On the nature of radio filaments near the Galactic Centre

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ABSTRACT

We suggest that narrow, long radio filaments near the Galactic Centre arise as kinetic jets — streams of high-energy particles escaping from ram pressure confined pulsar wind nebulae (PWNe). The reconnection between the PWN and interstellar magnetic field allows pulsar wind particles to escape, creating long narrow features. They are the low-frequency analogues of kinetic jets seen around some fast-moving pulsars, such as The Guitar and The Lighthouse PWNe. The radio filaments trace a population of pulsars also responsible for the Fermi GeV excess produced by the Inverse Compton scattering by the pulsar wind particles. The magnetic flux tubes are stretched radially by the large-scale Galactic winds. In addition to PWNe accelerated particles can be injected at supernovae remnants. The model predicts variations of the structure of the largest filaments on scales of \( \sim \) dozens of years – smaller variations can occur on shorter time-scales. We also encourage targeted observations of the brightest sections of the filaments and of the related unresolved point sources in search of the powering PWNe and pulsars.

Key words: acceleration of particles – stars: neutron – ISM: magnetic fields – Galaxy: centre.

1 INTRODUCTION

The central part of the Galaxy shows numerous non-thermal filaments (NTFs) (Yusef-Zadeh, Morris & Chance 1984; Yusef-Zadeh & Morris 1987; Morris & Serabyn 1996; MeerKAT Collaboration 2018), the largest been the Snake, G359.1-00.2, (Gray et al. 1995).

Key observational facts of NTFs are:

(i) Filaments are few parsecs to few tens of parsecs long, with mostly linear morphology.

(ii) Many NTFs show a clear bright central part, not associated with any resolved source; sometimes NTFs have associated compact sources.

(iii) Some filaments seem to be connected to an SNR.

(iv) Most of the NTFs are perpendicular to the Galactic plane to within 20 deg (Morris & Yusef-Zadeh 1985; Anantharamaiah et al. 1991).

(v) NTFs have constant flat spectral index \( F_\nu \propto \nu^0 \) (Yusef-Zadeh et al. 1984).

(vi) Polarization indicates magnetic field along the filaments (Gray et al. 1995; Lang, Morris & Echevarria 1999).

(vii) A turnover of the hard synchrotron spectrum at \( \sim 10\,\text{GHz} \) is observed (Boldyrev & Yusef-Zadeh 2006).

(viii) The brightest NTFs reach a total power of the order of \( 10^{33} \text{erg s}^{-1} \) at 5 GHz (Gray et al. 1995).

The most natural explanation for the radio filaments is that of a magnetic flux tube populated by highly relativistic particles (Yusef-Zadeh et al. 1984; Yusef-Zadeh & Morris 1987; Morris & Serabyn 1996). Shore & LaRosa (1999), Rosner & Bodo (1996), and Boldyrev & Yusef-Zadeh (2006) developed models of NTF as separate hydrodynamic entities. Alternatively, and we favour these interpretations, the observed filaments are the magnetic flux tubes that happen to be illuminated by the local injection of relativistic particles (Morris & Serabyn 1996). But what is the source of these particles?

In this paper we advance a model of Galactic Centre’s NTFs as low-frequency analogues of extended features seen around some ram pressure-confined PWN, such as the Guitar (Wong et al. 2003; Hui & Becker 2007; Johnson & Wang 2010) and the Lighthouse (Pavan et al. 2016). Using 3D relativistic MHD simulations (Barkov, Lyutikov & Khangulyan 2019a; Barkov et al. 2019b) showed that these features can’t have hydrodynamical origin and have to be kinetically streaming pulsar wind particles that escaped into the interstellar medium (ISM) due to reconnection between the PWN and ISM magnetic fields (see also Bandiera 2008).

In our model, see Fig. 1, the magnetic field is accumulated in the gaseous disc (Sofue, Fujimoto & Wielebinski 1986; Molinari et al. 2011; Barkov & Bosch-Ramon 2014), while the disc winds stretches the field lines open in vertical direction (Ponti et al. 2019).
The gas in outflow is hot with characteristic pressure 200 eV cm$^{-3}$, which corresponds to magnetic field strength about 10$^{-4}$ G. The width of the magnetic filaments can be connected with size of the turbulent cell in the gaseous disc around Galactic Centre, so can be much smaller compare the disc radius. On other hand the vertical size can be comparable with significant fraction of the disc radius.

