Astronomical and Astrophysical Transactions (*AApTr*), 2022, Vol. 33, Issue 3, pp. 285–296,
ISSN 1055-6796, Photocopying permitted by license only, ©Cambridge Scientific Publishers

Shadows around Sgr A* and M87* as a tool to test gravity theories

Alexander F. Zakharov*

Bogoliubov Laboratory for Theoretical Physics, JINR, 141980 Dubna, Russia

Received 14 December, 2022

In the framework of Randall–Sundrum theory with extra dimension Reissner–Nordström black hole solutions with a tidal charge have been found. The shadow around the supermassive black hole in M87 was reconstructed in 2019 based on observations with the Event Horizon Telescope (EHT) in April 2017. In May 2022 the EHT Collaboration presented results of a shadow reconstruction for our Galactic Center. Earlier, for Reissner–Nordström metric we derived analytical expressions for shadow size as a function of charge and later generalized these results for a tidal charge case. We discuss opportunities to evaluate parameters of alternative theories of gravity with shadow size estimates done by the EHT Collaboration, in particular, a tidal charge could be estimated from these observations.

Keywords: Supermassive black holes, Galactic Center, M87, synchrotron radiation, VLBI observations

1 Introduction

Several years ago the Event Horizon Telescope (EHT) Collaboration was formed. The astronomers use telescopes located over the globe and they are operating at 1.3 mm wavelength in VLBI regime or in other words the corresponding network acts as a giant telescope with Earth size. An angular resolution of the network is around 25 μas which is comparable with angular sizes of event horizons for supermassive black holes in Sgr A* and M87*. In spite of huge differences in black hole masses and distances toward these objects these shadows have similar sizes (52 μas for Sgr A* and 42 μas for M87*). In April 2017 the EHT Collaboration observed the Galactic Center and the center of M87 galaxy. In 2019 the EHT Collaboration presented results of a shadow reconstruction for M87* and in May 2022 it presented a shadow reconstruction for Sgr A*. Now these images with shadows around M87* and Sgr A* are used as logos for these supermassive black holes or sometimes more generally for any astrophysical black holes. Since it is impossible to observe dark regions (shadows) astronomers

*Email: alex.fed.zakharov@gmail.com

found bright regions of synchrotron emission in 1.3 mm and reconstructed shapes and sizes of shadows. These remarkable achievements in precise observations and data analysis are based on three pillars: synchrotron emission which is generating in many astronomical objects including environments of supermassive black holes, VLBI ideas which were efficiently implemented in the EHT network and relativistic analysis of geodesics in the black hole metrics.

2 Synchrotron radiation

Radiation of electrons moving in magnetic fields (it is now called synchrotron radiation) was discussed in detail in a fundamental book by Schott (1912) but in those times there were no facilities to detect it in experiments or in astronomical observations[1]. Scientists came back to this theory in the forties and fifties of the last century due to an opportunity to detect a synchrotron radiation in accelerators and in astronomy, initially, in radio band and later, in a wide spectrum of electromagnetic radiation from radio up to γ-radiation. An existence of synchrotron radiation was re-discovered by I. Pomeranchuk[2] and his co-authors, see papers by Pomeranchuk (1940); Iwanenko and Pomeranchuk (1944); Artsimovich and Pomeranchuk (1945). Later, a theoretical analysis of synchrotron radiation was given by Schiff (1946); Blewett (1946); Schwinger (1949), the first detection of X-ray radiation from accelerated electrons in the General Electric 70-MeV synchrotron was reported by Elder et al. (1947). Very often the paper by Schwinger (1949) is treated as a key theoretical paper in the field. In 1950, D. Ivanenko, A.A. Sokolov and I. Pomeranchuk were awarded the State prize of the second grade for works on synchrotron radiation, presented in book "Classical Field Theory" written by D.I. Ivanenko, A.A. Sokolov in Russian. Famous Soviet astrophysicist I.S. Shklovsky (1946) recalled that in forties of the last century he followed a talk about a discovery of radio emission from the Sun and he concluded that the radio emission from Sun was generated due to a synchrotron radiation phenomenon. He also concluded that the synchrotron effect is a cause of electromagnetic radiation in wide spectral band and this idea was the most brilliant of all his ideas in his entire scientific career as it was noted in book by Shklovsky (1991). For Crab Nebula, Shklovsky interpreted electromagnetic radiation in a wide spectral band (from radio to X-ray) as the synchrotron emission (Shklovsky (1953, 1976)), see also English translation of the first edition of book by Shklovsky (1968). Martin Rees (1971) supposed that radio emission from extended radio source may be explained by synchro-Compton radiation (in this case electrons are accelerating by electromagnetic waves).

