Acta Polytechnica **53**(Supplement):617–620, 2013
doi:10.14311/AP.2013.53.0617

available online at http://ojs.cvut.cz/ojs/index.php/ap

RX-J0852−4622: THE NEAREST HISTORICAL SUPERNOVA REMNANT – AGAIN

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Abstract. RX-J0852−4622, a supernova remnant, is demonstrated to be closer than 500 pc, based on the measurements of the angular radius, the angular expansion rate and the TeV γ-ray flux. This is a new method of limiting the distance to any supernova remnant with hadronic induced TeV γ-ray flux. The progenitor star of RX-J0852−4622 probably exploded in its blue supergiant wind, like SN 1987A, preceeded by a red supergiant phase. A cool dense shell, expected around the outskirts of the red wind, may have been identified. The distance (200 pc) and age (680 yr) of the supernova remnant, originally proposed, are supported.

Keywords: supernova remnants, stellar evolution, multi-wavelength, X-rays, TeV γ-rays, cosmic rays, individual: RX-J0852−4622, Vela Jr., SN 1987A, SN 1006.

1. Introduction

RX-J0852−4622, nicknamed Vela Junior (Vela Jr.), is a supernova remnant (SNR) discovered in the ROSAT all-sky survey [3]. It is located along the direction towards the south-eastern corner of the Vela SNR, and it is completely covered, even beyond its boundaries, by the emission from the Vela SNR, such that Vela Jr. does not shine up against the very bright soft X-ray emission from the Vela SNR. Only at X-ray energies > 1.3 keV does Vela Jr. become X-ray visible. It is a patchy narrow shell-type source with a diameter of 2° of almost perfect circular shape. Since the discovery multi-wavelength obsersations have confirmed the SNR status, including non-thermal radio emission; hard X-ray emission with soft X-ray emission apparently missing; MeV γ-ray line emission from radioactive ^{44}Ti, ^{26}Al, ^{44}Ca, of low significance, though; GeV γ-ray continuum emission; and TeV γ-rays. A summary of the observations and interpretations can be found e.g. in [2, 10, 12]. Aharonian et al. [2] provide evidence that the TeV γ-rays are likely not to be of leptonic origin (inverse Compton scattering of electrons and photons) but of hadronic origin (nuclear collisions between SNR produced cosmic ray protons and nuclei of the ambient matter). This is supported by the MeV γ-ray measurements of Tanaka et al. [12]. An open question still is the distance and the age of Vela Jr.; the numbers range between 200 pc and 1 kpc, and 680 yr and 5000 yr. I show that Vela Jr. is very close, and likely to be as young as originally suggested [4].

2. Implications of observations

Three unambiguous key measurements of Vela Jr. have been made: the angular radius $R_\mathrm{a} = 1°$ [3], the angular velocity of the shock wave $v_\mathrm{s,a} = 0.84''/\mathrm{yr} \pm 0.23''/\mathrm{yr}$ [8] and the total energy of cosmic ray protons W_p to explain the TeV γ-ray flux, $W_\mathrm{p} = 10^{49}\,\mathrm{erg}\, d_2^2/n_0$ [2]. Units are cm^{-3} for the particle density n_0 of the ambient matter; 200 pc for the distance to the source, d_2. From X-ray measurements additional information is obtained for an upper limit of the ambient density of $n_{0,\mathrm{x}} < 0.029\,\mathrm{cm}^{-3}(d_1 f)^{-1/2}$ [11], where d_1 is distance in kpc, and f is a filling factor < 1. In contrast to other information, this is not definite, because it depends on the interpretation of the X-ray spectral measurements.

