

Intergalactic magnetism in a γ -ray beam as a model of Porphyrior

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ABSTRACT

We estimate the magnetic field in the jets of the recently discovered 7 Mpc long Porphyrior system. We use non-detection of the system in gamma-rays to derive a lower bound on the co-moving magnetic field strength at the level of ~ 10 nG. This value is consistent with recent estimates of magnetic fields in the filaments of the Large Scale Structure. We discuss the possibility that, instead of being the extreme case of a radio jet formation scenario, Porphyrior actually traces a very-high-energy γ -ray beam emitted by an active galactic nucleus. In such a model, jets do not need to spread into the voids of the Large Scale Structure to appear straight on a very large distance range, and several anomalies of the standard radio jet scenarios can be solved at once.

1. Introduction

Outflows from Active Galactic Nuclei (AGN) may spread high-energy particles and magnetic fields over very large, Megaparsec-scale volumes in the intergalactic medium. The recent discovery of the 7 Mpc scale jet structure of the Porphyrior galaxy (Oei et al. 2024) at the redshift $z \simeq 0.9$ shows that the sizes of such outflows may reach a significant fraction of the size of the voids of the Large Scale Structure (LSS). If such jets penetrate into the voids, they may transport magnetic fields as well as relativistic particles into the voids.

Void magnetic fields may be measured using the technique of γ -ray astronomy through the effect of secondary γ -ray emission from electron-positron pairs deposited in the voids by very-high-energy γ -rays (Neronov & Semikoz 2009). Observations with current generation γ -ray telescopes impose a lower bound on the void magnetic fields at the level of $10^{-17} - 3 \times 10^{-14}$ G (Acciari et al. 2023; Neronov & Vovk 2010; Aharonian et al. 2023), depending on the assumptions on the duty cycle of the parent source of γ -rays. The void magnetic fields may be of cosmological origin (Durrer & Neronov 2013), and in this case the measurement of their properties would provide a useful cosmological probe. While the general consensus from simulations is that the collective activity of galaxies alone cannot magnetize voids to the level implied by the γ -ray lower bound (e.g. Bondarenko et al. 2022; Tjemsland et al. 2024), the magnetic fields spread by radio galaxies like Porphyrior may “pollute” the voids and prevent measurement of the relic voids fields there.

The Porphyrior jets have a number of remarkable properties. They remain collimated over at least ≈ 3.5 Mpc on both sides of the parent AGN. This is puzzling (Oei et al. 2024) because one generically expects development of magneto-hydrodynamical

(MHD) instabilities in the directed relativistic plasma flow, either intrinsic or induced by the prolonged entrainment of gas from the surrounding Inter-Galactic Medium (IGM). Straightness of the jet also implies a low velocity of the parent AGN and the absence of variations of the orientation of the axis of the supermassive black hole in its core over a prolonged period of its activity of ~ 2 Gyr. Modelling of such a remarkably stable jet (Oei et al. 2024) suggests that the AGN should have been working at nearly the Eddington limit during this entire time.

In what follows, we propose an alternative explanation for the formation of Porphyrior (also applicable to other similar objects) and we argue that the Porphyrior jets do not necessarily need to spread into the voids to keep their direction stable over a very large distance. We discuss the possibility that the observed structure is a jet-like feature produced by a beam of very-high-energy γ -rays producing electron-positron pairs in the IGM. Such γ -ray beam traces do not need to transport charged particle plasma from the AGN nucleus nor do they need to sustain their own magnetic fields.

