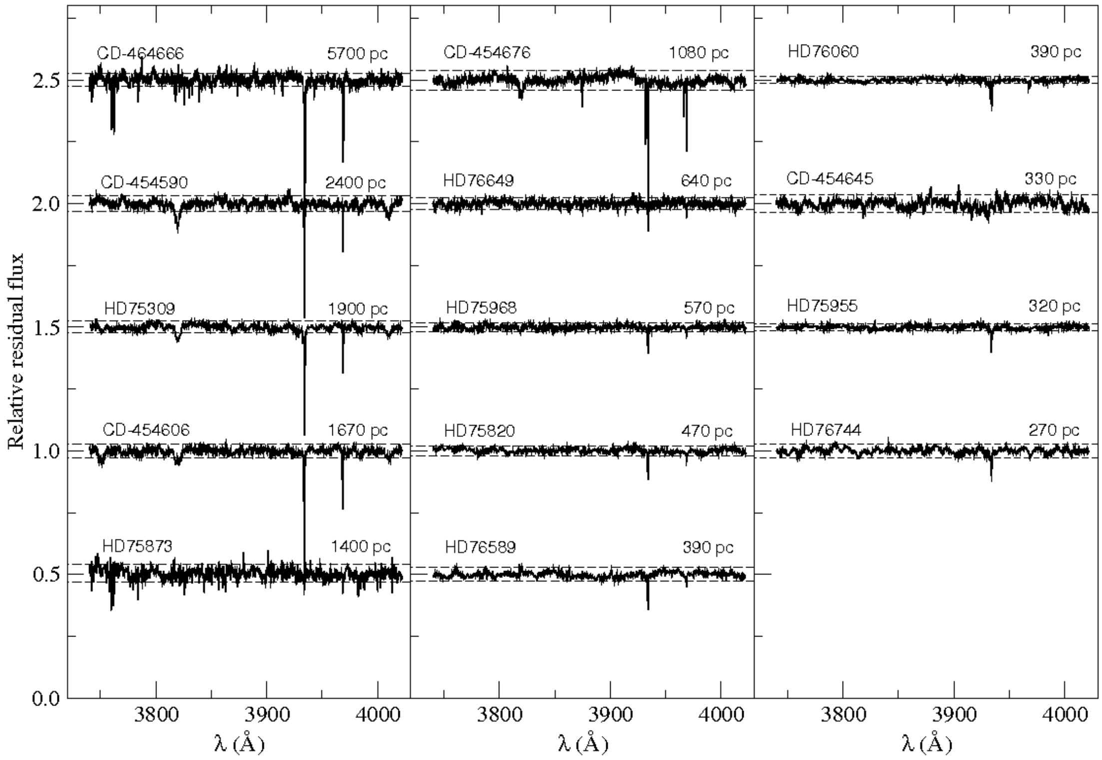

Figure 1: The relative residual spectra with 3σ error box. The distance to each star is also indicated.

Table 2: Adopted parameters of supernovae

Parameters	SN Ia	SN IIP	SN Ibc	SN Ic(h)
M ($M_\odot$)	1.4	10	3	4
E ($10^{51} erg$)	1.4	1	1.5	20

The absence of Fe I and Ca II broad absorption in stellar spectra towards Vela Jr. requires a confirmation with modeling the broad Ca II absorptions expected at the given age for the different SN types. The predicted profiles of the Ca II doublet at the age of 700 yr for different of SNe are shown in Fig. 2 assuming that all Ca is in Ca II state. We assume that in SN IIP and SN Ibc the Ca abundance is solar, while for SN Ia we adopt that Ca/Fe mass ratio is solar, while the total mass of iron in the ejecta is 0.6 $M_\odot$. Ejecta parameters for different SNe are given in Table 2. The boundary velocity of the unshocked ejecta is taken to be 5000 km s^{-1}in accordance with the distance of 200 pc and the age of 700 yr. The density distributions $\rho(v)$ in the unshocked ejecta are assumed to be exponential for compact pre-SNe and plateau with the outer power law $\rho \propto v^{-9}$ for SN IIP. The shown profiles are computed for three values of impact parameter in units of the angular radius: 0, 0.5, and 0.8. The predicted absorption turns out to be deep for all the impact parameters in the case of SN Ia, rather deep for SN IIP, very weak for SN Ibc, and negligible (relative depth < 0.006) in case of SN Ic(h). If Vela Jr. age and distance are close to the values adopted above, the progenitor was unlikely to be of type SN Ia or SN IIP; association of the SNR with a SN Ibc or SN Ic(h) is therefore preferred.