2.1. Distance

The kinetic energy E_0 available from an SN explosion is shared mainly between the acceleration of particles to cosmic rays (W_p) and the expansion of the explosion wave into the ambient medium driven by some energy E_k, such that $E_0 \geq W_\mathrm{p} + E_\mathrm{k}$ with $E_\mathrm{k} = 4.1 \times 10^{49}\,\mathrm{erg}\, n_0 d_2^5$. E_k represents the sum of the kinetic energy and the associated thermal energy, the latter of which is due to the shock-wave heating of the ambient matter. As W_p scales with (d_2^2/n_0) and E_k scales with $(d_2^5 n_0)$ a single absolute maximum of d_2 exists for any given E_0, which also fixes n_0. Any filling factor, additionally introduced, does not change the maximum distance. The normalization factors for W_p and E_k are known from the measurements. For Vela Jr. they are $W_\mathrm{p,1} = 10^{49}$ erg and $E_\mathrm{k,1} = 4.1 \times 10^{49}$ erg, respectively, (see above) for $d_2 = 1$ and $n_0 = 1$.

For $E_0 = 10^{51}$ erg the distance d is < 500 pc. For $E_0 = 3 \times 10^{50}$ erg, $d < 355$ pc, and for $E_0 = 10^{50}$ erg, $d < 260$ pc. The maximum of d is realized if E_0 is shared evenly between W_p and E_k. For instance, for $W_\mathrm{p} = 0.1 E_0$ and $E_0 = 10^{51}$ erg, $d < 435$ pc, and 225 pc for $E_0 = 10^{50}$ erg, respectively. The reverse case, i.e. $W_\mathrm{p} = 0.9 E_0$ does not change the upper limit of d, but it changes the associated n_0, slightly. Finally, the uncertainties of the measured values of $v_{\mathrm{s,a}}$, $\pm 0.23''/\mathrm{yr}$, change the distances quoted by at most 10 %. This means that there exists a firm upper limit of $d < 550\,\mathrm{pc}$. Only if the event were a hypernova, the distance could be larger.

The method outlined above can, of course, be applied to any other SNR, which emits TeV γ-rays of hadronic origin. The upper limit of the distance, i.e., $d_{2,\max}$ is generally given by the relation

$$d_{2,\max} = \left(0.25\left(E_0^2/(W_{\mathrm{p},1}E_{\mathrm{k},1})\right)v_{\mathrm{s,a}}^{-2}R_{\mathrm{a}}^{-3}\right)^{1/7};$$

$E_0 = 10^{51}\,\mathrm{erg}$ is the maximum energy generally attributed to a SN explosion; $W_{\mathrm{p},1}$ is the cosmic ray proton energy, derived from the measured TeV γ-ray spectrum normalized to $d_2 = 1$ and $n_0 = 1\,\mathrm{cm}^{-3}$ (for the procedure see [2]); $E_{\mathrm{k},1} = 5.8 \times 10^{49}\,\mathrm{erg}$ is the energy computed for $d_2 = 1$ and $n_0 = 1\,\mathrm{cm}^{-3}$, and an angular expansion (shock velocity) of $1''/\mathrm{yr}$ and an angular radius of 1°. This method appears to be a powerful tool for setting a distance upper limit of TeV γ-ray emitting SNRs, because this method depends just on angular measurements. For instance, the TeV γ-ray flux, if of purely hadronic origin, and the measurements of $v_{\mathrm{s,a}}$ and R_{a} quoted [1], predict an upper limit of $d = 1.85\,\mathrm{kpc}$ to SN 1006, using this new method.

2.2. Density

Thermal X-ray emission is expected from the shock wave heating of the ambient medium. The upper limit of $n_{0,x}$ of Slane et al. [11] sets further constraints to the distance when used in the expressions for W_{p} and E_{k}. For $E_0 = 10^{51}\,\mathrm{erg}$ and $f = 1$ the upper limit of d is reduced to $< 420\,\mathrm{pc}$ and $n_{0,\max} = 0.05\,\mathrm{cm}^{-3}$. For $E_0 = 10^{50}\,\mathrm{erg}$, $d < 250\,\mathrm{pc}$ and $n_{0,\max} = 0.06\,\mathrm{cm}^{-3}$. Values of $f < 1$ lower the acceptable maximum distance further, but do not change the acceptable n_0 significantly.

