

Modeling of the non-thermal emission from the cloudlet-dominated Vela SNR

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Abstract: Supernova remnants (SNRs) are widely considered to be sites of Galactic cosmic-ray (CR) acceleration. Vela is one of the nearest Galactic composite SNRs to the Earth, accompanied by the Vela pulsar and its pulsar wind nebula (PWN) Vela X, which is a powerful γ -ray emitter. The Vela SNR is one of the most studied remnants and it benefits from precise estimates of various physical parameters such as distance and age. Therefore, it is a perfect object for a detailed study of physical processes in SNRs. The Vela SNR expands into the highly inhomogeneous cloudy interstellar medium (ISM) and its dynamics is determined by the heating and evaporation of ISM cloudlets. It features an asymmetrical X-ray morphology which is explained by the expansion into two media with different densities. This could occur if the progenitor of the Vela SNR exploded close to the edge of the stellar wind bubble of the nearby Wolf-Rayet star in the γ^2 Velorum binary system and hence one part of the remnant expands into the bubble. The interaction of the main shock with ISM cloudlets causes formation of secondary shocks at which additional particle acceleration and magnetic field enhancement occurs. This leads to the close to uniform distribution of relativistic particles inside the remnant. We calculate the synchrotron radio emission within the framework of the new hydrodynamical model which assumes the supernova explosion at the edge of the stellar wind bubble. The simulated radio emission agrees well with the observed flux and complicated morphology of the remnant. We also give an estimate of the expected γ -ray flux from the remnant generated in inelastic proton-proton interactions. A possibility of detection of the predicted γ -ray emission with next generation instruments is discussed.

Keywords: Vela SNR, γ^2 Velorum, radio radiation, cosmic rays, γ -rays.

1 Introduction

Vela Supernova remnant (SNR) is one of the most studied and closest SNRs to the Earth. The age and the distance to the Vela SNR are well determined what makes it a perfect object for the investigation of the physical processes. The age of the Vela SNR is determined as the age of the Vela pulsar (PSR B0833-45) and is about 1.1×10^4 years [13]. Several estimates of the distance to the remnant exist (see [16] and references therein) the most reliable of which is determined from the VLBI parallax measurements of the Vela pulsar and is $D_{\text{Vela}} = 287_{-17}^{+19}$ pc [7]. Equatorial coordinates (J2000 epoch) of the Vela SNR center are $\alpha_{\text{Vela}} = 08^{\text{h}}35^{\text{m}}20.66^{\text{s}}$ and $\delta_{\text{Vela}} = -45^{\circ}10'35.2''$.

Early radio observations of the Vela constellation [14] revealed three localized regions of enhanced brightness temperature Vela X, Vela Y and Vela Z. Vela X is the most intense emission region which is believed to be a pulsar wind nebula (PWN) of the Vela pulsar (see e.g. [1] and references therein). It was first interpreted as a PWN associated with the Vela pulsar by [18]. Subsequent observations at 29.9, 34.5 and 408 MHz revealed one more region of intensified emission Vela W, which features two peaks and is weaker than Vela Y and Vela Z [4]. The spectral shape of the Vela W radio emission is similar to the spectral shape of the radio emission from Vela Y and Vela Z, which suggests the same nature of these localized emission regions [4].

Vela SNR is one of the brightest sources on the X-ray sky. The X-ray emission appears to be dimmer but more extended in the south-western (SW) part in comparison

Table 1: Physical parameters of the Vela SNR derived in [16]