[1] In recent book (Connerade (2021)) the author described the life and times of George Adolphus Schott, who criticized the planetary atom model (Schott (1939)) which was proposed by Bohr (1913) based on the results of remarkable experiments done by E. Rutherford.

[2] Academician I.Ya. Pomeranchuk was one of the most favorite students of L.D. Landau. Isaac Pomeranchuk was the founder of the Theoretical Department at the Institute of Theoretical and Experimental Physics (ITEP) and L.D. Landau was a half-time researcher at the department. In 1998, ITEP established the Pomeranchuk Prize (see `https://en.wikipedia.org/wiki/Pomeranchuk_Prize`) and three Pomeranchuk Prize laureates later got a Nobel prize in physics: Yoichiro Nambu, Roger Penrose and Giorgio Parisi (perhaps the number of people getting both Pomeranchuk and Nobel Prizes could be more than three but according to Pomeranchuk Prize rules of awarding a Nobel prize winner can not be chosen as a Pomeranchuk Prize laureate). L. Okun (2004) wrote a short scientific biography of I. Pomeranchuk.

Shklovsky (1975) assumed that there is a black hole at the Galactic Center with mass around $3 \times 10^4 M_\odot$ and radiation has a non-thermal origin and probably a synchrotron radiation is responsible for a significant part of radiation from the Galactic Center (earlier Linden-Bell and Rees (1971) emphasized arguments supporting a necessity for a presence of supermassive black hole at the Galactic Center with mass estimates in the range $[4 \times 10^3, 10^7] M_\odot$). In spite of the underestimation of the black hole mass, ideas about a presence of a black hole at Sgr A* and the synchrotron emission from the Galactic Center region received confirmation in subsequent studies.

Synchrotron radiation is a cause of energy losses in accelerators, but it plays an extremely important role in astrophysics as it was noted by Ginzburg and Zheleznyakov (1958, 1959); Ginzburg (1965). A more recent review on different aspects of synchrotron radiation in astrophysical sources is given in reviews by Ginzburg (1984, 1985); Bisnovatyi-Kogan (1999).

3 Early VLBI in the USSR

A Soviet radio engineer Leonid Matveenko was one of the first to understand the opportunity of inter-continental radio observations and early history of these studies is described in papers by Matveenko (2007a,b). In the fall of 1962, Matveenko reported ideas of VLBI in Pushchino at a seminar of the Radio Astronomy Laboratory and he did not get a support to conduct such an experiment in Crimea as it was proposed. However, these ideas were supported by participants of a seminar at Sternberg State Astronomical Institute (SSAI) of Moscow State University where the SSAI director D.Ya. Martynov recommended to take out a patent due to the high scientific and technological importance of this proposal. Instead of patent a scientific paper on the issue has been published in Soviet journal "Radiophysics" (Matveenko et al. (1965)). In this paper the authors proposed independent recording of the signals and subsequent processing of the data. In the initial version of the paper the authors proposed to use a ground–space interferometer but the editorial board of the journal recommended to remove this idea from the accepted version of the paper as it was noted by Matveenko (2007a,b), however, we should mention that earlier Papaleksi (1947) proposed to develop radio interferometers for geodesy and emphasized the importance of radio observations, in particular in the direction toward Galactic Center, where a strong radio source Sgr A* was discovered (Janski (1933)). In summer 1963 the director of the Jodrell Bank Observatory, B. Lovell visited the Soviet Union as a guest of the Soviet Academy of Sciences. Matveenko delivered a talk about potential opportunities of interferometers with very large bases and Lovell noted that this idea looks feasible but he did not see any astronomical problem where such a resolution is needed (Matveenko (2007b)). Both sides signed a memorandum of understanding about joint observations of Crimean and British telescopes at 32 cm wavelength. But these plans were not realized.

The VLBI technique for observations of compact bright radio sources has been proposed in USSR in sixties of the last century and these ideas were realized in the joint US–Russian experiment proposed by M. Cohen and K.I. Kellermann where the 22-m Pushchino and 43-m Green Bank antennas were planned to be used, but in the experiment the Pushchino antenna was substituted with the Simeiz antenna (Kellermann

(1992); Lovell (1973)). The results of the observations with the first Soviet–American interferometer at 2.8 cm and 6 cm in September and October 1969 were published by Broderick et al. (1971). The interferometer consisted of the 42-m radio telescope of the National Astronomical Observatory at Green Bank (West Virginia) and the 22-m radio telescope at Simeiz (Crimea). The results of Soviet–American VLBI observations were discussed in the popular Soviet journal "Science and Life" where Matveenko (1973) described VLBI as "a telescope the size of the Earth".