2. Inverse Compton emission from Porphyrior

The synchrotron radio emission from the Porphyrior jets is produced mostly by electrons with energies E_e that may be inferred from the frequency of the synchrotron radiation,

$$\nu_s \simeq 100 \left[\frac{B}{10 \text{ nG}} \right] \left[\frac{E_e}{30 \text{ GeV}} \right]^2 \text{ MHz}, \quad (1)$$

if the magnetic field B in the emission region is known. For example, if the field is at the level of the fields found in the filaments of the LSS, $B \sim 10$ nG (Carretti et al. 2022), the

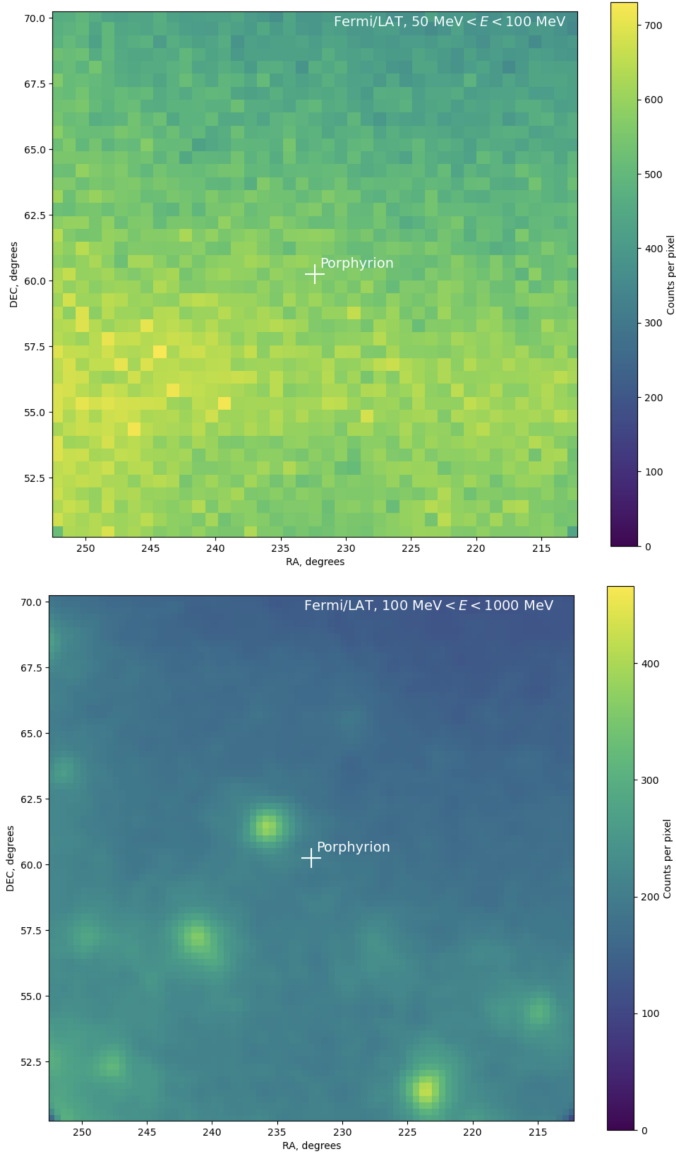


Fig. 1. Fermi/LAT countmaps of the region around Porphyrior in the energy ranges $50 \text{ MeV} < E_\gamma < 100 \text{ MeV}$ (top) and $100 \text{ MeV} < E_\gamma < 1000 \text{ MeV}$ (bottom). The size of the Porphyrior source is smaller than the size of the cross at the source position. Brighter spots in the lower image are sources, other than Porphyrior, detected by Fermi/LAT.

synchrotron-emitting electrons have energies in the 10–100 GeV range.

The same electrons also produce inverse Compton scattered photons from the CMB photons at the source redshift with energies (Neronov & Semikoz 2009)

$$E_\gamma \simeq 6 \left[\frac{E_e}{30 \text{ GeV}} \right]^2 \text{ MeV.} \quad (2)$$

The ratio of the inverse Compton to synchrotron fluxes from the jet, F_{IC} to F_s , is determined by the ratio of the energy densities of the CMB and the magnetic field:

$$\frac{F_{IC}}{F_s} = \frac{U_{CMB}}{U_B} \simeq 10^6 \left[\frac{B}{10 \text{ nG}} \right]^{-2} \quad (3)$$

at redshift $z \simeq 0.9$, where the energy density of the CMB is increased by a factor of $(1+z)^4 \simeq 13$ compared to the local Universe.