A collection of millisecond pulsars (MPSs) (Bartels, Krishnamurthy & Weniger 2016) are orbiting the central regions with virial velocities of $\sim$300 km s$^{-1}$. Interaction of the MSPs with the surrounding plasma creates bow-shock PWNe, with sizes too small to be resolved, a fraction of an arcsecond, equation (1).

As the pulsars move through ISM, the external magnetic field is draped around PWN creating a narrow layer of near-equipartition magnetic field at the contact discontinuity (Spreiter, Summers & Aksne 1966; Lyutikov 2006; Dursi & Pfrommer 2008). As a result, the contact discontinuity becomes a rotational discontinuity with magnetic fields of similar strength on both sides. Rotational discontinuities are prone to reconnection (see e.g. Komissarov, Barkov & Lyutikov 2007; Barkov & Komissarov 2016, and references therein). The efficiency of reconnection at a given point on the contact/rotational discontinuity will depend on the relative orientation of the PWN and ISM magnetic fields – reconnection occurs when the internal and external fields are approximately counter-aligned. As a result, an effective ‘hole’ appears in the PWN through which particles accelerated at the termination shock can escape into the ISM (Barkov et al. 2019b).

## 2 MAGNETIC FILAMENTS CONNECTED TO RAM PRESSURE CONFINED PWNE

### 2.1 Length and brightness estimates

Consider a pulsar with spin-down power $E$ moving with velocity $v_p$ through a medium of particle density $n$ (see e.g. Kargaltsev et al. 2017, for review). The stand-off distance is

$$r_s = \left( \frac{E}{4\pi n m_p c^3 v_p^2} \right)^{1/2} = 1.3 \times 10^{-3} E^{1/2} n_0^{-1/2} v_p^{-1} \text{ pc},$$

(1)

here $m_p$ is proton mass, $c$ is speed of light. At the distance of 8.2 kpc this corresponds to $\sim$0.1 arcsec. In this paper we use the following notation $A_e = A/10^6$ in cgs units.

A typical connection time to a given field lines is several times of travel the stand-off distance

$$t_s = \frac{r_s}{v_p} = 1.3 \times 10^2 E^{1/2} n_0^{-1/2} v_p^{-2} \text{ yr}.$$  

(2)

The connection time $t_s \sim \eta v_c$ is unintentional parameter order 1–10 (Barkov et al. 2019b). Thus a slow pulsar with high $E$ pulsar is expected to remain connected to a given flux tube for a long time.

The pulsed produces a wind with typical Lorentz factor $\gamma_w \sim 10^2$–10$^3$ and magnetization $\sigma_w$ (Kennel & Coroniti 1984). Termination shocks in the nebula accelerate particles to a power-law distribution with typical minimal Lorentz factor $\gamma_{we}$ as the particles escape from the PWN and enter the ISM they produce synchrotron emission in the ISM magnetic field. The peak of synchrotron emission at $\nu F_\nu$ have place at 1.33 times higher relative to $F_\nu$, and peak have place at 0.29 $v_{\text{critical}}$.

$$v_{\text{critical}} = \frac{3 e B}{4\pi m_e c^2} \gamma_e^2 = 16 B_{-2} \nu_{4-5}^2 \text{ GHz}$$

(3)

here $e$, $m_e$, and $\gamma_e$ are electron charge, mass, and Lorentz factor, respectively.

During the connection time $t_s$ a pulsar produces a number of e$^{\pm}$ pairs

$$N_e = t_s n_e$$

(4)

If a fraction $\eta$ escapes, then the radio luminosity can be estimated as

$$L_{\text{rad}} = \eta N_e \frac{2 e^4}{3 m_e^2 c^3} \gamma_e^2 B^2$$

(5)

and expressing $\gamma_e$ from equation (3), $N_e$ from (4), and assuming $\gamma_e = \gamma_w$ we finally get

$$L_{\text{rad}} = \frac{0.6 \eta e^3 \nu_{4-5}^7}{m_e^2 m_p n_0^{1/2} \sigma_w^{1/2} \nu_p^{1/2}} \frac{E^{3/2}}{B_{-2}^{1/2} \nu_{10\text{GHz}}^{1/2}} \text{ erg s}^{-1}.$$  

(6)

This estimate matches, given a number of the unknown parameters, the maximal radio luminosity of the NTBs.