Slane et al. [11] note that the upper limit of $n_{0,\mathrm{x}}$ is valid only for temperatures of $kT > 1\,\mathrm{keV}$, which corresponds to a shock velocity of $v_{\mathrm{s}} = 860\,\mathrm{km/s}$; with $v_{\mathrm{s,a}} = 0.84''/\mathrm{yr}$, the upper limit of $n_{0,x}$ is therefore not applicable for $d < 235\,\mathrm{pc}$. This is about the distance to the Vela SNR, and the temperatures of the Vela SNR across the area of Vela Jr. range between 0.5 and 0.9 keV [9]. This means that the thermal X-ray emission from Vela Jr. and the Vela SNR can be easily mixed up, and they cannot even be spectroscopically discriminated. The majority of the soft X-ray emission received from the Vela Jr. covered area could be attributed to Vela Jr. rather than to the Vela SNR. Taking the ROSAT soft X-ray measurements n_0 could be a factor of 10 or more higher than the Slane et al. limit, i.e., $> 0.6\,\mathrm{cm}^{-3}$ [9].

2.3. Age

The evolutionary state of an SNR is often described by the expansion parameter β, defined by $R \sim t^{\beta}$, with R the radius and t the age. This relation leads to $\beta = v_{\mathrm{s}}/v$, with v_{s} the current shock velocity and the mean expansion velocity $v = R/t$. Given the angular value of v_{s}, i.e. $v_{\mathrm{s,a}}$, and the angular radius R_{a}, the age would be calculated to $t = \beta R_{\mathrm{a}}/v_{\mathrm{s,a}}$. Formally, $0 \le \beta \le 1$. The value of β close to 1 means that the SNR is almost freely expanding; $\beta = 0.4$ describes the adiabatic state with the SNR expansion slowed down by the ambient matter. For this case to apply the mass overrun by the shock wave (swept-up mass) should be much greater than the mass of the SN ejecta. The radiative phase starts around $v_{\mathrm{s}} \sim 250\,\mathrm{km/s}$, equivalent to $kT \sim 0.1\,\mathrm{keV}$. Given $v_{\mathrm{s,a}}$, the SNR would be located at a distance of 65 pc. This would have made Vela Jr. a very bright EUV source, which, however, is not listed in any of the EUV catalogues.

For $\beta = 0.4$, Vela Jr. being in the adiabatic phase, $t \sim 1700\,\mathrm{yr}$ ($1300 \div 2400\,\mathrm{yr}$). The maximum explosion energy of $E_0 = 10^{51}\,\mathrm{erg}$ and the maximum density of $n_{0,x} = 0.05\,\mathrm{cm}^{-3}$ allow a maximum distance of 420 pc. $v_{\mathrm{s,a}}$ then corresponds to 1700 km/s equivalent to $kT \sim 4\,\mathrm{keV}$. The expected thermal hard X-ray flux is fairly low at the level of $n_{0,x}$ and is probably not detectable given the sensitivity of present instruments, but see [7]. But it is noted that the energy in cosmic ray protons would be $8.8 \times 10^{50}\,\mathrm{erg}$. A cosmic ray acceleration efficency of 88 % would be a surprise, and an overrun mass of just 2.4 solar masses casts doubts on the assumption of the adiabatic state.

Finally, for Vela Jr. being close to free expansion, the ambient density, which needs to be low for free expansion to apply, is nevertheless high, such that it is inconsistent with $d > 500\,\mathrm{pc}$ and $W_{\mathrm{p}} \le 10^{51}\,\mathrm{erg}$.

Summarizing, the analysis shows that the concept of an explosion of the Vela Jr. progenitor star into a medium of constant isotropic matter density distribution is not applicable, and estimates of age and density on this basis are irrelevant.

