Search for wormhole candidates in active galactic nuclei: radiation from colliding accreting flows

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ABSTRACT
The underlying hypothesis of this work is that the active galactic nuclei (AGNs) are wormhole mouths rather than supermassive black holes (SMBHs). Under some—quite general—assumptions such wormholes may emit gamma radiation as a result of a collision of accreting flows inside the wormholes. This radiation has a distinctive spectrum much different from those of jets or accretion disks of AGNs. An observation of such radiation would serve as evidence of the existence of wormholes.

Key words: galaxies: active - galaxies: nuclei - galaxies: Seyfert - gamma-rays: galaxies - accretion, accretion discs - black hole physics.

1 INTRODUCTION
According to an interesting recent hypothesis AGNs are not SMBHs, but rather mouths of primordial macroscopic wormholes (Kardashev et al. 2007; Bambi 2013; Li & Bambi 2014; Zhou et al. 2016). In this paper we show that the validity of such a hypothesis may have observable consequences.

2 MODEL AND BASIC EQUATIONS
Consider a traversable wormhole connecting two galactic centers (see Fig.1). To make the situation as simple as possible assume that the wormhole is spherically symmetric, static and empty everywhere beyond a spherical layer $L$. Assume further that the gravitational force acting on a radially falling test particle in any point of that wormhole is directed towards the throat.

An example of a wormhole satisfying all these requirements is a “Schwarzschild-like wormhole”

$$ds^2 = -e^{2h(l)}c^2 dt^2 + dl^2 + r(l)(d\theta^2 + \sin^2 \theta d\phi^2), \ l \in \mathbb{R}, \ (1)$$

studied in its capacity as a particle accelerator in (Krasnikov 2018). $c$ in (1) is the speed of light, $l$ is (up to the sign) the proper radial distance from the wormhole’s throat (Morris & Thorne 1988), and $r(l)$ and $h(l)$ are smooth even functions monotone increasing at positive $l$ (almost all these conditions may be weakened, but we consistently keep avoiding unnecessary complications) and obeying the following relations

$$dr = \sqrt{1 - \frac{1}{x}} dl, \ \ x \equiv r/r(0), \ (2)$$

$$h(x) \big|_{r>r_*} = \frac{1}{2} \ln(1 - 1/x), \ (3)$$

where $r_*$ is some constant greater than $r(0)$. We choose this constant to be close to the radius of the wormhole’s throat

$$2r(0) > r_* > r(0), \ (4)$$
i. e. the wormhole is required to be short (again, this condition might be dropped and $r_*$ be made a free parameter of the model, but we don’t need such generality, while the hypothesis (4) will be helpful for the subsequent calculations).
Thus, for all $r > r_*$, the metric (1) is that of Schwarzschild with mass
\[ M \equiv \frac{c^2} {2G} r(0) \approx \frac{c^2} {2G} r_*. \] (5)
At smaller $r$, the shape of $h(l)$ [not of $r(l)$] differs from its Schwarzschild counterpart $h_{Sch}$, i.e. from $\frac{1}{2} \ln(1+1/x)$, which means that this region is non-empty (it is, in fact, the layer $L$ mentioned above). As shown in Morris & Thorne (1988), if the Einstein equations hold, the matter filling $L$ unavoidably is exotic, i.e. its energy density as measured by some observers in some points (including the points of the sphere $l = 0$) is negative. There are several proposals in the literature on what could serve as exotic matter, see, e.g., Lobo (2017) and Visser (1995) for a review, but in this paper we shall not consider them (for lack of need: as long as the matter supporting the wormhole does not interact electromagnetically, its nature is irrelevant). Two remarks, however, are in order:

2. As “normal” matter—with the stress-energy tensor $t_{\mu\nu}$ accretes to a wormhole (in such a manner that $t_{\mu\nu}$ remains diagonal in the coordinate basis), the matter inside the latter presumably becomes “less and less exotic” (assuming that the stress-energy tensor near the throat is the sum $T_{\mu\nu} + t_{\mu\nu}$, which is justified by our condition that the two kinds of matter do not directly interact). Consequently, in some time $T_{stab}$ the components of $t_{\mu\nu}$ may cease to be negligible and the wormhole may lose stability and collapse. Unfortunately, for the reasons discussed in the previous item, it is hard to find an estimate on $T_{stab}$ valid for all types of wormhole.