The corresponding cooling time-scale is much longer than the connection time (2)

$$\tau_c \approx \frac{N_e m_e c^2 \gamma_e}{L_{\text{rad}}} \approx 2 \times 10^5 B_{-2}^{-3/2} \nu_{10\text{GHz}}^{-1/2} \text{ yr}.$$  

(7)

This explains the homogeneous spectral index along the filaments.

As an example, consider the largest filament G359.1-00.2 (the Snake; Gray et al. 1995). It has length of 300 arcsec $\sim 12$ pc (at the distance of 8.2 kpc), width 10 arcsec $= 0.4$ pc, maximal surface brightness $10^{-4}$ Jy arcsec$^{-2}$. The total luminosity at frequency window width 5 GHz evaluates to $10^{29}$ erg s$^{-1}$.

The length and the luminosity are consistent with our estimates (2) and (5). The apparent thickness of the filament may increase both to field meandering and to kinetic scattering of the escaped particles by the MHD turbulence in the ISM.

\textsuperscript{1}It is difficult to estimate value of $\eta$ which can be in the range 0.01–1.
Higher frequencies reduces the effects of scattering, but (i) pulsars scattering of time-variable radio sources is important. Going to brighter and for longer time, equation (2), the searchers for pulsars should prefer the NTF associated with the Guitar Nebula, Chatterjee & Cordes (2004).

The model has a number of clear predictions:

2.2 Possible kinks in the NTFs

The Snake shows an interesting feature resembling a kink. This can be produced by the charged flow of the PWNe wind driving the current along the filament, Fig. 2. The pulsar produces a charge-separated flow that carries a total current \( I \sim \sqrt{\dot{E}c} \). If the connection of the external field line is such that a fraction of that current escapes with the kinetic flow of the particles through a flux tube of size \( r_s \eta_p \), then the resulting toroidal magnetic field is

\[
B_{\phi} \approx \eta_p \frac{\dot{E}^{1/2}}{2\pi \sqrt{c\eta p r_s}}. \tag{8}
\]

A kink will occur if toroidal field (8) is larger than the external field. This requires

\[
\frac{\eta_p}{\eta} \geq \frac{B}{\sqrt{\eta \mu_0 n v}} \approx 10. \tag{9}
\]

Thus, under certain conditions the escaping kinetic jet may carry enough current to become kink unstable. (Since the pulsar wind is a charge-separated flow, the escaping current is carried by charge density (not the relative motion of charges). Electrostatic effects may further complicate the global dynamics.

2.3 Predictions

The model has a number of clear predictions:

(i) Most importantly, the NTFs should vary on fairly short time-scales, dozens of years, equation (2). Smaller variations can be detected on shorter time-scales (compare with variations seen in the NTF associated with the Guitar Nebula, Chatterjee & Cordes 2004).

(ii) The pulsar powering the filaments is most likely located near the brightest section of the filament.

(iii) Similarly, many filaments show compact sources – these could be the powering bow-shock PWNe. These PWNe harbour pulsars.

(iv) Since higher \( \dot{E} \) pulsars remain connected to a given flux tube for longer time, equation (2), the searchers for pulsars should prefer bright and long wisps.

Since the filaments are located towards a dense CG region, scattering of time-variable radio sources is important. Going to higher frequencies reduces the effects of scattering, but (i) pulsars are weaker at higher frequencies; (ii) radio telescopes beams are narrower. Perhaps the best frequency range is 2–5 GHz. At these frequencies the GBT beam is about arcminute. Filaments are few acrmin long and less than acrmin thick – this matches the resolution of the GBT. We encourage observations of central parts of the filaments and associated point sources in search of pulsars. (We thank Scott Ransom for pointing out these details.)

3 DISCUSSION

We discuss the origin of Galactic Centre radio filaments as kinetic jets powered by the particles accelerated in bow-shock PWNe. In our interrelation the filaments are not hydrodynamically separate entities – they are just illuminated by a present of accelerated particles that propagate \textit{kinetically}. They are the low-frequency analogues of kinetic jets seen around some fast-moving pulsars, such as the Guitar and the Lighthouse (Kargaltsev & Pavlov 2008), Bandiera (2008), and Barkov et al. (2019b). The filaments length are limited by a scale there magnetic field is strong and comparable to maximal one in the filament.