Parameter	NE	SW
Explosion energy E_{SN} [erg]	1.4×10^{50}	
Radius R [pc]	18	23
Hot component		
Density n_{hot} [cm^{-3}]	0.04	0.01
Filling factor f_{hot}	0.93	0.91
Temperature T_{hot} [K]	9×10^6	1.5×10^7
Cool component		
Density n_{cool} [cm^{-3}]	0.38	0.10
Filling factor f_{cool}	0.07	0.09
Temperature T_{cool} [K]	1×10^6	1.7×10^6

to the north-eastern (NE) part of the remnant [5, 10]. The bulk of the X-ray emission is distributed all over the SNR without an evidence of the main shock. Both features were recently explained in [16] within the assumption that the Vela SNR progenitor supernova exploded on the border of the stellar wind bubble (SWB) of the nearby Wolf-Rayet (WR) star in the binary system γ^2 Velorum and that the remnant expands in a highly inhomogeneous, cloudy, interstellar medium (ISM). Indeed, exploding at the border of the SWB, the remnant would expand in two media with different densities, what, in turn, would cause a change of the X-ray luminosity and size from the NE part of the

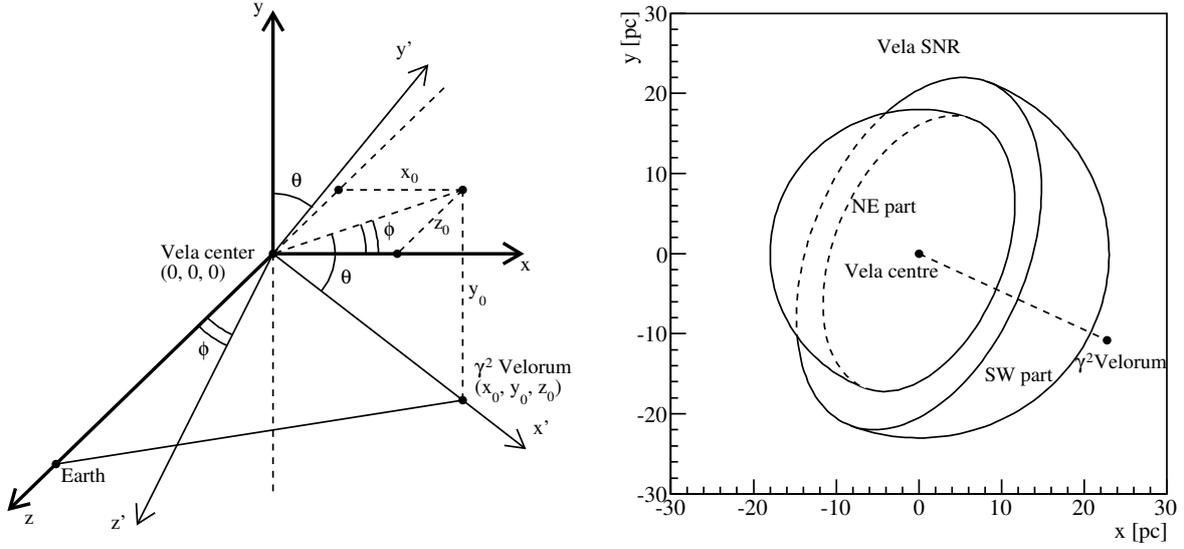


Fig. 1: Left panel: the definition of rotation angles ϕ and θ (see text for explanation). Right panel: a schematic illustration of the xy -projection of the Vela SNR in \mathbf{K} coordinate systems

remnant to the SW part. If the remnant expands into the cloudy ISM, its X-ray emission is generated mainly through the heating and evaporation of the cloudlet's matter [16].

γ^2 Velorum is the WC8+O8-8.5III binary system whose WR component (WR11) is the closest WR star to the Earth. There are several recent estimates of the distance to γ^2 Velorum which are based on different measurements but reveal similar results. An interferometric estimate of the distance $D_{\gamma^2\text{Vel}} = 368^{+38}_{-13}$ pc was derived in [11]. The estimate based on the orbital solution for the γ^2 Velorum binary obtained from the interferometric data is $D_{\gamma^2\text{Vel}} = 336^{+8}_{-7}$ pc [12]. Finally, the estimate of the distance based on HIPPARCOS parallax measurements is $D_{\gamma^2\text{Vel}} = 334^{+40}_{-32}$ pc [17]. The latter is used for calculations in this paper. Equatorial coordinates (J2000 epoch) of γ^2 Velorum are $\alpha_{\gamma^2\text{Vel}} = 08^h09^m31.95^s$ and $\delta_{\gamma^2\text{Vel}} = -45^\circ20'11.7''$ [17].

