Kinetic ‘jets’ from fast-moving pulsars

Maxim V. Barkov, Maxim Lyutikov, Noel Klingler and Pol Bordas

1Department of Physics and Astronomy, Purdue University, West Lafayette, IN 47907-2036, USA
2Astrophysical big bang Laboratory, RIKEN, 351-0198 Saitama, Japan
3Space Research Institute of the Russian Academy of Science (IKI), 84/32 Profsoyuznaya Stc, Moscow, Russia, 117997
4Department of Physics, The George Washington University, Washington, DC 20052, USA
5Departament de Física Quàntica i Astrofísica, Institut de Ciències del Cosmos (ICCCUB), Universitat de Barcelona, IEEC-UB, Martí i Franquès 1, E-08028 Barcelona, Spain

Accepted 2019 February 18. Received 2019 January 28; in original form 2018 February 26

ABSTRACT

Some fast-moving pulsars, such as the Guitar and the Lighthouse, exhibit asymmetric non-thermal emission features that extend well beyond their ram pressure confined pulsar wind nebulae (PWNe). Based on our 3D relativistic simulations, we analytically explain these features as kinetically streaming pulsar wind particles that escaped into the interstellar medium (ISM) due to reconnection between the PWN and ISM magnetic fields. The structure of the reconnecting magnetic fields at the incoming and outgoing regions produces highly asymmetric magnetic bottles therefore and result in asymmetric extended features. For the features to become visible, the ISM magnetic field should be sufficiently high, $B_{\text{ISM}} > 10 \, \mu G$. We also discuss archival observations of PWNe displaying evidence of kinetic jets: the Dragonfly PWN (PSR J2021 + 3651), G327.1–1.1, and MSH 11–62, the latter two of which exhibit symmetric ‘snail eyes’ morphologies. We suggest that in those cases the pulsar is moving along the ambient magnetic field in a frisbee-type configuration.

Key words: magnetic reconnection – MHD – pulsars: individual: PSR J2021 + 3651 – ISM: jets and outflows – ISM: magnetic fields.

1 INTRODUCTION

Rotation-powered pulsars produce relativistic winds that interact with the surrounding medium to form pulsar wind nebulae (PWNe). Strong shocks at the wind/medium interface lead to efficient particle acceleration and radiation of non-thermal (NT) emission (see e.g. Rees & Gunn 1974; Kennel & Coroniti 1984a; Gaensler & Slane 2006, for reviews). When a pulsar travels through the interstellar medium (ISM) at supersonic velocities, the structure of the system is strongly affected, and the morphological and spectral properties of these high-velocity PWNe depart significantly from their more common low-velocity analogues. The ram pressure exerted by the oncoming ISM confines the pulsar wind to the direction opposite to that of the pulsar’s motion, forming a bow shock compact nebula (CN) and an extended pulsar tail. Best observed in X-rays, where high-resolution morphological studies are technologically feasible with the current space-based facilities, about 30 of such fast-moving PWNe have been imaged to date (see e.g. Kargaltsev & Pavlov 2008; Kargaltsev et al. 2017b).

The typical size of a ram pressure-confined PWN can be taken as the stand-off distance $r_s$ of the bow shock apex, where the pressure of the pulsar wind, $E/(4\pi r_s^2 c)$, is balanced by the ram pressure of the ISM, $\rho_{\text{ISM}}v_s^2$. The stand-off distance is given by

$$r_s = \sqrt{\frac{E}{4\pi c \mu m_p n_{\text{ISM}} v_s^2}} \approx 4 \times 10^{-3} \frac{E^{1/3}}{v_p^{1/2} n_0^{1/2}} \text{pc},$$

(1)

where $E$ is the pulsar’s spin-down luminosity, $n_{\text{ISM}}$ is the ISM number density, $v_p = v_p/10^6$ cm s$^{-1}$ is the pulsar velocity, $m_p$ is the proton mass, and $\mu$ is the ISM specific weight. The numerical value for the luminosity can be scaled to $E_{10} = E/10^{36}$ erg s$^{-1}$ and the ISM number density to $n_0 = 1$ particle cm$^{-3}$. In the tail, the PWN can extend well beyond the length-scale of the stand-off distance (e.g. up to parsec-scale distances), but in the head of the CN, (1) provides an estimate of the expected forward extent of the nebula.

Contrary to the hydrodynamical expectation that pulsar wind should be contained within the boundaries of the contact discontinuity that separates the wind from the ISM, observations of some high-velocity PWNe have revealed the presence of elongated features extending well beyond the stand-off distance $r_s$ in the forward or sideways directions; see e.g. the cases of the Lighthouse PWN of PSR J1101–6101 (Pavan et al. 2016, Fig. 1), the Guitar PWN of PSR B2224 + 65 (Wong et al. 2003; Hui & Becker 2007; Johnson & Wang 2010), PSR J1509–5850 (Klingler et al. 2016a) and the Mushroom PWN of PSR B0355 + 54 (Klingler et al. 2016b). These
feature are misaligned with respect to the pulsars’ proper motion directions and extend rather deep into the medium, far outside the bow shock boundary, reaching parsec-scale lengths in some instances.

These so-called ‘misaligned outflows’ are sometimes interpreted as jets. However, they cannot be jets in the sense of a confined hydrodynamic flow, as any such flow cannot propagate much further than the stand-off distance (1). Also, in two of the known cases, J1509-5850 and B0355 + 54, both pulsar jets and counter-jets have been resolved and are confined within the bow shock, thus ruling out this explanation. To stress this difference, in this paper we will refer to these misaligned outflows as ‘kinetic jets’. As we demonstrate in this study, these features can be produced by the kinetic streaming of high-energy NT particles that escape the shocked pulsar wind near the head of the bow shock nebula, a scenario proposed by Bandiera (2008) to explain the linear feature observed in the Guitar Nebula.

Importantly, in nearly all cases, these extended features show a remarkable asymmetry with respect to the PWN axis, displaying emission much more extended in one direction than in the other – previously interpreted as a ‘counter-jet’ (see e.g. Pavan et al. 2014, 2016; no counter-feature is seen in J1509). Furthermore, these ‘double-jet’ features can display significantly differing surface brightnesses, often attributed to the Doppler boosting of synchrotron emission from these collimated outflows in opposite directions. However, the spectral properties of these jet-like features are difficult to explain in a ballistic jet scenario for some systems (Johnson & Wang 2010; Pavan et al. 2016), for which alternative mechanisms (e.g. particle re-acceleration along the jets) may be invoked (see Bykov et al. 2017).