2.4. Circumstellar environment of the SN progenitor star

Recalling SN 1987A, it is proposed that the Vela Jr. progenitor was a star with a very low density wind, like a blue supergiant, shortly before its explosion. After passing the low density region the SN shock wave may have hit the base of the preceeding red wind which is of much higher density, preserving pressure equilibrium, i.e., $(nv^2) = \mathrm{const.}$ The relevant density before the velocity slow-down is the mean density delivered by the blue wind up to the density jump and the density of the red wind at the radius of the density jump afterwards. The relevant velocities are the initial quasi-free expansion velocity v_{fr} of the SN taken over the full distance up to the location of the density jump, on the one hand, and the current shock velocity v_{s} on the other hand. The jump condition translates into

$$Q = \frac{\frac{\mathrm{d}M_\mathrm{b}/\mathrm{d}t}{v_\mathrm{b}}}{\frac{\mathrm{d}M_\mathrm{r}/\mathrm{d}t}{v_\mathrm{r}}} = \frac{16}{27}\left(\frac{v_\mathrm{s,a}}{v_\mathrm{fr,a}}\right)^2$$

with $v_\mathrm{s,a}$ the current angular shock velocity and $v_\mathrm{fr,a}$ the initial angular velocity during the quasi-free expansion phase.

Chevalier & Fransson [6] published typical mean values for the wind parameters, i.e., mass loss rate over wind velocity, of red supergiants and of blue supergiants, respectively, which are around

$$\frac{\mathrm{d}M_\mathrm{b}/\mathrm{d}t}{v_\mathrm{b}} = \frac{10^{-6}\ \text{solar masses/yr}}{550\,\mathrm{km}}$$

for a blue wind and

$$\frac{\mathrm{d}M_\mathrm{r}/\mathrm{d}t}{v_\mathrm{r}} = \frac{10^{-5}\ \text{solar masses/yr}}{20\,\mathrm{km}}$$

for a red wind. The blue wind parameters are consistent with the observations of the SN 1987A observations, the progenitor star of which had been identified as a blue supergiant. With this set of wind parameters and $d_2 = 1$, one gets $v_\mathrm{s} = 800\,\mathrm{km/s}$ and $v_\mathrm{fr} = 10\,200\,\mathrm{km/s}$ for the quasi-free expansion phase velocity. For $t = 680\,\mathrm{yr}$, the encounter of the quasi-free expanding shock wave with the red wind base would have occurred at $0.91R$ after $333\,\mathrm{yr}$. A dense shell, made up mainly of the red wind matter, with a width of $0.09R$, is traversed by the shock wave at a speed of $800\,\mathrm{km/s}$.

The outer zone of a stellar wind is expected to be surrounded by a thin, dense and cool shell, made up of the ambient swept-up interstellar matter. In the north-westerly direction of Vela Jr., just outside the outer boundary of the Vela SNR, the SNR Puppis-A is located, which is a very bright X-ray source with a diameter of $45'$. A spatially resolved spectral study of the ROSAT measurements across the surface of Puppis-A shows an excess of low energy absorption above the mean interstellar absorption. The excess absorption is spatially confined to a region looking like a slighty curved lane, or filament, which stretches right through the middle of Puppis-A from its northeastern boundary to its southwestern boundary. This indicates the presence of some cool matter leading to extra, spatially confined absorption on top of the interstellar absorption [5, 9]. This absorption lane could be considered as a fraction of a complete shell produced by the red wind. The majority of the shell cannot be observed because sufficiently bright background X-ray sources are missing. From this interpretation it follows that

$$\frac{\mathrm{d}M_\mathrm{r}/\mathrm{d}t}{v_\mathrm{r}} = \frac{M_\mathrm{l}}{(R_\mathrm{abs,a}d)}$$

with M_l the total mass loss of the progenitor star by its red wind, or numerically,

$$\frac{\mathrm{d}M_\mathrm{r}/\mathrm{d}t}{v_\mathrm{r}} = \frac{9\times 10^{-6}\,\text{solar masses/yr}}{20\,\mathrm{km}}\frac{M_\mathrm{l,10}}{d_2},$$