In this paper, we present the simulation of the radio synchrotron emission from the Vela SNR. The simulation was performed in the framework of the model presented in [16] using estimates of physical parameters of the Vela SNR and its interior (consisting of hot and cool components) derived in that work (see Table 1). The simulated radio emission from the remnant is compared to the observational data presented in [4].

It is believed that supernova remnants are responsible for the acceleration of cosmic rays (CR) in our Galaxy and that they can be the main "accelerators" of electrons, protons and nuclei with energies up to 10^{17} eV. In this paper, we calculate the expected γ -ray flux from the Vela SNR produced in inelastic proton-proton interactions in the frame of the hydrodynamical model of the Vela SNR presented in [16]. The detectability of this flux with the next generation instruments is discussed.

2 The geometrical model of the system

The geometrical model of the system is basically defined by angles ϕ and θ , which are rotation angles for the conversion of the \mathbf{K}' coordinate system to the \mathbf{K} coordinate system (Fig. 1, left panel). The coordinate frame \mathbf{K} is defined by its origin at the centre of the Vela SNR, the z -axis coincided with the direction towards Earth, the y -axis tangent to a line of declination and the x -axis tangent to the circle right ascension of the celestial sphere with the radius $r = D_{\text{Vela}}$. A \mathbf{K}' frame is then defined as

$$\mathbf{K}' = R_{z'}(\theta)R_y(\phi)\mathbf{K}, \quad (1)$$

where $R_{z'}(\theta)$ and $R_y(\phi)$ are rotation matrices for the rotation around z' -axis through angle θ and around y -axis through angle ϕ respectively. The rotation is performed in a way that x' -axis coincides with the direction towards γ^2 Velorum (Fig. 1, left panel). The xy -projection of the Vela SNR in the \mathbf{K} coordinate frame (schematically shown on Fig. 1, right panel) can be then easily converted into equatorial coordinates using coordinate transformations

$$\begin{aligned} x &= D_{\text{Vela}} \cos \delta_{\text{Vela}} \sin(\alpha_{\text{Vela}} - \alpha), \\ y &= D_{\text{Vela}} \sin(\delta - \delta_{\text{Vela}}), \end{aligned} \quad (2)$$

assuming that $(\alpha - \alpha_{\text{Vela}})$ and $(\delta - \delta_{\text{Vela}})$ are small.

For given coordinates (x_0, y_0, z_0) of γ^2 Velorum in the \mathbf{K} -frame rotation angles ϕ and θ can be estimated as

$$\tan \phi = \frac{|z_0|}{|x_0|}, \quad \tan \theta = \frac{|y_0|}{\sqrt{x_0^2 + z_0^2}}. \quad (3)$$

In turn, x_0 , y_0 and z_0 can be calculated using known distances and equatorial coordinates of the sources by transformation equations

$$\begin{aligned} x_0 &= D_{\text{Vela}} \cos \delta_{\text{Vela}} \sin(\alpha_{\text{Vela}} - \alpha_{\gamma^2\text{Vel}}), \\ y_0 &= D_{\text{Vela}} \sin(\delta_{\gamma^2\text{Vel}} - \delta_{\text{Vela}}), \\ z_0 &= D_{\text{Vela}} - D_{\gamma^2\text{Vel}} \cos \Delta, \end{aligned} \quad (4)$$