The most important difference between $h_{Sch}$ and $h$ is that the latter, in contrast to the former, is bounded. That is to say the spacetime (1) is a wormhole rather than a black hole. It has no horizon and is therefore traversable (Morris & Thorne 1988). This fact makes it possible to use a Schwarzschild-like wormhole as a super accelerator. Indeed, the matter attracted by mouths of such a wormhole will form two fluxes colliding at the throat. To analyze this process, consider, first, a particle of mass $\mu$ that falls freely from infinity (with zero initial velocity) and in the throat of the wormhole (1) hits head-on exactly the same oncoming particle. The energy of this collision (in the center-of-mass system) is, see eq. (12) in (Krasnikov 2018),
\[ E_{cm} = 2\mu c^2 \Gamma [1 + O(\Gamma^{-2})], \]
\[ \Gamma \equiv c \max \left( |g_{tt}|^{-1/2} \right) = e^{-h_{min}}, \] (6)
where $g_{tt}$ is the corresponding component of the metric (1). Note that the function $h$ attains its minimal value $h_{min}$ at the throat $l = 0$. So, $h(0)$ is the only wormhole’s characteristic on which $E_{cm}$ depends. Though $h(0)$ is fixed for any given wormhole, one may call the Schwarzschild-like wormhole a super accelerator, because that fixed value can be arbitrarily high.

As a result of the pair collisions discussed above, an observer watching the wormhole will see two spheres (these are the spheres with radii $r_*$ bounding $L$) of ultra relativistic plasma. These spheres radiate with a distinctive spectrum, see below, much different from those of jets or accretion disks, which makes it possible to identify the wormhole.

3 ESTIMATES

3.1 Assumptions

The phenomenon in discussion is rather complex and to explore it we will make as much simplifying assumptions as possible. Specifically, we consider a pair of AGNs with the masses $M \approx 5 \times 10^8 M_\odot$ connected by a Schwarzschild-like wormhole (1). We assume that

(i) the galaxies in question are Narrow-line Seyfert 1 Galaxies (NLS1) (Paliya et al. 2019; Kynoch et al. 2019; Madejski & Sikora 2016; Baghmanyan & Sahakyan 2018), which have a fairly weak gamma radiation, so our supposed WH gamma radiation will be less diluted;

(ii) the plasma layer is heated (only) by the collision of the fluxes;

(iii) the magnetic field, the interaction of the infalling matter with the outcoming radiation, and the backreaction of the spheres on the metric of the wormhole are negligible.

Now we can roughly estimate plasma temperature and spectrum.

3.2 Plasma parameters

The characteristic accretion rates of NLS1 lie (Bian & Zhao 2003; Collin & Kawaguchi 2004) within the range of
\[ m \approx 0.1 - 1 M_\odot/\text{year}. \] (7)

According to estimates of duty cycles of AGNs of this type (Shankar et al. 2013; Aversa et al. 2015; Tucci & Volonteri 2017), this accretion regime should exist for at least $10^9$ years. So, the mass of the plasma spherical layer is at least
\[ m \approx 10^8 M_\odot, \] (8)
where the layer’s mass $m$ is understood as the integral of density rather than a characteristic of the wormhole’s metric.