Bandiera (2008) proposed a scenario in which the long jet-like X-ray feature observed in Guitar Nebula arises due to the leakage of high-energy electrons accelerated at the bow shock region. When the gyroradii of high-energy particles exceed the bow shock standoff distance, they can no longer be contained within the bow shock and escape, crossing the contact discontinuity and gyrating along the ISM magnetic field. This scenario explains the apparent linear morphology and seemingly random offset from the pulsar velocity of these features (which trace the ISM field lines) as well as their relatively large sizes.

In this paper, we further develop this model and confirm the properties of extended jet-like features expected in that scenario through dedicated 3D numerical simulations of ‘kinetic jets’ emanating from fast-moving pulsars, assuming a range of conditions for the system and surrounding ISM properties. The set-up of these numerical simulations is outlined in Section 3.2, and the obtained results are reported in Section 4, where it is shown that ISM magnetic field lines reconnect with pulsar wind magnetic field lines, leading to an asymmetrical configuration for NT particle escape. The applications of our simulations to some fast-moving PWNe displaying extended X-ray jet-like features are discussed in Section 5. The final conclusions of this study are summarized in Section 7.

2 KINETIC JETS IN BOW SHOCK PWNE

2.1 Overall properties

About 30 runaway pulsars moving through the ISM at supersonic velocities have been identified so far, based on observational properties obtained either in optical (e.g. through the detection of Hα emission lines produced around their bow-shocks) or via the synchrotron emission seen in radio and X-rays (see e.g. Kargaltsev et al. 2017b for a review).

In the four previously reported instances of kinetic jets mentioned above, the pulsars move at velocities ranging from about \( v_p = 61 \text{ km s}^{-1} \) (\( \mu = 12.3 \pm 0.4 \text{ mas yr}^{-1} \) for B0355 + 54, Chatterjee et al. 2004) to \( v_p = 765^{+158}_{-85} \text{ km s}^{-1} \) (Deller et al. 2018), and possibly up to \( v_p \sim 1000 \text{ km s}^{-1} \) for PSR J1101-6101 (inferred from the measurements of the bow shock stand-off distance; see equation (1) and Pavan et al. 2016). The pulsar characteristic ages span from about 10^6 yr, considered ‘middle-aged’ for PWNe, to 10^9 yr for B2224 + 65, which is the oldest pulsar known with an X-ray PWN.\(^1\) Their spin-down powers range from \( E = 1.3 \times 10^{36} \text{ erg s}^{-1} \) (PSR J1101-6101), typical of young to middle-aged energetic pulsars, to \( E = 1.2 \times 10^{35} \text{ erg s}^{-1} \) (PSR B2224 + 65), the least energetic pulsar with an X-ray nebula. Total X-ray luminosities for these sources lie between \( L_X \sim 10^{36} \) and \( 10^{35} \text{ erg s}^{-1} \) (see Kargaltsev & Pavlov 2008 and references therein). Compared to the larger population of X-ray PWNe, the Guitar is an outlier both in its low spin-down power, old age, and extremely high velocity. Kinetic jets from PWN can show lengths from a few to more than 10 pc (e.g. in the Lighthouse Nebula), and display an orientation with respect to the pulsar proper motion (misalignment) in the range of \( \sim 33^\circ \) (e.g. in J1509-5850; Klingler et al. 2016a), to \( \sim 118^\circ \) (in the Guitar Nebula; Hui et al. 2012). The outflows are remarkably narrow, with width-to-length ratios of \( \sim 0.15 \) to 0.20, and can have counter-jets extending along the same direction symmetrically with respect to pulsar position, but displaying a much lower luminosity. The width, on the other hand, can be attributed (in the kinetic jet scenario studied here) to the diffusion of high-energy particles into several quasi-parallel magnetic field lines of the surrounding medium.

The X-ray luminosity of kinetic jets can range from \( \sim 1/3 \) of the total X-ray luminosity of the PWN (e.g. in the Lighthouse Nebula; Pavan et al. 2014; and J1509) to 0.07 (in B0355). Their spectra do not show significant changes either along the main axis nor in the transverse direction,\(^2\) implying that cooling time-scales (e.g. via

\(^1\)Note that in the Guitar Nebula, only an Hα bow shock and the kinetic jet are present; no synchrotron tail is seen, unlike the other instances.

\(^2\)The J1509 outflow shows possible evidence of spectral cooling, as \( \Gamma \) changes from 1.50 ± 0.20 to 1.98 ± 0.11 between the near- and far-halves
synchrotron emission) are longer than the particles’ propagation time-scale along across the jet. Kinetic jets display relatively high spectra, $\Gamma_{\text{Guitar}} \approx 1.3 \pm 0.1$, $\Gamma_{\text{Lighthouse}} = 1.7 \pm 0.1$, $\Gamma_{\text{J1509}} = 1.81 \pm 0.10$, and $\Gamma_{\text{B055}} = 1.6 \pm 0.3$. In all cases (except the Guitar, which does not have a detectable synchrotron bow shock CN), the spectra of the kinetic jets are approximately the same as the spectra of the CN from which they originate. It is also worth noting that none of the kinetic jets are seen in radio, even when their PWNe are (e.g. J1509 and the Lighthouse). This is likely because the magnetic bottling effects that occur near the reconnection zones suppress the escaping of low-energy particles that produce the radio emission.

Additionally, evidence of another kinetic jet has been reported in the PWN of the old ($\tau = 1.2 \text{Myr}$) radio-quiet, $\gamma$-ray pulsar J2055 + 2539 ($E = 5 \times 10^{35} \text{erg s}^{-1}$) by Marelli et al. (2016). This PWN features highly collimated 12 arcmin and 4 arcmin outflows, interpreted as a kinetic jet and synchrotron tail (though it is not clear which is which, as the proper motion of the pulsar is not yet known). Although both extensions feature spectra typical of kinetic jets and tails, $\Gamma = 1.82 \pm 0.08$ and $1.62 \pm 0.2$, their spectra can also be described by thermal bremsstrahlung models. This is reminiscent of PSR J0357 + 3205 (a.k.a. Morla; Marelli et al. 2013), which also features a collimated outflow whose spectrum can be adequately described by either a power-law (PL) or bremsstrahlung model, but which is aligned with the direction of pulsar motion yet puzzlingly ‘disconnected’ from the pulsar by $\sim 30$ arcsec.