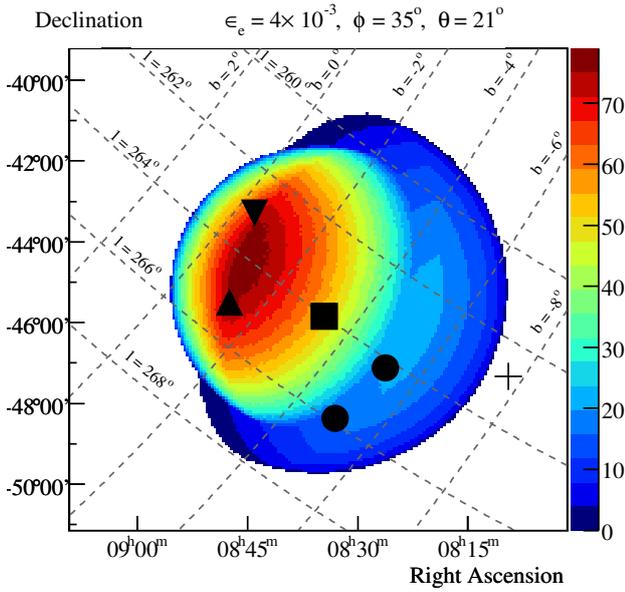


Fig. 2: Simulated brightness temperature map at 408 MHz calculated for $\epsilon_e = 1.4 \times 10^{-3}$, $\phi = 35^\circ$ and $\theta = 21^\circ$. The color reflects the brightness temperature in K. Filled down- and up-pointing triangles denote peak locations of Vela Y and Vela Z correspondingly, two filled circles show locations of two peaks of Vela Z, a filled square denotes the position of the Vela X peak, and a cross reflects the location of γ^2 Velorum.

where Δ is the angular distance between Vela and γ^2 Velorum given by

$$\cos \Delta = \sin \delta_{\text{Vela}} \sin \delta_{\gamma^2 \text{Vel}} + \cos \delta_{\text{Vela}} \cos \delta_{\gamma^2 \text{Vel}} \cos(\alpha_{\text{Vela}} - \alpha_{\gamma^2 \text{Vel}}) \quad (5)$$

3 Simulated radio emission from the Vela SNR

Synchrotron radio emission from the remnant expanding in the cloudy ISM is different from the one in the homogeneous ISM. The interaction of the main shock with cloudlets causes formation of secondary shocks on which sufficient electron acceleration takes place. This leads to the close to uniform distribution of relativistic electrons inside the SNR. Thus, the luminosity of the SNR will grow towards the center where more electrons are situated on the line of sight. It differs from usual shell-type SNRs where relativistic electrons are concentrated in the shell of the remnant.

The Vela SNR is approximated with a combination of two hemispheres, NE and SW, with different radii, R_{NE} and R_{SW} correspondingly. The explosion of the supernova is assumed to be spherically symmetrical, i.e. the energy transferred to relativistic electrons is the same in both hemispheres and equals to a half of the total energy in electrons. Due to the different sizes of the SNR hemispheres the distribution of the luminosity across the remnant strongly depends on the position of the observer and does not necessarily have to peak in the centre of the SNR.

We assume that relativistic electrons are uniformly distributed within each hemisphere of the remnant and the dis-

tribution of the electron density $N_{e,\text{NE/SW}}(\gamma)$ with energies follows a power law

$$\frac{dN_{e,\text{NE/SW}}}{d\gamma} = K_{e,\text{NE/SW}} \gamma^{-\Gamma_e}, \gamma \geq \gamma_{\text{min}}, \quad (6)$$

where γ is the electron Lorentz factor, γ_{min} is the minimal electron Lorentz factor, which is assumed to be $mc^2 \gamma_{\text{min}} = 100$ MeV, $K_{e,\text{NE/SW}}$ is the normalisation constant and Γ_e is the electron spectral index. Then the overall synchrotron flux density at emitted photon frequency ν per unit volume dV at distance D can be calculated as [15]