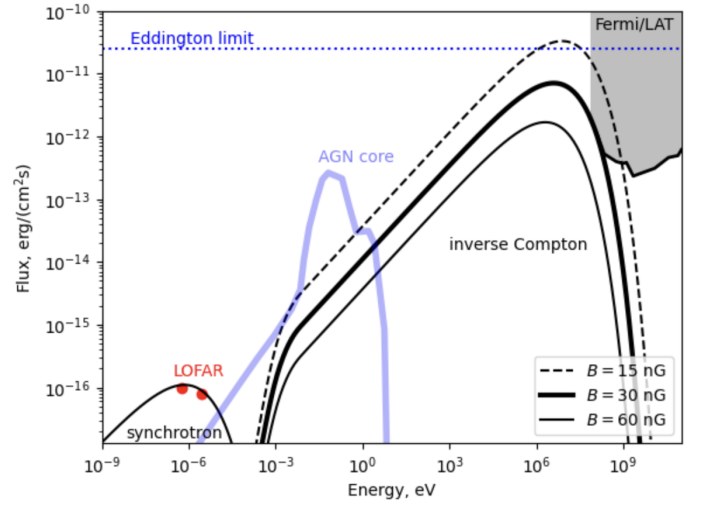


Fig. 2. Spectral energy distribution of Porphyrior modelled as synchrotron and inverse Compton emission. Lack data points show the radio flux of the jet. The grey-shaded region shows an upper limit on γ -ray flux from Fermi/LAT. The light blue curve shows the host AGN spectral energy distribution model from Oei et al. (2024). Dashed horizontal line shows the level of flux expected from a source powered by a $10^9 M_\odot$ black hole emitting at Eddington limit. Red, blue and green points show the expected inverse Compton flux level from electrons emitting synchrotron radiation in the LOFAR frequency range, for different proper magnetic field levels.

The synchrotron flux of Porphyrior is at the level $F_s \sim 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1}$. This suggests that the γ -ray flux may be as high as $F_{IC} \sim 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$ in $E \sim 10 \text{ MeV}$ band, yielding a very bright γ -ray source. Such a flux is potentially detectable with the Fermi Large Area Telescope (LAT) (Atwood et al. 2009) that has an energy threshold in the $E_{\text{thr,LAT}} \sim 50 \text{ MeV}$ range.

3. Upper bound on the γ -ray flux of the jet

We use Fermi/LAT data publicly available through the Fermi Science Support Center¹ to measure the flux of Porphyrior or to derive an upper limit on it. We consider γ -ray events with energies between 50 MeV and 100 GeV within 15° distance from the source collected between 2008 and 2024. We filter the events of P8R3_SOURCEVETO_V3 type using the `gtselect-gtmktime` tool chain to retain only the highest quality events most likely expected to be γ -rays.

Figure 1 shows the countmaps of the Porphyrior region in Fermi/LAT in the energy ranges 50–100 MeV and 100 MeV–1 GeV. As there is no excess in the direction of the source, we derive an upper limit on the source flux in logarithmically spaced energy bins, using the aperture photometry method. We extract the photon counts from circles of the radius 2° (1°) in the energy bins below (above) 1 GeV. We define the 95% upper bound on the source flux as $2\sqrt{N}$, where N is the number of counts in the source circle. Then, we estimate the exposure corrected for the fraction of the source flux contained within the fixed radius, using the `gtexposure` tool. The resulting upper limit on the source flux is shown by the thick gray curve Fig. 2.