### 2.2 Kinetic jets of the Dragonfly PWN (PSR J2021 + 3651)

PSR J2021 + 3651, producing the Dragonfly PWN, is a young ($\tau_c = P/(2P) = 17 \text{kyr}$), energetic ($E = 3.4 \times 10^{36} \text{erg s}^{-1}$), Vela-like pulsar with period $P = 103.7$ ms. Its dispersion measure of 369 pc cm$^{-3}$ suggests a distance $d \sim 10.5$ kpc (using the Yao, Manchester & Wang 2017 electron density model), however, after accounting for deep Chandra observations, Van Etten, Romani & Ng (2008) argue its estimated distance is more likely in the 3–4 kpc range. Although its velocity is not known, the PWN clearly displays a bow shock head and a small pulsar tail (see Fig. 2). The large projected stand-off distance of the bow shock apex (43 arcsec; 0.8 pc at 4 kpc) and the fact that the torus and jets are not deformed by the ram pressure suggest that the pulsar is only mildly supersonic. Indeed, estimating the pulsar velocity from balancing the pulsar wind and ram pressure gives $v_p = (E/4\pi cmn_r^2)^{1/2} \sim 10 \text{ km s}^{-1}$, suggesting the pulsar is mildly supersonic with the ISM in the cold phase (in which the sound speed $c_s \sim 0.1$ km s$^{-1}$) for an assumed typical hydrogen number density $n_H = 1 \text{ cm}^{-3}$ (where $m$ is the mass of hydrogen). Note that the above estimate assumes an isotropic wind, which is not the case here; thus the actual velocity is likely higher. The orientation of the torus with respect to the pulsar’s direction of motion suggests it is moving with a velocity vector offset from its spin axis by $\sim 45^\circ$, making it a useful reference with which to compare our simulations of the slow case (see next).

An extended narrow structure is seen protruding from the bow shock up to 7 arcmin ahead of the pulsar (see Fig. 2). Van Etten et al. (2008) report that the spectrum of the so-called ‘arc’ structure is best fit with an absorbed PL model with slope $\Gamma = 1.66 \pm 0.25$ – a hard spectrum that is typical of kinetic jets.

### 2.3 G327.1–1.1 and MSH 11–62: ‘snail eyes’ morphology

Two young PWNe residing in their host SNRs have been observed to feature prong-like outflows (morphologically resembling ‘snail eyes’) ahead of their bow shocks, oriented parallel to the direction of pulsar motion: the ‘snail PWN’ in G327.1–1.1 (Temim et al. 2009) and MSH 11–62 (G291.0–0.1; Slane et al. 2012), see Fig. 3. These structures exhibit PL spectra typical of kinetic jets, with $\Gamma \approx 1.8$ and $\approx 1.4$, respectively (see figs 1 and 3 of Kargaltsev et al. 2017a and Temim et al. 2015, respectively). The proper motion of these pulsars is not known, although simulations by Temim et al. (2015) suggest a typical velocity $v_p \sim 400$ km s$^{-1}$ for the pulsar producing...
3.3 Magnetic field geometries

One of the most surprising facts about kinetic jets is that they are highly asymmetric, extending much further out on one side of the pulsar than they do on the other (see e.g. Fig. 1). These asymmetries can be explained as the effects of asymmetric magnetic bottling at
the incoming and outgoing parts of magnetic field lines, see Fig. 4. Qualitatively, the paths for escaping particles along incoming and outgoing parts of the magnetic field lines are somewhat different due to intrinsic asymmetries of the PWN and orientation of the ISM field.

The PWN–ISM interaction depends both on the intrinsic properties of the PWN and the orientation of the ISM magnetic field. To distinguish various intrinsic asymmetries, we introduce three distinct orientations of pulsar spin axis relative to its direction motion in the ISM and the plane of the sky: (i) bullet geometry, where the pulsar rotation axis is parallel to the direction of motion and both are in the plane of the sky; (ii) frisbee geometry, where the pulsar rotation axis is perpendicular to the direction of motion and lies in the plane of the sky; and (iii) cartwheel geometry, where the pulsar rotation axis is parallel to the direction of motion and is perpendicular to the plane of the sky (for more details see Barkov et al. 2019). The frisbee and cartwheel configurations are physically the same, but have different lines of sight (with respect to the pulsar spin axis).

If the ISM magnetic field lines are perpendicular to the direction of the pulsar motion and the pulsar has a frisbee or bullet orientation, then each of the ISM magnetic field lines has another magnetic field line in the ISM that, after reconnection, will be equally likely to leak NT particles from the pulsar wind zone. Such configurations will form symmetric kinetic jet-like structures. For asymmetric kinetic jets to form, the symmetry must be broken. This can happen by a mixed configuration between frisbee and bullet (i.e. if the pulsar spin axis is not perpendicular or parallel to the direction of motion), or if the magnetic field is not oriented perpendicular to the direction of motion. Next, we will model the former configuration.

### 3.4 Initial set-up

We start our simulation from a non-equilibrium configuration and evolve it up to a time at which quasi-stationary solutions will be settled. From the left edge ($X = -4$), we inject the ISM with Mach number $M = 85$ ($M \equiv v_p/c_{ISM}$). We set-up the ISM speed (pulsar speed) as $v_p = 0.0033c$ (slow model) and $v_p = 0.1c$ (fast model). Unrealistically high ISM speed leads to drastic saving of computational resources, which is proportional to $\propto 1/v_p$. The density of the ISM was adopted so that in the case of non-magnetized spherical pulsed wind, the bow shock will be formed at a position near $(-1, 0, 0)$, so our grid is scaled to the stand-off distance $r_s$ (see equation 1). The smaller value of the ISM speed value is more realistic and corresponds to the velocity of PSR J1101–6101, the higher velocity corresponds to the ISM velocity of our another study (Barkov et al. 2019).

Here, we use the pulsar wind set-up described by Porth, Komissarov & Keppens (2014) and Barkov et al. (2019). A pulsar with radius 0.2 is placed at the point (0, 0, 0). The pulsar emits unshocked magnetized pulsed wind with a toroidal magnetic field that changes its polarity in the North and South hemispheres.