$$\frac{dS_\nu}{dV} = \frac{K_{e,\text{NE/SW}}}{4\pi D^2} \Gamma \left(\frac{\Gamma_e}{4} + \frac{19}{12} \right) \Gamma \left(\frac{\Gamma_e}{4} - \frac{1}{12} \right) \frac{\sqrt{3} q^3 B_{\text{NE/SW}} \sin \theta}{mc^2 (\Gamma_e + 1)} \left(\frac{2\pi mc}{q B_{\text{NE/SW}} \sin \alpha} \nu \right)^{-\frac{(\Gamma_e-1)}{2}}, \quad (7)$$

where $B_{\text{NE/SW}}$ is the interior magnetic field in NE and SW part of the remnant correspondingly, q is the electron charge, m is the electron mass, c is the speed of light and α is the angle between the magnetic field and electron velocity. It is assumed that electron velocities are isotropically distributed within the remnant and a root mean square value $\sin \alpha = \sqrt{2/3}$ can be used. The magnetic field is assumed to be uniform within each hemisphere of the remnant and can be estimated from the equilibrium condition of the magnetic pressure and the thermal pressure of particles (assuming that the thermal gas dominates over the non-thermal energy content) as

$$B_{\text{NE/SW}} = \sqrt{8\pi n_{\text{hot,NE/SW}} k_B T_{\text{hot,NE/SW}}}, \quad (8)$$

where $n_{\text{hot,NE/SW}}$ is the particle number density and $T_{\text{hot,NE/SW}}$ is the kinetic temperature of the hot component (dominant across the remnant) in NE and SW parts of the remnant (see Table 1). In the NE part of the remnant the magnetic field is estimated to be $B_{\text{NE}} = 35 \mu\text{G}$ and in the SW part it is $B_{\text{SW}} = 23 \mu\text{G}$.

For a known value of the total energy in electrons $K_{e,\text{NE/SW}}$ can be estimated as

$$K_{e,\text{NE/SW}} = \frac{E_e}{\frac{2}{3} \pi R_{\text{NE/SW}}^3 mc^2 \int_{\gamma_{\text{min}}}^{\infty} \gamma^{-\Gamma_e+1} d\gamma}. \quad (9)$$

To reproduce the observed flux density at 408 MHz [4], the total energy in electrons has to be equal 5.6×10^{47} erg. It corresponds to a fraction of the supernova explosion energy of $\epsilon_e = 4 \times 10^{-3}$, which is of the same order as a typical value 10^{-3} for SNRs [8]. For this calculation the electron spectral index $\Gamma_e = 2.47$ is assumed, which is implemented from the fit of the combined radio spectrum of Vela Y and Vela Z. Then, $K_{e,\text{NE}} = 5.8 \times 10^{-6} \text{ cm}^{-3}$ and $K_{e,\text{SW}} = 2.8 \times 10^{-6} \text{ cm}^{-3}$ for the NE and SW hemispheres correspondingly.

To reproduce the observed brightness temperature map we assume a combination of rotation angles $\phi = 35^\circ$ and $\theta = 21^\circ$. These values are chosen in order to be in the same time consistent with distance estimates for the Vela SNR and γ^2 Velorum and to explain the radio morphology of the Vela SNR. The simulated map assuming these angles and $\epsilon_e = 4 \times 10^{-3}$ is shown on Fig. 2. The simulated map

features two peaks, in the NE and SW part of the remnant, which appear only due to the specific geometry of the system. The NE peak coincides with the localised emission regions Vela Y and Vela Z and the position of the SW peak is close to the location of two peaks of Vela W. Maximal brightness temperatures of the simulated peaks are also in good agreement with observed brightness temperatures of Vela Y, Vela Z and Vela W: about 80 K for the NE peak (~ 90 K for Vela Y, Vela Z) and about 25 K for the SW peak (35 – 40 K for Vela W peaks). Therefore, we suggest that the complicated radio morphology of the source might be completely due to the specific direction to the observer and the assymetry of the SNR. The detection of two peaks (instead of one as predicted) in the NE part of the remnant as well as the offset of the predicted SW peak from Vela W can be explained by the existence of the PWN Vela X inside the remnant whose dynamics may influence the distribution of relativistic electrons within the remnant. This hypothesis needs more detailed investigation.