To find an upper bound on the magnetic field, we model synchrotron and inverse Compton emission from a cutoff powerlaw

¹ <https://fermi.gsfc.nasa.gov/ssc/>

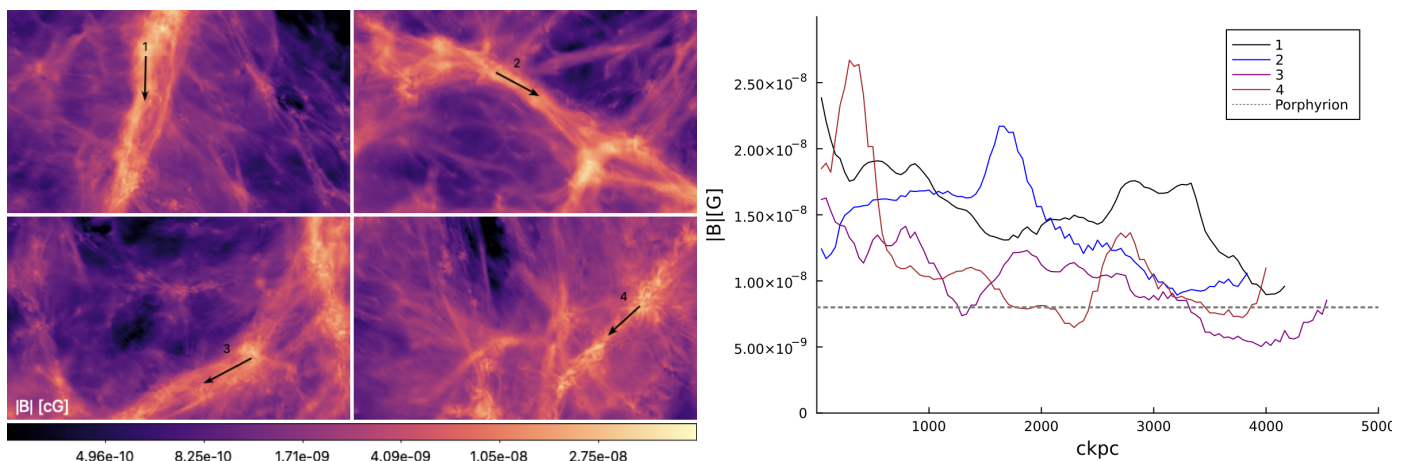


Fig. 3. Left panels: mass-weighted mean comoving magnetic field strength for four different filaments in a cosmological simulation at $z = 1$. Right panels: corresponding profiles of comoving magnetic field strength through the same filaments, for a total extent compatible with the longest jet of Porphyrior.

distribution of electrons,

$$\frac{dN_e}{dE} \propto E^{-\Gamma} \exp\left(-\frac{E}{E_{\text{cut}}}\right), \quad E > E_{\text{min}}. \quad (4)$$

The seed photons for the inverse Compton scattering are provided by the CMB at the redshift of the source. The resulting model is shown by the black solid line in Fig. 2 for the minimal possible magnetic field strength,

$$B_{\text{min}} \simeq 30 \text{ nG}. \quad (5)$$

If the magnetic field were below this bound, the inverse Compton flux would be observable in Fermi/LAT, because the inverse Compton component of the source spectrum (the right bump of the model curve) would move in the upper-right direction and exceed the Fermi/LAT upper bound.

4. Comparison with magnetic fields in the filaments of the LSS

The comoving minimal field strength,

$$B_{\text{min,comoving}} = \frac{B_{\text{min}}}{(1+z)^2} \simeq 8 \text{ nG} \quad (6)$$

is close to the global estimate of the magnetic field in the filaments of the Large Scale Structure (e.g. Carretti et al. 2022; Mtchedlidze et al. 2024). If the jets of Porphyrior are occasionally aligned along the filament direction, the field present in the synchrotron emission region may well be the background magnetic field in the LSS, rather than the field transported by the jet plasma.

To more closely compare with the geometry of Porphyrior, we extracted from a large cosmological simulation at $z = 1$ (e.g. Vazza et al. 2019) several 1-dimensional slices of magnetic fields starting from small-mass halos within approximately straight filaments, and out to a ≈ 3.5 Mpc distance from the halo to reproduce the separation between the core and the outer lobes of Porphyrior. The simulation used a simple initially uniform “primordial” magnetic field seed of 0.1 nG (comoving) inserted at the start of the simulation ($z = 50$) and evolved under ideal MHD conditions with dark and baryonic matter in the ENZO code. This simple model was shown to produce a very good

match to the properties of stacked polarized radio emission from the cosmic web in the recent observations by Vernstrom et al. (2023).