The pulsar wind was injected with initial bulk Lorentz factor $\Gamma_{lor} = 1.9$, magnetization $\sigma = 1$, and Mach number 15, the temperature of the pulsar wind was small, but not zero, and the wind accelerated in the end up to $\Gamma_{lor, final} = 2.5$.

We choose one orientation, frisbee bullet, which is formed by a clockwise rotation of the frisbee configuration$^6$ around $\gamma$-axis by angle $\theta = \pi/4$ (see for more details Barkov et al. 2019) i.e. we set an angle of $\pi/4$ between spin axis and the pulsar velocity, see Fig. 5.

The ISM has a weak magnetization $\sigma_{ISM} = 0.01$, formed by a uniform magnetic field, which is normal to the velocity vector (parallel to the $z$-axis) and inclined by $\pi/4$ counterclockwise relative to the $z$-axis.

### 4 RESULTS

The anisotropic ram pressure of the ISM forms a bow shock (see Fig. 6). The pulsar wind is deflected to the direction opposite of the pulsar motion. Inside the contact discontinuity, the pulsar winds form two jet-like outflows. The part of the top front outflow is deflected and turned down and back. This deflected flow has a magnetic field with an opposite twist direction compared to the magnetic field twist of the bottom back flow. The pulsar wind forms an asymmetric structure that has a relatively simple jet-like structure on top with homogeneous twist; the bottom flow is stronger and has a more complicated magnetic field topology with the reverse magnetic field twist structure, see Fig. 7. The magnetic field lines there are launched in both directions from starting points on a sphere of radius 1.5 placed at point (0, 0, 0).

The anisotropic pulsar wind forms a curved shock that appears to come close to the injection radius, but they are separated by at least several computational cells.

Comparing the slow and fast models, we see generally similar solutions: the formation two jet-like structures with simpler structures at the upper part and more sophisticated at lower parts. On the other hand, Fig. 8 shows significant differences in the number of magnetic field lines from the ISM that penetrate into the pulsar wind zone. This fact can be explained by differences in the ISM speed and instabilities, which trigger the reconnection and have more time to grow in the slow model.

### 4.1 Emissivity maps

Here, we create illustrative emissivity maps of two kinds, using the same approach as described in our previous work (Barkov & Bosch-Ramon 2018; Barkov et al. 2019). In an ideal RMHD simulation, we have no direct information about NT particle spectra and densities,

$^6$The limitations in computational resources and requirements to solve many dynamical scales of the system push us to have a relatively low spatial resolution near the pulsar. Thus, we are limited by the values of pulsar wind Lorentz factors that can be stably calculated. In reality, the Lorentz factor should be larger, but as a first step this is sufficient approximation that produces all the main features of ultrarelativistic flows (e.g. see the comparison of the dynamics of $\Gamma = 2$ and $\Gamma = 10$ in the paper by Bosch-Ramon et al. 2012).
so we assume that in the shocks some fraction of the thermal energy is transferred to NT particles. Also, here we did not take into account effects connected to NT particle spectra. The volume emissivity for synchrotron radiation is proportional to the NT particle’s density and inversely proportional to the cooling time, which is proportional to the co-moving magnetic field energy density (see Fig. 9).

In both left-hand and right-hand panels of Fig. 9, we see the formation of asymmetric jet-like structures and fainter equatorial outflows. In the synchrotron maps, jet-like structures appear to be much more visible. If the pulsar moves towards us (upper panels), we see an asymmetric structure with a brighter bottom/back jet structure. If we look at the PWNe from the side (perpendicular to its direction of motion), we see the asymmetric jet-like structure. If we view the system from the ‘top’, jet-like structures merge and become a bright head narrow tail structure. In all cases, on the synchrotron maps, the equatorial flow is less visible. Morphologically, the fast and slow models are similar.

Both slow and fast models show therefore very similar morphologies and emissivity maps, so the results of Barkov et al. (2019) can be safely extrapolated to much slower pulsars.

5 DYNAMICS AND MORPHOLOGY OF KINETIC JETS

5.1 Magnetic field connection time

The stand-off distance, equation (1), is $r_s \approx 10^{16} n_0^{-1/2} v_p^{-1}$ cm. The travel time to the stand-off distance is given by

$$t_s = \frac{r_s}{v_p} = 4 n_0^{-1/2} v_p^{-2} \text{ yr.}$$

We expect that $t_s$ is the typical time that any ISM field line remains connected to the pulsar wind.
Kinetic ‘jets’ from rapid pulsars

For an ISM field of value $B$ and observed photon energy $\epsilon$, the required Lorentz factor of the radiating particles is

$$\gamma_w \sim \sqrt{\frac{m_e c^2 \epsilon}{e B}} = 2 \times 10^{7.5} \epsilon^{1/2} \gamma, \quad 1 \text{ k.e.V} \ B^{-3/2},$$

(3)

Such values can be expected in pulsar winds, cf. Kennel & Coroniti (1984a). Leptons with such Lorentz factors have a relatively small Larmor radius ($r_L = 3 \times 10^{14} \epsilon^{1/2} \gamma, \text{1 keV} B^{-3/2}, \text{cm}$) as compared to the stand-off distance $r_s$. In the pulsar tail, the magnetic field drops and the Larmor radius of high-energy electrons can be comparable with the tail cross-section, so they can start to escape. This fact can explain some shift of kinetic-jet foot-point in the case of PSR J1101–6101. The escape region for high-energy particles should be closer to the PWNe bow shock head, and this can be verified observationally as a spectral shift. The spectra of the leading edge of the kinetic jet near its origin should be harder. The corresponding synchrotron cooling time

$$\tau_c = \left(\frac{3}{2}\right)^{5/2} \frac{1}{e^2} \left(\frac{m_e c^2}{e \epsilon}ight)^{1/2} \gamma, \text{1 keV} B^{-3/2}, \text{yr},$$

(4)

is comparable, but somewhat larger than the travel time (2). Thus, we do not expect any spectral evolution along the kinetic jets.

5.2 Structure of kinetic jets away from the PWN: magnetic bottles/antibottles?

Next, let us discuss what determines the morphology of the kinetic jets away from the PWN. For example, in the case of the Lighthouse Nebula, Fig. 1, the kinetic jets consist of several elongated features. This prompts the question of what processes give rise to these features. Importantly, the elongated features show nearly constant emissivity along their length. This places interesting constraints on their nature as we discuss next.