Now let us estimate the proton concentration in the accreting plasma. To that end assume (following (Bian & Zhao 2003; Collin & Kawaguchi 2004)) that the region external to a sphere $r = \text{const} \gg r_*$ is left by $M_\odot$ of matter in a year. Then (since the matter does not accumulate between that sphere and the sphere $r = r_*$) the latter will be left by exactly the same amount of plasma every year of the coordinate time $t$. This plasma moving with (almost) the speed of light, will fill the layer of proper (with respect to an observer whose $r_*$, $\phi_*$, and $\theta_*$ coordinates are constant) volume $V_{prop} = 4\pi r_*^2 \cdot \sqrt{-g_{tt}(r_*)} \cdot 1 \text{ly}$. So, the proton concentration is
3.3 Spectral peak

At such high temperatures in the plasma the production of $\pi^0$ mesons begins (Kolykhalov & Syunyaev 1979; Marscher et al. 1980; Dermer 1986). $\pi^0$ mesons decay into two photons with energies $\sim 68$ MeV. For $T = 2.5 \times 10^{13} \text{K}$ and $T = 10^{14} \text{K}$ the gamma-ray production spectra of plasma for this radiation mechanism (in Minkowski space) were found in Marscher et al. (1980). The latter spectrum has a peak value of $Q_{\max} \approx 10^{-13} \text{erg cm}^{-3} \text{s}^{-1}$ at about $68$ MeV, where $Q$ is the gamma-ray production value. To find the spectrum of the wormhole (as measured by an observer resting out of the wormhole) we extrapolate Marscher’s result (Fig.3 from Marscher et al. (1980)) and assume that the peak value in the spectrum is reached at $\sim 68 \Gamma^{-1}$ MeV (the factor $\Gamma^{-1}$ is due to the red shift experienced by a photon on its way from the throat to infinity) and equal to $Q_{\max}(T) \approx Q_{\max}(T = 10^{14} \text{K}) (T/10^{14} \text{K})^{0.25}/\Gamma$.

3.3.2 Observability

In order to evaluate possible observed flux value of plasma cloud we will use the relation (Marscher et al. 1980):

$$F(E_{\gamma}) = \frac{V}{4\pi D^2} Q(E_{\gamma}),$$

(11)

where $E_{\gamma}$ is the photon energy, $F$ is the flux value, $V$ is the total volume of the plasma cloud and $D$ is the distance to the observer.

In order to obtain peak flux value comparable in order of magnitude to observed values for NLS1 ($\sim 10^{-13} \text{erg cm}^{-2} \text{s}^{-1}$) using Eq.(11), we have to assume that $V/(4\pi D^2) \geq 0.1 \text{cm}$. Characteristic distance for observed AGNs of this type is about $10^9$ light-years or $\sim 10^{27}$ cm, so the volume of the radiating plasma must be at least $10^{34} \text{cm}^3$.

In (Marscher et al. 1980) the plasma is optically thin, so we consider radiation only from outer layers of plasma cloud with a volume of $10\%$ of the total volume of cloud. Thus full cloud volume will be $\sim 10^{35} \text{cm}^3$. Taking into account (9) we obtain the mass of the plasma cloud

$$m = n_{acc} m_p V \approx 2.4 \times 10^{38} \text{kg} \sim 10^3 M_\odot$$

(12)

Comparing this with characteristic mass of accreted matter for NLSy1 $10^9 M_\odot$ (8), we see that the NLSy1 observed accretion rate $0.1 - 1 M_\odot/\text{year}$ (7) is sufficiently high for WH radiation to be observable.

The resulting spectrum for $V/(4\pi D^2) \approx 0.1 \text{ cm}$ (11) looks (qualitatively) as shown in Fig.2.

4 CONCLUSIONS

We can conclude that a peak at about $68 \Gamma^{-1}$ MeV should appear on the AGN spectrum. It should be emphasized that this peak in the spectrum can be quite high ($\sim 10^{-13} \text{erg cm}^{-2} \text{s}^{-1}$), comparable to flux value of jet radiation of NLS1.

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DATA AVAILABILITY

The data underlying this article are available in the article.
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