The general finding is that all paths have $B_{\text{comoving}} \sim 10 - 15$ nG magnetic fields for a large fraction of Porphyrior’s projected extension, with frequent fluctuations of order $\times 2$ in magnetic field strength over scales of $\sim 10^2$ kpc, corresponding to the typical size of substructures in filaments.

This suggests that the jet may be contained within a filament of the Large Scale Structure. The alignment of the jet with the filament direction need not to be strong. Indeed, the typical width of a filament is $r_f \sim 1.5-2$ Mpc (Colberg et al. 2005), so that only a mild alignment, by an angle $\Theta \sim \arcsin(r_f/R_j) \simeq 30^\circ$ along the filament is needed for a jet of the length $R_j \simeq 3.5$ Mpc to be contained in a filament. Considering that longer jets require a better large scale alignment with surrounding filaments to produce detectable radio emission in this scenario, this might qualitatively explain why this phenomenon is relatively rare to observe. A quantitative exploration of the statistics of such configuration with full cosmological simulations is deferred to future work.

5. Gamma-ray beam model of the system

Observations with γ -ray telescopes have revealed a population “TeV blazars”, AGNs that emit narrow beams of γ -rays with energies in excess of 10 TeV (Biteau et al. 2020). Alignment along the line of sight leads to strong Doppler boosting of γ -ray emission in blazars and facilitates their observations in the γ -ray band. In the absence of alignment, the γ -ray beam may not be detectable by γ -ray telescopes, but it should leave a trace in the intergalactic medium that is observable at lower energies (Neronov et al. 2002). The trace is produced by synchrotron and inverse Compton emission by electrons and positrons deposited along the beam by the effect of pair production of γ -rays interacting with the visible/infrared Extragalactic Background Light (EBL) (Gould & Schröder 1967). The mean free path of the γ -rays with energies E_{γ_0} through the EBL at the redshift $z \sim 1$ (Fitoussi et al. 2017)

$$D_{\gamma_0} \simeq \begin{cases} 10 \text{ Mpc}, & E_{\gamma_0} = 10 \text{ TeV}, \\ 1 \text{ Mpc}, & E_{\gamma_0} = 30 \text{ TeV}, \end{cases} \quad (7)$$

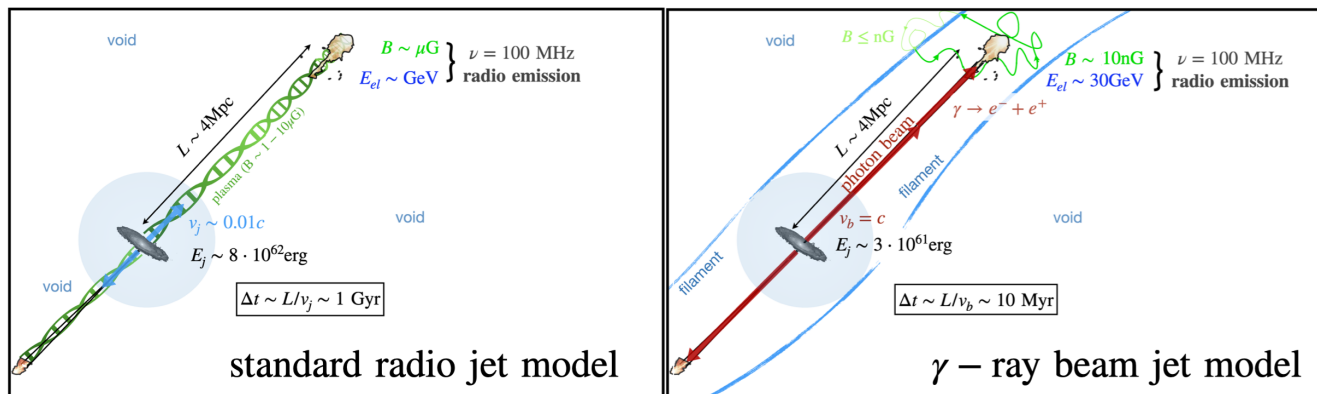


Fig. 4. Cartoon views of the two physical models for Porphyryon discussed in this work.