One way to produce disconnected elongated features is with magnetic bottles in the ISM (see Fig. 10). Consider a beam of particles with angular distribution $f \propto \mu_0$ at the bottle neck (where the magnetic field is maximal, $B_{\text{max}}$). As the beam propagates into the regions of smaller magnetic field with $R = B/B_{\text{max}} < 1$, the pitch angle of the particles decreases; at any given $R$ the maximal pitch angle corresponds to $\mu_{\text{min}} = \sqrt{1 - R}$. The synchrotron emission integrated over the bottle cross-section is then

$$\propto R^2 \frac{1}{R} \int_{\mu_{\text{min}}}^{1} f_0(\mu_0(\mu, R))(1 - \mu^2),$$

(5)

where the terms $R^2$ and $(1 - \mu^2)$ account for synchrotron luminosity $\propto B^2 \sin^2 \psi$, the term $1/R$ accounts for changing cross-section of the bottle $S$ (magnetic flux is conserved, $SB = \text{constant}$), and in the distribution function the initial pitch angle $\mu_0$ should be expressed in terms of current $\mu$ and mirror ratio $R$. 
As an example, let us consider two cases of isotropic distributions $\alpha = 0$ and parallel beam $\alpha = 2$. Let the magnetic bottle have a minimal magnetic field two times smaller than in the bottle neck, e.g. $R = 1 - (1/2)\sin z$, where $z$ is the coordinate along the magnetic field line. The resulting synchrotron profile has peaks near the bottles’ necks, contrary to observations. We conclude that the morphology of the kinetic jets is not due to magnetic bottles in the ISM.

Analogously, in the case of antibottle, the synchrotron flux peaks in the region of highest magnetic field (approximately by the mirror ratio $R > 1$), defined with respect to some fiducial value. For long bottles with nearly constant cross-section, this will produce nearly constant synchrotron luminosity.

In conclusion, both ballistically moving kinetic jets as well as magnetic antibottles in the ISM may reproduce the morphological feature. The key distinction is the temporal changes: in the case of ballistically moving jets we expect to see very quick morphological changes. In another case, we predict changes in the features on the time-scales on the order of a decade, see equation (2).

### 5.3 Jet anisotropy

One of the most surprising facts about kinetic jets is that often they are highly asymmetric, extending far out on the one side of the pulsar, e.g. Fig. 1. Next, we discuss two possibilities for this asymmetry: Doppler boosting and asymmetric magnetic bottles. After rejecting the Doppler-boosting possibility, Section 5.3.1, we explain these asymmetries due to effects of asymmetric magnetic bottling, see Sections 5.3.2 and 5.2.
5.3.1 Doppler boosting?

Can the brightness difference between the X-ray structures propagating out of the Lighthouse Nebulae be due to Doppler boosting/de-boosting?

The luminosity of the continuous jet with Doppler boosting can be written as (Sikora et al. 1997)

\[ L_{\text{obs}} = \frac{\delta^3}{\Gamma_{\text{jet}}} L_{\text{emitted}}, \]

where \( \delta = 1/|\Gamma_{\text{jet}}(1 - \beta \cos \theta)| \) is the Doppler factor, \( \Gamma_{\text{jet}} = 1/\sqrt{1 - \beta^2} \) is the Lorentz factor of the jet particles, and \( \beta = v_{\text{jet}}/c \) is the bulk flow velocity of the jet. If we have two symmetrical jets, the relative brightness is given by \( A \equiv (L_{\text{obs}}/L'_{\text{obs}})^{1/3} \geq 1 \), where ‘′ and ″ denote the ‘approaching’ and ‘receding’ outflows, respectively. From equation (6), we obtain the following expression

\[ \beta \cos \theta = \frac{A - 1}{A + 1}. \]  

Thus, we can place a very modest restriction on the bulk Lorentz factor and mildly relativistic outflow with \( \beta > 0.4 \) or \( \Gamma > 1.1 \) to explain the brightness difference \( A \sim 2 \) or \( L_{\text{obs}}/L'_{\text{obs}} \sim 10 \).

On the other hand, large Lorentz factors will lead us to \( \beta \approx 1 \) and a viewing angle cosine of \( \cos \theta \sim (A - 1)/(A + 1) \). The Doppler factor will take the following form \( \delta \approx (A + 1)/2\Gamma_{\text{jet}} \). The Doppler boosting will require a jet luminosity on the level

\[ L_{\text{obs}} \approx \frac{8\Gamma_{\text{jet}}^4}{(A + 1)^3} L_{\text{emitted}}. \]

Taking into account the total energy budget of the PWNe (\( L_{\text{emitted}} \ll \dot{E} \)), we can find an upper limit on the bulk jet’s Lorentz factor as

\[ \Gamma_{\text{jet}} \ll \left( \frac{A + 1}{8} \right)^{1/4} \dot{E}^{1/4} \sim 5 E_{16}^{1/4} L_{\text{obs},3.5}. \]

Hence, we conclude that the brightness difference between the oppositely propagating highly relativistic jets cannot be only due to Doppler boosting/de-boosting.

5.3.2 Jet anisotropy – non-symmetric magnetic bottles

As the external magnetic field connects to the pulsar wind, we expect that the incoming and outgoing parts of magnetic field lines will have different structure, see Figs 4–11 for qualitative descriptions. The paths for escaping particles along incoming and outgoing parts of the magnetic field lines are somewhat different due to intrinsic asymmetries of the PWN and orientation of the ISM field. Fluctuations of the magnetic field will generate in the collisionless plasma magnetic bottles that will partially prevent the particles from escaping.

Let us consider isotropic injection of relativistic particles on to an open field line (e.g. near the point \( x = 6 \) in Fig. 11). As particles propagate along the field, they experience partial reflection at magnetic bottles due to the requirement of the conserved first adiabatic invariant \( \sin^2 \psi R \), where \( \psi \) is the pitch angle and \( R \equiv B/B_0 \geq 1 \) is the mirror ratio. In the case of no scattering, the flux of particles that pass through depends on the highest value of the mirror ratio along a given field line.