4 Predicted γ -ray flux from the Vela SNR

The resulting spectrum of γ -radiation as a result of proton-proton (pp) interactions of cosmic-ray protons with energy spectrum

$$dN_p(E_p)/dE_p = K_p E_p^{-\Gamma_p} \quad (10)$$

with target protons of ISM or protons inside the SNR with number density n is ([9] and references therein):

$$\nu L_{\nu pp} = C_{pp}(\Gamma_p) 2E_p \frac{dN_p}{dE_p} \sigma_{pp}^{\text{inel}} n c h \nu [\text{erg s}^{-1}], \quad (11)$$

where $E_p dN_p/dE_p$ is to be evaluated at $E_p = 10h\nu$ (the typical proton energy for which photons with energy $E_\gamma = h\nu$ are emitted.), $\sigma_{pp}^{\text{inel}} \simeq 3 \cdot 10^{-26} \text{cm}^2$ is the inelastic proton-proton cross section, c is the light speed, h is the Planck constant, ν is the frequency of an emitted photon. Eq. 11 shows that each pp interaction creates two photons with energies $E_\gamma = 0.1E_p$. The correction factor $C_{pp}(\Gamma_p)$ is of order of 1 ($C_{pp}(2) \approx 0.85$, $C_{pp}(2.2) \approx 0.66$) and we omit it hereafter.

We assume that the CR energy spectrum inside Vela SNR follows a power law with the index $\Gamma_p = 2.1$

$$\frac{dN_p(E_p)}{dE_p} = K_p E_p^{-2.1}, \quad (12)$$

where K_p determines the amount of explosion energy transferred into CRs. The spectral index of 2.1 was assumed to predict the maximal flux at TeV energies. The total energy of CRs in the SNR is the integral over the SNR volume V :

$$W_{\text{CR}} = \int_{E_{\text{min}}}^{E_{\text{max}}} \int_V k E_p^{-\Gamma_p+1} dE_p dV, \quad (13)$$

where E_{min} and E_{max} is the minimum and maximum energy of accelerated protons, respectively, $k E_p^{-\Gamma_p}$ is the energy spectrum of CRs in unit volume and can vary depending on position inside SNR. We accept here that the CRs in Vela SNR are distributed uniformly and $K_p = kV$. In this case we have:

$$W_{\text{CR}} = \int_{E_{\text{min}}}^{E_{\text{max}}} K_p E_p^{-\Gamma_p+1} dE_p, \quad (14)$$

where $E_{\text{min}} \approx 1 \text{GeV}$ is the assumed minimal proton kinetic energy of the effective pion creation and $E_{\text{max}} \simeq 100 \text{TeV}$ is the maximal proton energy calculated for the Vela SNR parameters assuming the diffusion ξD_{Bohm} , where $\xi = 10$ and D_{Bohm} is the Bohm diffusion coefficient. With this assumption we can find the parameter $K_{p,\text{GeV}}$ for the CR spectrum, responsible for hadronic γ -ray radiation:

$$K_{p,\text{GeV}} = \frac{W_{\text{CR}}(\Gamma_p - 2)}{E_{\text{min}}^{2-\Gamma_p} - E_{\text{max}}^{2-\Gamma_p}} \quad (15)$$

Then for $n = 10^{-2} n_{-2} \text{cm}^{-3}$ and $W_{\text{CR}} = 10^{49} W_{49} \text{erg}$, a γ -ray flux from the distance $D = 300 D_{300} \text{pc}$ can be presented as

$$F(E_\gamma) = \frac{1}{4\pi D^2} \frac{L_{\nu pp}(E_\gamma)}{E_\gamma} \\ = 4 \times 10^{-14} n_{-2} W_{\text{CR},49} D_{300}^{-2} E_{\gamma,\text{TeV}}^{-2.1} [\text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}], \quad (16)$$

where $E_{\gamma,\text{TeV}} = E_\gamma / (1 \text{TeV})$.