is comparable to the length scale of Porphyryon-type beams for $E_{\gamma_0} \gtrsim 10$ TeV. This means that all the energy of the γ -ray beam is converted into the energy of electrons and positrons deposited nearly homogeneously in the intergalactic medium on a several Mpc distance scale.

The electrons and positrons are initially injected in the energy range $E_e \sim (0.1-1)E_{\gamma_0}$. Once injected, these electrons and positron cool via inverse Compton scattering on Cosmic Microwave Background (CMB) at $z \simeq 1$ on the time scale

$$t_{\text{cool}} \simeq 1.5 \left[\frac{E_e}{30 \text{ GeV}} \right]^{-1} \text{ Myr} \quad (8)$$

that becomes comparable to the light-crossing time of Porphyryon, which is $t_{lc} \simeq 10$ Myr for electrons with energies in the GeV energy range. This leads to the formation of a low-energy tail of the electron-positron distribution.

If the source remains active at constant luminosity, the low energy tail spectrum is $dN/dE \propto E^{-2}$ (Neronov et al. 2002). Otherwise, the shape of the electron spectrum depends on the history of the luminosity of the γ -ray beam on the cooling time scale. The spectrum of inverse Compton emission from an E^{-2} distribution of electrons has the slope $dN_{\gamma}/dE \propto E^{-1.5}$ and the inverse Compton emission from TeV electrons is expected to be in the 10–100 GeV range. Non-detection of this emission by Fermi/LAT suggests that the AGN core luminosity in very-high-energy γ -rays should have been decreasing over the last millions of years so that only electrons and positrons that cooled down are surviving. Otherwise, if the magnetic field in the jet is an order-of-magnitude stronger than the lower bound derived above, the level of the inverse Compton flux would be below the Fermi/LAT upper bound, even if the source of the TeV γ -rays would remain active till now. In any case, the population of cooled electrons and positrons which remains along the trace of the γ -ray beam over $t \gtrsim 10$ Myr is expected to produce a radio synchrotron glow along the path of the γ -ray beam. It is thus well possible that the straight jet of Porphyryon is a trace of a very-high-energy γ -ray beam emitted by the AGN core in the past ($\leq 10-15$ Myr ago).

6. Discussion

The stability of jets in the relativistic regime has been thoroughly studied with analytical and numerical approaches, to explore the role of jet parameters (bulk Lorentz factor, composition, density, temperature) and environment (e.g. Blandford et al. 2019; Komissarov & Porth 2021; Perucho & L3pez-Miralles 2023, for

recent reviews). A general finding is that the most important instabilities which can disrupt or de-collimate jets (like Kelvin-Helmholtz modes) grow faster in slower and hotter flows than in cold and fast ones. Faster jets with a high bulk Lorentz factor, Γ , develop short-wavelength and high-order modes that get amplified in the shear layer and eventually saturate the growth of the instabilities, without loss of collimation, and generating a hot shear layer around the core of the jet (Perucho et al. 2022). Based on this, in order to explain the very high degree of stability of Porphyryon, one needs to assume a very relativistic jet ($\Gamma \sim 2$) travelling as a bullet, in an extremely low density environment. It is, however, not clear if this picture, developed to interpret the jet stability on $\leq 10^2$ kpc scales, would hold up to Mpc scale distances. There are currently no available numerical or semi-analytical models which can test its validity of this scenario on the much longer time and spatial scales implied by Porphyryon. At the same time, several more objects with similar characteristics but slightly smaller overall extension were already detected by recent LOFAR surveys (e.g. Oei et al. 2023; Simonte et al. 2024).