with $M_\mathrm{l,10}$ in units of 10 solar masses. The density n_r of the red wind at its base hit by the SN shock wave is then $n_\mathrm{r} = 0.1\,\mathrm{cm}^{-3}M_\mathrm{l,10}/d_2^3$. Using the measured flux of the TeV γ-rays [2] it follows that $W_\mathrm{p} = 10^{50}\,\mathrm{erg}\,d_2^5/M_\mathrm{l,10}$. This demonstrates that even under extreme conditions, i.e., large values of W_p and $M_\mathrm{l,10}$, d can be only somewhat larger than 200 pc. In fact, the result suggests that $d < 200\,\mathrm{pc}$. If so, the requirements for the associated total SN energy and cosmic ray energy would be somewhat relaxed.

The age t of the SNR is limited by the acceptable value of $Q = 16/27(v_\mathrm{s,a}/R_\mathrm{a})2(t/A)2$ with $A = v_\mathrm{fr}/v > 1$, $v = R/t$. $\frac{\mathrm{d}M_r/\mathrm{d}t}{v_\mathrm{r}}$ is basically fixed by the observation of the absorbing outer shell built up by the red wind. For $v_\mathrm{fr} = 10\,000\,\mathrm{km/s}$ the required density jump is consistent with the blue wind parameters suggested for SN 1987A, shown above. Observations have shown that $v_\mathrm{fr} \sim 40\,000\,\mathrm{km/s}$ over the first 6 yr for SN 1987A with an abrupt deceleration following. Applying this extreme case of such a quasi-free exansion velocity to Vela Jr. for a duration of up to about 100 yr after the explosion one gets

$$\frac{\mathrm{d}M_\mathrm{b}/\mathrm{d}t}{v_\mathrm{b}} = \frac{10^{-7}\ \text{solar masses/yr}}{1000\,\mathrm{km}}.$$

But an upper limit of v_fr can be derived from the width of the SNR shell. Figure 3 of Iyudin et al. [7] shows that the hard X-ray emission is confined to a shell of $< 6'$ to $7'$ thickness measured by XMM-Newton. This would result in v_fr less than $15\,000\,\mathrm{km/s}$. It appears that the Chandra images show a shell as thin as $5'$ [10], implying $v_\mathrm{fr} \sim 10\,000\,\mathrm{km/s}$. In summary, the blue wind parameters of the Vela Jr. progenitor star were probably in a range of

$$\frac{10^{-6}\ \text{solar masses/yr}}{550\,\mathrm{km}} \quad \text{and} \quad \frac{10^{-7}\ \text{solar masses/yr}}{1000\,\mathrm{km}}$$

during its final evolutionary phase. The wind parameters of the red wind and blue wind respectively, are surprising close to the typical mean values.

SN 1987A appears to be the only example so far of a blue supergiant SN, and Vela Jr. may be a further example. Such SNe might be very hard to be detected in the radio and low energy X-ray regimes, because the luminosity depends heavily on the ambient matter density. For instance, SN 1987A escaped detection for 6 years and might have escaped so for a much longer period of time. But after these 6 years the shock wave started to encounter the 'inner ring' with its much higher density, which slowed down the propagation of the shock wave dramatically. When, and whether, it will have reached the base of the red wind, like in the case of Vela Jr., remains to be seen. In this sense the observation of an absorbing shell produced by the red wind in case of Vela Jr. appears to be unique.