The conservation of the first adiabatic invariant in a collisionless plasma leads to the following gyration-averaged equation for the distribution function (Roelof 1969; Kulsrud 2005, Chapter 8)

\[ \mu \dot{\psi} f = -\frac{1}{2} \frac{\partial}{\partial \mu} \ln B (1 - \mu^2) \dot{\mu} f = 0, \]

where \( \mu = \cos \psi \), and \( \psi \) is the pitch angle. Equation (10) can be integrated along particles’ trajectories \( (1 - \mu^2)/R = \text{constant} \) to give

\[ f = f ((1 - \mu^2)/R) = f_0(\mu_0), \]

where \( f_0(\mu_0) \) is a given pitch angle distribution at \( R = 1 \).

Suppose a magnetic mirror forms between the internal PWN plasma with isotropic distribution and the ISM. The distribution of the escaping particles in the ISM then remains isotropic, while the fraction of particles that pass through the mirror is

\[ p_{\text{esc}} = 1 - \sqrt{1 - \frac{1}{R}} \approx \frac{1}{2R}, \]

where the last relation assumes \( R \gg 1 \) (at the same time the escaping flux is 1/R). For multiple mirrors and without any scattering, it is the maximal \( R \) that determines the escaping fraction.

Thus, we expect that if two escaping trajectories (at the entry/exit points of the magnetic field lines) encounter different magnetic bottles, the ratio of the escaping fraction will be of the order of the ratio of the maximal mirror ratios \( R \).

For example, according to Fig. 11, the average field near the origin is \( B \sim 0.2 \) (in arbitrary units), while the maximal field at
Figure 11. Right-hand panel: Magnetic field streamlines for the slow model. The magnetic field lines enter the pulsar wind via reconnection at the boundary. Left-hand panel: value of magnetic field along the magnetic field lines. Note the left–right asymmetry (corresponding to the incoming–outgoing parts of magnetic field lines). In the particular example, the left section (negative abscissa points) has much larger fluctuations of field strength. This will lead to the formation of magnetic bottles that would reflect a larger fraction of PWN particles than the smoother section on the opposite side (positive abscissa points), leading to asymmetric outflows. On the other hand, we see many field lines with more or less symmetrical outflow paths.
negative line coordinates is $B \sim 2$. Thus, $R_{\text{PWN}} \sim 10$ and $p_{\text{esc}} \approx 0.05$ – suggesting only 5 per cent of injected particles will escape. On the other hand, at positive line coordinates, the maximal field is $B \sim 0.5$, which gives $R \sim 2.5$ and $p_{\text{esc}} \approx 0.22$ – approximately four times larger.

The particle speed along the field line is close to the speed of light. The distance along the field lines is of the order of several tens of standing radii, so we can estimate the escape time to be $20 r / c$. The advection time in the pulsar wind tail is about $r_{\text{wind}} / v_{\text{stream}} \sim 15 r / c$, so both time-scales are similar. Taking into account the fast change of the reconnection structure (the escape lines change strongly from time snapshot to time snapshot) in the tail, the escape processes can have a chaotic behaviour with some statistical preference along one direction with respect to another.

In the case of the Lighthouse PWN, Pavan et al. (2016) find that the ratio of jet-counter jet surface brightness is much higher, $\sim 40$. This high ratio can be due to, e.g. special configurations of the fields not captured in our simulation (due to high computational costs we were not able to explore in detail such specific configurations). Alternatively, pitch angle scattering between the multiple magnetic bottles may lead to a higher jet-counter jet brightness ratio. (For example, if particles are isolated between each bottle, the total escaping fraction will be the product of the escaping fractions from each bottle.)

5.3.3 Jet anisotropy – magnetic antibottles in ISM

Last but not the least, the explanation of the ‘jet’ anisotropy can be due to a non-uniform distribution of magnetic fields in the ISM. The NT particles can escape from the shocked pulsar wind in all directions. As we discussed in Section 5.2, the so-called ‘antibottles’ (filaments with high magnetic fields in ISM) can make these particles visible in X-rays. So, if a pulsar crosses an antibottle not close to its centre, but near its side, then we may see strongly anisotropic ‘jets’.

5.4 Jet-induced kink instability

Finally, let us comment on a suggestion by Pavan et al. (2014) that the features of the kinetic jet arise due to kink instabilities produced by the streaming of escaping particles. Pulsars produced charge separated flows with typical currents of the order of

$$I \sim \sqrt{eE}. \tag{13}$$

If a fraction $N_{\text{esc}} \ll 1$ of this current escapes through a hole of the typical size $r_{\text{esc}} \sim \sqrt{N_{\text{esc}} r}$, this will produce an induced (toroidal) magnetic field in the ISM order of $B_{\text{ind}} \sim 2 v_{\text{esc}} / c r_{\text{esc}} \sim v_e \sqrt{4\pi N_{\text{esc}} \rho_{\text{ISM}}}$. The ratio of the induced magnetic field to the ISM field is then

$$B_{\text{ind}} / B_{\text{ISM}} \sim \sqrt{N_{\text{esc}} \rho_{\text{ISM}}}, \tag{14}$$

where $M_{\text{ISM}} \gg 1$ is the Mach number of the pulsar with respect to the ISM sound speed, and $\rho_{\text{ISM}} = p_{\text{ISM}} / \rho_e \leq 1$ is the ISM beta parameter. This ratio can be, under certain circumstances, larger than unity, so that the magnetic field induced by the escaping charge-separated flows can indeed distort the ISM fields considerably.

6 APPLICATION

6.1 The Lighthouse PWN (PSR J1101–6101)

In this system, a fairly energetic pulsar, PSR J1101–6101 (spin-down power $E = 1.36 \times 10^{36}$ erg s$^{-1}$, distance $\sim 7$ kpc), produces an emission feature extending $\sim 11$ pc with a total X-ray luminosity $L \sim 3 \times 10^{33}$ erg s$^{-1}$ (Pavan et al. 2016). The kinetic jet light crossing time $t_{\text{esc}} = D_\parallel / c \approx 40$ yr can be close to the NT particle propagation time. Thus, we do not expect spectral evolution along the kinetic jet, which is consistent with the roughly constant spectrum $\Gamma \approx 1.6$ reported by Pavan et al. (2016).

In the case of the Lighthouse PWN, the X-ray luminosity of the kinetic jet is $L \sim 3 \times 10^{33}$ erg s$^{-1}$ (for a distance of 7 kpc). This then requires

$$N_{\text{em}} \approx \frac{t_{\text{esc}} L}{\gamma_{\text{em}} m_c c^2} \approx 2 \times 10^{44} \tag{15}$$

emitting particles.