This context makes it interesting to explore our radically different interpretation, which bypasses the anomalies that Porphyryon poses to our understanding of radio jets. Figure 4 gives a schematic view of the most important differences implied by the two models of Porphyryon discussed in this work. The γ -ray beam trace model considered above provides such alternative interpretation. Contrary to the conventional jet models, the problem of directional stability does not even exist in the γ -ray beam trace model. γ -rays are generically expected to deposit electrons and positrons along a straight line of the length comparable to the γ -ray mean free path. Thus, straight Mpc-scale line-like features like Porphyryon are good candidates for being traces of γ -ray beams from their parent AGN.

In principle, straight jet-like features that are electron-positron pair traces of γ -ray beams should be present in all AGNs that emit TeV γ -rays. It is also likely that the γ -ray beams in such AGN are ejected in the direction of the black hole spin axis in which case they are expected to be aligned along the directions of the AGN jets. TeV γ -rays can also be produced by high-energy particles accelerated in the jets. A TeV γ -ray beam propagating through the jet may simply provide an additional source of high-energy electrons and positrons in the jet. It is not obvious how to distinguish this source from other possible sources of high-energy particles in the jets such as, e.g., shock acceleration in the jet knots.

According to the model for Porphyryon, given in Oei et al. (2024), the jet had an average power of $P \sim 10^{46}$ erg s $^{-1}$ active

for $\tau \sim 1.9$ Gyr, and the total deposited energy is $\sim 8 \cdot 10^{62}$ erg in the jets. This implies a total accreted mass of $\Delta M \sim 10^9 M_\odot$, which makes the association of Porphyryon with the quasar in the region (total mass $M_q \sim 2 \cdot 10^8 M_\odot$) impossible.

In the γ -ray beam model, $E \sim 30$ GeV electrons emitting synchrotron radiation at 100 MHz (the latter being energetically negligible), have been initially injected with $E \sim$ TeV energy by a γ -ray beam. The injection should have lasted at least ~ 10 Myr (the time needed for γ -rays to propagate over the jet length). The present-day luminosity of Porphyryon in γ -ray band (Fig. 2) is of $\lesssim 5 \times 10^{45}$ erg/s (depending on the unknown magnetic field strength in the jet). This suggests an energy output of $\lesssim 10^{60}$ erg on 10 Myr time scale. The energy injected by the γ -ray beam must have been $\sim 1\text{TeV}/30\text{GeV} \sim 33$ times larger in the past, i.e. the total energy of the γ -ray beam should have been $\lesssim 3 \cdot 10^{61}$ erg. We can thus estimate an overall $\gtrsim 30$ times lower energy budget to explain Porphyryon according to the γ -ray beam scenario, compared to the conventional radio jet model.

Our study of the non-detection of inverse Compton emission from Porphyryon in γ -rays yields a lower bound on the magnetic field in the jet. This constraint can be further improved via a search of inverse Compton flux at lower energies, as it is clear from Fig. 2. GeV energy electrons are generically expected to be present in the jet because of their relatively long cooling time scale; see Eq. (8). Such electrons produce inverse Compton emission in the hard X-ray energy range (2). The $E \sim 100$ keV inverse Compton emission from such electrons is unfortunately out of the reach of existing and planned telescopes in this energy range. If the activity time scale of the γ -ray beam from the parent AGN is in the $\gtrsim 100$ Myr range, cooling of electrons to sub-GeV energies may result in the inverse Compton emission in the X-ray range, where the sensitivity of existing telescopes may be sufficient for its detection.

7. Conclusion

To summarize, our proposed γ -ray model for Porphyryon presents the following advantages: (a) it naturally explains the straightness of the jet on such large scales, (b) it makes no critical requirements on the jets' internal physical parameters, (c) it lowers the energy requirements for the central AGN, and (d) it does not require jet propagation in the very low density environment of the LSS voids. The model can be observationally tested with future hard X-ray observations, and through the statistical comparison of larger dataset of Porphyryon-like systems in future radio surveys.

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