The absorbing shell attributed to the red wind is located at an angular distance of $R_\mathrm{abs,a} = 6.5°$ measured from the center of Vela Jr., which corresponds to $R_\mathrm{abs} = 22\,\mathrm{pc}$ for $d_2 = 1$. It shows a core width of $\sim 5'$ and a full width of $\sim 30'$, the latter of which is limited by the sensitivity of the measurements. The absorbing column density in the core region is $N_{\rm H} = 1.7 10^{21}\,{\rm cm}^{-2}$ $(0.8 \div 1.9 10^{21}\,{\rm cm}^{-2})$ [5]. This allows computing the ambient density $n_{\rm am}$ of the matter through which the red wind propagated, i.e., $n_{\rm am} = 0.55\,{\rm cm}^{-3} N_{\rm H,21} d_2^{-1}$. The analysis of the Vela SNR at a distance of 250 pc reveals a mean ambient density of $\sim 0.35\,{\rm cm}^{-3}$, derived also independently from the interstellar absorption column density, with spatial variations of a factor of > 2. It appears that the identification of the absorption lane as fraction of an absorption shell produced by the red wind of the Vela Jr. progenenitor star and the distance of ~ 200 pc are fairly plausible.

2.5. Interstellar absorption

The fits of models, available in standard X-ray spectral software packages, to the measured broad band X-ray spectra $(0.5 \div 10\,{\rm keV})$ of Vela Jr. appear to be consistent with a pure non-thermal spectrum with an absorption column density of $N_{\rm H} > 2 \times 10^{21}\,{\rm cm}^{-2}$ [10], which is at least 20 times higher than the absorption in front of the Vela SNR at a distance of 250 pc. This value of $N_{\rm H}$, interpreted as interstellar absorption, and therefore some measure of the distance, has raised the claim that Vela Jr. lies behind the Vela SNR, and that it is even much more distant. But even at the largest distances suggested the mean interstellar density needs to be close to or to exceed $1\,{\rm cm}^{-3}$, for which there is no observational evidence otherwise. Narrow band $(0.2 \div 2\,{\rm keV})$ analysis of the ROSAT spectra is consistent with a much flatter non-thermal spectrum, and $N_{\rm H}$ is consistent if not lower than that measured for the Vela SNR [4]. In particular at the low energy end $(< 2\,{\rm keV})$, the statistical quality of the fits to the broad band measurements is not convincing, and one may wonder whether the source spectrum is not much more curved than the modified power-law models of the standard software packages offer. The flattening of the observed spectrum for $E < 2\,{\rm keV}$, which is the energy range extremely sensitive to interstellar absorption, is more likely not be caused by interstellar absorption but to be of intrinsic origin, i.e., the SNR produced cosmic ray electron spectrum for which a turn-over might occur at energies $\sim 0.1\,{\rm keV}$ (see, e.g., the models shown in Fig. 17 of Aharonian et al. [2]). One could turn the argument around and can perhaps learn something about the electron acceleration to cosmic ray energies and the shape of the spectrum close to the turn-over at the highest energies, through the measurements.

3. Conclusions

Angular radius, angular shock velocity and TeV γ-ray flux limit the distance to Vela Jr. to < 500 pc for an explosion with an available energy of $< 10^{51}$ erg. The upper limits on the density associated with a high temperature plasma $(> 1\,{\rm keV})$ reduce the distance further. The SN explosion into a stellar wind environment can explain the observational results. The wind parameters, i.e., mass loss rate over wind velocity, are in agreement with those known for blue supergiant winds and red supergiant winds. It appears that the progenitor star of Vela Jr. exploded in its blue wind developing a few thousand years before the end of the progenitor's life. The blue wind phase was preceeded by an expected red wind phase. The base of the red wind was probably hit by the SN explosion shock wave after 200 to 300 years. Because of the high density at the red wind base the shock wave velocity significantly dropped and the bulk of the expected thermal X-ray emission is expected at temperatures $< 1\,{\rm keV}$, and may be hidden among the Vela SNR emission as the temperatures are very similar. The wind model, in particular the explosion of a blue supergiant is reminiscent of the findings for SN 1987A. The application of a wind model also suggests that protons are preferentially accelerated to cosmic ray energies in an environment of continuous high shock velocity and low density, which keeps helping the losses by collisions with ambient ions low, and, in addition, little energy is being spent for expanding and heating. This could make blue supergiant explosions favourable TeV γ-ray emitters, explaining their rareness among the SNR populations.

Acknowledgements

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