In June 1971, the Soviet and American teams of radio astronomers carried out interferometric observations of water vapour maser line at 1.35 cm. This interferometer was formed by the 37-m radio telescope of the Haystack Observatory at Westford (Massachusetts), see Burke et al. (1972). Several observations were done with this interferometer in 1976–1977 as it was noted by Matveenko et al. (1978).

On April 28 and May 6, 1976, the first multi-continental interferometric observations were carried out at 1.35 cm wavelength by Batchelor et al. (1976). Astronomers from four radio telescopes participated in these observations. These telescopes were the 64-m NASA telescope in Tidbinbilla (Australia), the 40-m antenna of the Owens Valley Radio Observatory (OVRO), the 26-m antenna at the Maryland Point Observatory of the US Naval Research Laboratory (NRL) and the 22-m antenna of the Crimean Astrophysical Observatory (Simeiz, Crimea).

4 Projects of ground–space interferometers

As it was noted earlier, in the first paper by Matveenko et al. (1965) on VLBI observations the authors discussed an opportunity for ground–space observations but these sentences were removed under request of the editorial board. However, later Soviet scientists and engineers formed a working group to develop a space radio antenna to act as a space component of ground-based interferometer. As Matveenko (2007a) recalled the head of the project was V.P. Mishin, the scientific head was L. I. Matveenko, the chief engineer was V.I. Kostenko. It was assumed that the ground–space interferometer would have an opportunity to observe compact maser sources and AGN at 1.35 cm wavelength. Taking into account the constraints of a space launcher on mass and size of the payload it was proposed to build 3.1 m radio antenna. Optimizing many parameters of the space antenna it was decided to use parabolic reflector and the Cassegrain design for irradiation as it was noted by Matveenko and Kostenko (1982). The orbit apogee of the spacecraft with the radio antenna was expected to be around 80×10^3 km, while the orbit perigee was planned to be around 30×10^3 km. Many of ideas introduced by Soviet scientists and engineers were successfully realised in the first ground–space project VSOP (VLBI Space Observatory Programme); HALCA (Highly Advanced Laboratory for Communications and Astronomy) or the code name MUSES-B (for the second of the Mu Space Engineering Spacecraft series) as it was noted by Matveenko (2007a). The Japanese HALCA satellite was moving along a highly elliptical orbit with an apogee altitude of 21,400 km and a perigee altitude of 560 km, with an orbital period of approximately 6.3 hours. HALCA was launched in February 1997 and made its final VSOP observations in October 2003. Initially it was planned to observe in three frequency bands: 1.6 GHz, 5.0 GHz, and 22 GHz, it was found that the sensitivity of the 22 GHz band

had severely degraded shape after orbital deployment and observations were done only in 1.6 GHz and 5.0 GHz. Clearly, the highest frequency band corresponds to the best angular resolution, therefore the expected highest resolution was not reached.

In 1980s, the idea of a Russian space–ground interferometer (Radioastron) was discussed again. It was expected that the interferometer would have an angular resolution at a level of a few microarcseconds at the shortest wavelength 1.3 cm as it was noted by Kardashev and Slysh (1988); Kardashev (2001). However, the space antenna was launched only in 2011 and Soviet astronomers lost an opportunity to built the first ground–space VLBI radio telescope and conduct observations in 1.35 cm wavelength with the best angular resolution before the realization of the Japanese HALCA mission. The Radioastron mission was successfully launched in 2011 and was operating until 2019, scientific results after five years of operation are given by Kardashev et al. (2017).

A perspective space–ground VLBI mission is Millimetron[3]. It will have a cryogenic antenna with 10 m diameter. A wavelength coverage is [70 μm, 1 mm]. Its orbit is around Lagrangian L2 point in the Sun–Earth two body system (as many other astronomical missions). A wavelength range for space Earth-VLBI observations is $[0.5, 10]$ mm. A wavelength for single dish observations is $[0.07, 3]$ mm. An expected launch date is 2029 or later.

5 GR effects in a strong gravitational field

In the 1970s, Bardeen (1973)[4] presented a picture of a dark region (a shadow) for a gedanken observation which corresponds to a bright screen located behind a Kerr black hole and a distant observer is located in the equatorial plane. Later, Chadrasekhar (1983) reproduced a similar picture in his book. However, neither Bardeen nor Chandrasekhar considered shadow as a possible test of GR since a) shadow sizes are extremely small to be detected for known black holes and b) there are no bright screens precisely behind black hole in astronomy. The authors represented a shadow shape as a function $\beta(\alpha)$, where β corresponds to impact parameter in rotation axis direction while α correspond to impact parameter in the equatorial direction. In addition we would like to note that perhaps Bardeen and Chandrasekhar did not suggest the use of the apparent shape of a black hole as GR test perhaps because the dark region (shadow) is too small to be detectable for all known estimates of black hole masses and distances toward them. Falcke et al. (2000); Melia and Falcke (2001) simulated shadow formation for the Galactic Center in the framework of a toy model, where the authors took into account electron scattering for a radiation in mm and cm bands. The authors concluded that it is possible to observe a dark region (shadow) around the black hole in mm band, while it is not possible to see a shadow in cm band due to electron scattering. It was expected to create a global network acting in 1.3 mm wavelength, therefore the best angular resolution of this interferometer is around 25 μas (similar to the resolution of EHT network as it was done by Event Horizon Telescope