The matter inside the Vela SNR is presented in the form of two components, hot and cool [16], which will both contribute to the total flux in γ -rays. Particle densities and filling factors of these two components for NE and SW parts of the remnant are presented in Table 1. The energy in hadronic CRs is assumed to be the same in the NE and SW hemispheres of the remnant due to the assumption of the spherically symmetrical explosion of the supernova. Then for the physical parameters obtained for the Vela SNR, the total γ -ray flux from the remnant is

$$F_\gamma \sim 3 \times 10^{-13} E_{\gamma,\text{TeV}}^{-2.1} [\text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}] \quad (17)$$

and the surface brightness distribution would have a similar appearance to the radio brightness map (Fig. 2). The estimated flux is below the sensitivity for the H.E.S.S. telescope array. Moreover, it would be problematic to detect the Vela SNR with H.E.S.S. also due to its large angular size which is larger than the H.E.S.S. total field of view of about 5° [3]. Nevertheless, the predicted flux should be detectable with the Cherenkov Telescope Array (CTA) which would have both higher sensitivity and larger field of view.

5 Conclusions

We show that the complicated radio morphology of the Vela SNR can be explained by the specific geometry of the system resulting from the interaction with the stellar wind bubble of the nearby WR star in the γ^2 Velorum binary system. The simulated brightness temperature at 408 MHz is in good agreement with observational data. We also calculate the expected γ -ray flux from the Vela SNR and show that it can be detected by the next generation of Cherenkov telescopes like CTA.

References

- [1] Abramowski, A., Acero, F., Aharonian, F., et al. 2012, A&A, 548, A38
- [2] Aharonian F. A. 2004 "Very high energy cosmic gamma radiation: a crucial window on the extreme Universe", NJ: World Scientific Publishing.
- [3] Aharonian, F., et al. 2006, A&A, 457, pp. 899-915

- [4] Alvarez, H., Aparici, J., May, J., & Reich, P. 2001, A&A, 372, 636
- [5] Aschenbach, B., Egger, R., & Trümper, J. 1995, Nature, 373, 587
- [6] Blondin, J. M., Chevalier, R. A., & Frierson, D. M. 2001, ApJ, 563, 806
- [7] Dodson, R., Legge, D., Reynolds, J. E., & McCulloch, P. M. 2003, ApJ, 596, 1137
- [8] Gabici, S. 2008, ArXiv e-prints
- [9] Katz B., Waxman E. 2008, JCAP, Is. 01, pp. 018
- [10] Lu, F. J. & Aschenbach, B. 2000, A&A, 362, 1083
- [11] Millour, F., Petrov, R. G., Chesneau, O., et al. 2007, A&A, 464, 107
- [12] North, J. R., Tuthill, P. G., Tango, W. J., & Davis, J. 2007, MNRAS, 377, 415
- [13] Reichley, P. E., Downs, G. S., & Morris, G. A. 1970, ApJL, 159, L35
- [14] Rishbeth, H. 1958, Australian Journal of Physics, 11, 550
- [15] Rybicki, G. B. & Lightman, A. P. 1985, Radiative processes in astrophysics.
- [16] Sushch, I., Hnatyk, B., & Neronov, A. 2011, A&A, 525, A154
- [17] van Leeuwen, F., ed. 2007, Astrophysics and Space Science Library, Vol. 350, Hipparcos, the New Reduction of the Raw Data
- [18] Weiler, K. W. & Panagia, N. 1980, A&A, 90, 269