The age-distance relations for all the discussed cases are shown in Fig. 3. The SN Ia exploded in the hot interstellar medium phase shows almost the same age-distance relation as SN Ibc and therefore is not shown in this figure. The minimal distance for a given age corresponds to a SN IIP expanding in the warm neutral interstellar medium phase, while the maximal distance corresponds to SN Ic(h) with 60 $M_\odot$ progenitor. In combination with the ^{44}Ti curves for the two extreme values of ejected ^{44}Ti mass results in allowed ranges of 450-900 yr and 150-1000 pc for the age and distance of Vela Jr. The major result of this plot is that the distance of Vela Jr. cannot exceed 1 kpc. We thus conclude that at least several stars in our sample (Table 1) lie behind the SNR.

The absence of a broad Ca II absorption features in the spectra of stars with distances > 1 kpc suggests

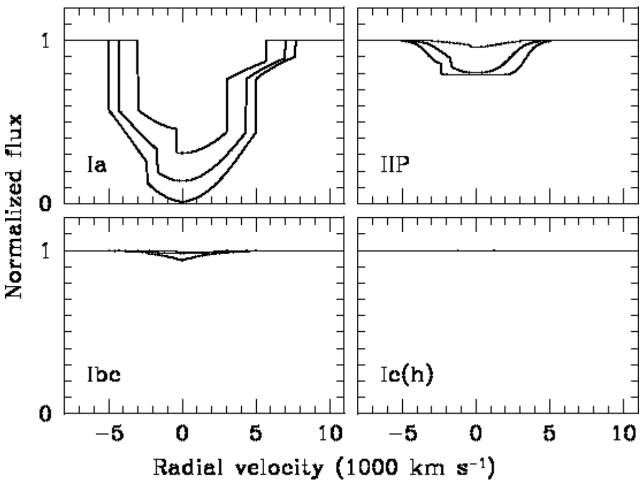

Figure 2: Absorption profile of Ca II doublet expected in the stellar spectrum for different progenitors of Vela Jr. The cases of impact parameter equal to 0, 0.5, and 0.8 are shown. The strongest absorption always corresponds to zero impact parameter

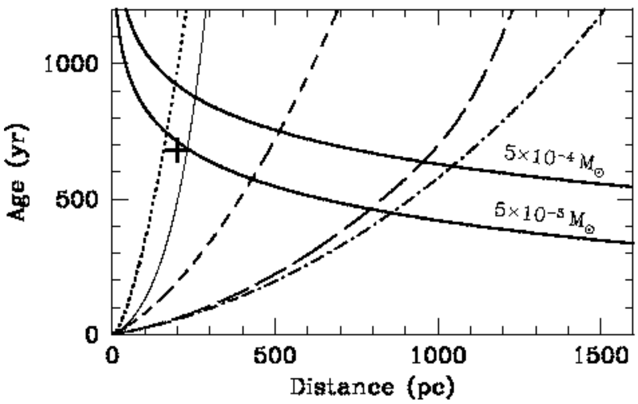

Figure 3: Age-distance relations provided by ^{44}Ti mass (thick solid lines) and radius of the supernova remnant. The radius is calculated for SN IIP (dotted line), SN Ia (thin solid line), SN Ibc (short-dashed line), SN Ic(h) with 35 $M_\odot$ progenitor (long-dash line) and 60 $M_\odot$ progenitor (dashed-dotted line).

that the SNR progenitor was either SN Ibc or SN Ic(h) because only for these SNe the expected absorption is weak and could remain undetected (Fig. 2). For the case of SN Ibc at the age of 650 yr the modeled width of ^{44}Ti γ-line is less than width of observed line. High velocities in profile of this line can be explained by distribution of ^{44}Ti in external parts of bi-polar jets in the case of SN Ic(h). Thus hypernova is the most possible progenitor of the Vela Jr.

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