Let us assume that, after the termination shock, the pulsar wind has magnetization $\sigma_s \sim 1$ and bulk Lorentz factor $\gamma_{\text{em}}$ given by equation (3), so that the spin-down power can be estimated as $E = \gamma_{\text{em}} m_c c^2 N$, where $N$ is number of pairs produced by the pulsar per second. The number of particles that a pulsar produces during time $t_e$ is then $N_p = N t_e$. Thus, the fraction

$$N_{\text{em}} / N_p = \frac{t_{\text{esc}} L}{E t_e} \approx \frac{L_{\text{esc}}^{1/2} v_{\text{esc}}}{E^{1/2} \gamma_{\text{em}} c t_{\text{esc}}^2} \ll 1 \tag{16}$$

is required to preserve the number of NT particles. Now, we can derive a lower limit for the ISM magnetic field strength as

$$B_{100 \mu G} \gtrsim 0.02 \left( \frac{L_{\text{esc}}^{1/2} v_{\text{esc}}}{E^{1/2} \gamma_{\text{em}} c t_{\text{esc}}^2} \right)^{1/3}. \tag{17}$$

Given the uncertainties in the parameters, $B_{100 \mu G} > 0.1$ is a reasonable estimation. In other words, the formation of kinetic jets requires not only the reconnection of the pulsar wind magnetic field with the ISM field, but also a high ISM magnetic field strength.

The estimate of the connection time (2) fits well with the linear size of the emission feature. Although the total size is 11 pc, the morphology of the feature (see Fig. 1) shows two separate seemingly disjointed components, each roughly half the size of the jet, $\sim 5$ pc. This gives an excellent correspondence to the connection time (2) of $\sim 15$ yr.

6.2 G327.1–1.1 and MSH 11–62: ‘snail eyes’ morphology

In the case of a magnetic field aligned with the direction of the pulsar motion, the most probable reconnection sites will appear in diagonally placed quadrants relative to pulsar equatorial plane. In Fig. 12, we provide a schematic sketch of the magnetic field topology formed in the frisbee configuration (see Fig. 8 and the magnetic field topology in the work of Barkov et al. 2019). The red ellipses indicate the most probable reconnection zones. Such reconnection zones can form foot-points for the formation of double kinetic jets as seen in the cases of G327.1–1.1 and MSH 11–62.

The symmetry of the jets (both structure and brightness) of G327.1–1.1 (the snail PWN) and MSH 11–62 indicates that the pulsars’ motions are symmetric with respect to the magnetic fields ahead of the bow shock (i.e. they are aligned with the directions of pulsar velocity), and that reconnection is occurring in opposite sides of the bow shocks, in the manner illustrated in Fig. 12. Indeed, radio
polarimetry measurements have revealed that the magnetic field in the snail PWN bow shock is aligned with the pulsar's direction of motion and the jets (see fig. 7 of Ma et al. 2016), and that the magnetic field both in and ahead of the bow shock are aligned with the jets and the inferred direction of motion of the pulsar in MSH 11–62 (see fig. 3 of Roger et al. 1986), thus providing evidence of the parallel reconnection scenario.7

7 CONCLUSIONS

In this paper, we advance a model of extended emission features observed in some bow shock PWNe as kinetic flows of high-energy particles that escaped pulsar winds due to reconnection between the wind and the ISM magnetic fields, confirming the model of Bandiera (2008). As the particles escape the PWN, they propagate along ISM magnetic fields producing synchrotron emission that highlights the structure of the ISM magnetic field.

We expect that the geometrical properties in each particular case – inclination of the pulsar magnetic moment to the spin axis, the direction of pulsar motion, and the orientation of the external magnetic field, as well as magnetic structures in the ISM – can lead to a variety of shapes of kinetic jets. For example, the strong asymmetry of the kinetic jets in case of the Lighthouse and the Guitar nebulae can arise from asymmetric structures of the reconnecting magnetic filed lines, while the double kinetic jets (‘snail eyes’ morphologies) can result in cases when a frisbee/cartwheel-type PWN propagates along the external magnetic field.

We argue that the appearance of the kinetic jets strongly depends on the structure of the magnetic field in the ISM, and, thus, can be used to probe magnetic fields in the ISM: kinetic jets highlight the high magnetic regions (antibottles) in the ISM.

If kinetic jets are triggered by the escape of NT particles from shocked pulsar wind, then this fact can be direct proof of the leakage of NT particles (electrons and positrons) into the ISM, and it serves as a bridge to observations with PAMELA and the AMS-2.

Finally, an important prediction of the model is that the morphology of the extended features should change on time-scales given by (2), i.e. on the order of a decade.

7We should remark that due to dynamical balance the magnetic field as in shocked ISM as in shocked pulsar wind should be the same order. It makes reconnection process faster.

ACKNOWLEDGEMENTS

We are very grateful to Oleg Kargaltsev, Shigehiro Nagataki, Susumu Inoe, and Rino Bandiera for the useful discussions. Also, we appreciate the anonymous referee for constructive suggestions and improvements in the quality of the paper. The calculations were carried out in the CFCA cluster of NAOJ. We thank the PLUTO team for the opportunity to use the PLUTO code and for providing technical support. The visualization of the results performed in the VISIT package (Hank Childs et al. 2012). This work had been supported by NSF grant AST-1306672, DoE grant DE-SC0016369, and NASA grant 80NSSC17K0757.