3.1 Fermi and VHE excess towards the GC

The model is possibly related to the Fermi and VHE gamma-ray excess towards the GC. The GC gamma-ray signal peaks at \( \sim 100 \) MeV with total power \( \sim 10^6 \) erg s\(^{-1}\) (see fig. 8 in van Eldik 2015). Though the VHE part of the excess is clearly of hadronic origin, the GeV–TeV range may have a different origin. Population of milliseconds pulsars seems to be the best explanation (Bartels et al. 2016). Thousands of MSPs are needed.

We suggest that IC scattering by the pulsars’ wind particles can contribute to the 100 MeV–100 GeV photon flux. In this model, the central pulsars produce a relativistic wind that eventually mixes with the ISM. The pulsar wind particles up-scatter via Inverse Compton process the soft photons. For a soft infrared or optical photon of energy \( \epsilon_s \), the expected IC energy is

\[
\epsilon_{\text{IC}} \sim \gamma_s^2 \epsilon_s = 10^8 \gamma_s^2 \epsilon_s \text{eV}, \tag{10}
\]

here \( \epsilon_s \), energy of soft photons is measured in eV. This matches the observed spectral peak of the GC gamma-ray excess.

The IC luminosity can be estimated using the following assumptions: (i) photon energy density is a fraction of the magnetic field energy density \( u_{\text{ph}} = \eta_E B^2/(8\pi) \); (ii) cooling is determined by synchrotron losses. The IC luminosity is then the number of pulsars \( n_p \), times the number of particles a pulsar injects during cooling time-scale, \( n_{\text{IC}} \) (all particles contribute to the IC signal, not only those which escapes), times the IC power of each particle. This gives

\[
L_{\text{IC}} \approx \frac{\eta_E}{\sigma_{\text{s}}^2} n_p \dot{E}. \tag{11}
\]

Thus, few hundred to a thousand pulsars with spin-down power of \( \dot{E} \sim 10^{33}–10^{34} \) erg s\(^{-1}\) can produce the required power of the GeV signal from the GC.

3.2 Conclusions

Let us next discuss how the model explains the key observational facts:

(i) The length of filaments reflects the duration of connection of a given field line to a PWN, equation (2); linearly morphology reflects the field lines stretched radially by the galactic wind.
(ii) Compact sources associated with NTFs could be PWNe harbouring pulsars.

(iii) Orientation of the NTFs is determined by the Galactic wind that stretches the magnetic field lines; this also determines polarization

(iv) Sometimes NTFs split into multiple filaments running parallel to each other Lang et al. (1999) – this reflects the non-stationary process of magnetic reconnection that ‘opens’ and ‘closes’ the pulsar magnetosphere.

An important advantage of this model over previous suggestions (e.g. tails of bow-shock PWN/analogues of cometary tails (Shore & LaRosa 1999), or other hydrodynamic flows (Rosner & Bodo 1996)) is that the non-thermal particles and magnetic field within the NTFs should not be in a pressure balance with the surrounding mediums (such requirement puts high demands on the correspond magnetic field and particle energy density). The emission is produced by a population of kinetically – as opposed to hydrodynamically propagating particles whose pressure and energy density are small if compared with the thermal plasma energy density.

One can imaging two possible types of structure of the magnetic field: a nearly completely volume-filling magnetic field, whereby only selected flux tubes are lit due to reconnection with the PWN. Alternatively, the magnetic field is highly inhomogenous and pulsar lit up the high magnetic field regions. The most feasible scenario can be superposition of two mentioned above.

Finally, some NTFs seem to connect to individual SNRs or to large-scale bubbles formed by merged SNRs or particle source in the galactic center. SNRs are well-known source of accelerated nonthermal leptons (Uchiyama & Aharonian 2008). Non-thermal particles that can escape along magnetic fields and can produce similar extended features. If SNR is an origin, one then expects a kinetic jet on both sides. One possibility is that kinetic jets end in SNRs: locally generated turbulence impedes propagation of particles, terminating the kinetic jet. The drop of magnetic field intensity on the scale SNR also can explain strong asymmetry of NTFs. We leave these hypotheses as an open question for further studies.

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