REFERENCES

Bandiera R., 2008, A&A, 490, L3
Barkov M. V., Bosch-Ramon V., 2018, MNRAS, 479, 1320
Barkov M. V., Komissarov S. S., 2016, MNRAS, 458, 1939
Barkov M. V., Lyutikov M., Khangulyan D., 2019, MNRAS, 484, 4760
Bosch-Ramon V., Barkov M. V., Khangulyan D., Peruchò M., 2012, A&A, 544, A59
Bosch-Ramon V., Barkov M. V., Peruchò M., 2015, A&A, 577, A89
Bykov A. M., Amato E., Petrov A. E., Krassilchichtchikov A. M., Levenfish K. P., 2017, Space Sci. Rev., 207, 235
Chatterjee S., Cordes J. M., Vlemmings W. H. T., Arzoumanian Z., Goss W. M., Lazio T. J. W., 2004, ApJ, 604, 339
Deller A. T. et al., 2018, preprint(arXiv:1808.09046)
Dursi L. J., Pfrommer C., 2008, ApJ, 677, 993
Gaensler B. M., Slane P. O., 2006, ARA&A, 44, 17
Hank Childs H. et al., 2012, High Performance Visualization–Enabling Extreme-Scale Scientific Insight, Chapman and Hall/CRC Computational Science, Taylor and Francis, p. 357
Harten A., 1983, J. Comput. Phys., 49, 357
Hui C. Y., Becker W., 2007, A&A, 467, 1209
Hui C. Y., Huang R. H. H., Trepl L., Tetzlaff N., Takata J., Wu E. M. H., Cheng K. S., 2012, ApJ, 747, 74
Johnson S. P., Wang Q. D., 2010, MNRAS, 408, 1216
Kargaltsev O., Pavlov G. G., 2008, in Bassa C., Wang Z., Cumming A., Kaspi V. M., eds, AIP Conf. Ser. Vol. 983, 40 Years of Pulsars: Millisecond Pulsars, Magnetars and More. Am. Inst. Phys., New York, p. 171
Kargaltsev O., Klingler N., Chastain S., Pavlov G. G., 2017a, J. Phys. Conf. Ser., 932, 012050
Kargaltsev O., Pavlov G. G., Klingler N., Rangelov B., 2017b, J. Plasma Phys., 83, 635830501
Kennel C. F., Coroniti F. V., 1984a, ApJ, 283, 694
Kennel C. F., Coroniti F. V., 1984b, ApJ, 283, 710
Klingler N., Kargaltsev O., Rangelov B., Pavlov G. G., Posselt B., Ng C.-Y., 2016a, ApJ, 828, 70

Figure 12. Qualitative explanation of the ‘snail eyes’ morphology. In the frisbee/cartwheel geometry, the internal magnetic field changes direction in the four quadrants. (The internal magnetic field is depicted with the black lines – the field lines in the forefront are solid, the field lines in the rear are dashed.) External magnetic fields lines are parallel to the velocity vector. In the two opposite quadrants, the external fields are counteraligned with the internal fields (the thick blue lines), resulting in a reconnection of external and internal fields (the red regions). Left-hand panel: side view, right-hand panel: head-on view.
APPENDIX A: SYNCHROTRON EMISSION MAPS

The observed X-ray emission from PWNe is generated via synchrotron radiation by NT particles, which are presumably accelerated at shocks and/or in magnetic reconnection events downstream of the termination shock. Conventional ideal RMHD simulations produce only hydrodynamic quantities – density, thermal pressure, velocity, and magnetic field. Thus, we have no direct information about the energy distribution and density of NT particles. To obtain this additional information, one needs to perform dedicated simulations of the evolution of NT particles (see e.g. Kennel & Coroniti 1984b; Vaidya et al. 2018). However, if the particle cooling is dominated by adiabatic losses, one can use a simplified approach to reconstruct the spectrum of NT particles based on RMHD parameters only (see Barkov & Bosch-Ramon 2018).

We then employ the following procedure to produce emission maps from a given simulation’s output.

(i) Our simulations produce 3D distributions of pressure, density, velocity, and magnetic field.

(ii) Using local quantities \( p, \rho, \) and \( B \), we calculate the synchrotron emissivity according to various prescriptions described in Barkov et al. (2019).

(iii) For a given local synchrotron emissivity, we then choose a given line of sight and integrate the emissivity, assuming the optically thin regime and taking into account the local velocity and the corresponding Doppler factor.

To calculate the synchrotron emissivity, we first find the thermal energy in a given cell in the flow frame (here \( dV = \Gamma dV \)):

\[
u_{\text{cell,NT}} = n_{\text{NT}} u_{\text{cell}} = n_{\text{NT}} 3P \Gamma dV,
\]

where \( 3P \) is internal energy, \( dV \) is the cell volume in the lab frame, \( \Gamma \) is the bulk Lorentz factor, and \( n_{\text{NT}} \) is the NT particle fraction parameter (see details in Barkov & Bosch-Ramon 2018; Barkov et al. 2019).

For a magnetic field of value \( B \) (in flow frame) and observed photon energy \( \epsilon = \epsilon_\delta \) (here \( \delta = 1/\Gamma (1 - (\bar{v} \bar{h})/c) \)) is the Doppler factor and \( \bar{h} \) is the unit vector towards the observer), the required Lorentz factor of the radiating particles is

\[
\gamma_w \sim \sqrt{\frac{m_e c^2 \epsilon_\delta}{\epsilon_{\gamma,1\text{keV}} B_{-3}^{3/2}}}.
\]

Such values can be expected in pulsar winds, cf. Kennel & Coroniti (1984b).

The corresponding synchrotron cooling time

\[
t_{\text{syn}} = \left( \frac{3}{2} \right)^{5/4} \left( \frac{m_e c^2 \epsilon_\delta}{\epsilon_{\gamma,1\text{keV}} B_{-3}^3} \right)^{1/2} \approx 6 \times 10^7 \epsilon_{\gamma,1\text{keV}} B_{-3}^{-3/2} \text{ s}.
\]

The travel time of shocked pulsar wind to the stand-off distance is given by

\[
t_{\text{sw}} \approx \frac{r_s}{c} \approx 4 \times 10^5 n_{-1}^{-1/2} v_{p,8} \epsilon_{\gamma,1\text{keV}}^{1/2} \text{ s}.
\]

This time \( t_{\text{sw}} \) can be treated as the typical time-scale for adiabatic losses.

The synchrotron emissivity is then proportional to the NT particles’ energy density divided by the local cooling time:

\[
\epsilon_{\text{SY}} \propto \frac{u_{\text{cell,NT}}}{t_{\text{syn}}}.
\]

The radiation of a fast-moving plasma is affected by Doppler boosting, so the observer will see

\[
\epsilon_{\text{SY},\delta} \propto \frac{u_{\text{cell,NT}}}{t_{\text{syn}}} \delta^3 \Gamma^{-2/3}.
\]

To better illustrate the results of the calculations, we produce two kinds of emission maps, scaling the emissivity with \( \int \epsilon_{\delta} d\delta / \Gamma d\xi \) if the pulsar is moving towards the observer, and scaling the emissivity with \( \sqrt{\int \epsilon_{\delta} d\delta / \Gamma d\xi} \) if the pulsar moves sideways. The latter (somewhat arbitrary) choice allows us to better highlight weaker emission features.

This paper has been typeset from a TeX/LaTeX file prepared by the author.