[3]https://millimetron.ru/en/general.

[4]The remarkable relativist James Maxwell Bardeen passed away on June 20, 2022 and he had an opportunity to see realizations of his theoretical picture for Sgr A* and M87*. It is a very nice case when a theoretical concept was coined in skies.

Collaboration: Akiyama et al. (2019), while the shadow diameter was estimated as small as 30 μas assuming that the black hole mass is $2.6 \times 10^6 M_\odot$ as it was evaluated by Eckart and Genzel (1996); Ghez et al. (1998)), therefore, expectations for shadow observations with these facilities were not very optimistic, however, now we know that the black hole mass is more than $4 \times 10^6 M_\odot$ and EHT Collaboration reconstructed the shadow at Sgr A* in 2022. Therefore, the problem of shadow reconstruction using EHT Collaboration observations is very hard but realizable.

At the time when the Radioastron mission was preparing for its launch it was known that its best angular resolution at the shortest wavelength 1.3 cm was around 8 μas and it was comparable with the Schwarzschild diameter for the black hole at the Galactic Center since its mass was evaluated as high as $5 \times 10^6 M_\odot$ (based on estimates done by Rees (1982)). Therefore it was expected that observations with so precise angular resolution will give an opportunity to find signatures of general relativistic effects. Zakharov et al. (2005a); Zakharov et al. (2005b) proposed to use shadow observations around the Galactic Center as a test of presence of a supermassive black hole at Sgr A* since in the case of black hole mass around $4 \times 10^6 M_\odot$ and a distance around 8 kpc toward the Galactic Center the shadow size is around 50 μas. Usually, there are no bright screens behind astrophysical black holes, however, following ideas proposed by Holz and Wheeler (2002) in the paper by Zakharov et al. (2005a) it was noted that a shadow should be surrounded by secondary images of many astrophysical sources and a presence of these secondary sources gives an opportunity to outline a shadow. It is important to note that the presence of a shadow depends only on black hole metric and it does not depend on uncertainties of our knowledge about accretion flows and only in the case if emitting regions are very close to black hole horizons for rapidly rotating black holes the shadow sizes and shapes may be different from the standard case of a bright screen behind a black hole. Zakharov et al. (2005a) showed that in the case of equatorial plane position of a distant observer the maximal impact parameter in the rotational axis direction is always (independently on a) $\beta_{max}(\alpha_{max}) = 3\sqrt{3}$ while $(\alpha_{max}) = -2a$. This claim was based on an analysis of critical curve for Chandrasekhar parameters $\eta(\xi)$ which separates scatter and capture of photons in Kerr metric. This analysis was done by Zakharov (1986), see Fig. 2 in the paper and discussion therein and if one considers critical values corresponding to multiple roots of the polynomial describing a radial photon motion as functions of radial coordinate r ($\xi(r)$, $\eta(r)$) and one has a maximal ($\eta(\xi)$) at $\xi = -2a$ one has $\eta(-2a) = 27$ and $r(-2a) = 3$ (see also the critical curve Fig. 34 (page 352 in book by Chandrasekhar 1983). If $\eta(\xi)$ is known, one could obtain $\beta(\alpha)$. Therefore, the function $\eta(\xi)$ determines information about shadows for any position angle.

Zakharov et al. (2005a) expressed a hope that the shadow may be detected with Radioastron facilities if electron scattering may be ignored, while the authors expressed a strong belief that the shadow can be detected with VLBI network acting in mm band or with the projected ground–space interferometer Millimetron. The recent results by Event Horizon Telescope Collaboration: Akiyama et al. (2022a) where the shadow was reconstructed for Sgr A* remarkably confirmed our predictions. Earlier, a shadow was reconstructed by Event Horizon Telescope Collaboration: Akiyama et al. (2019) for M87*. Later, there were presented polarization maps for M87* by Event Horizon Telescope Collaboration: Akiyama et al. (2021a) and possible distributions of magnetic fields were also given by Event Horizon Telescope Collaboration: Akiyama

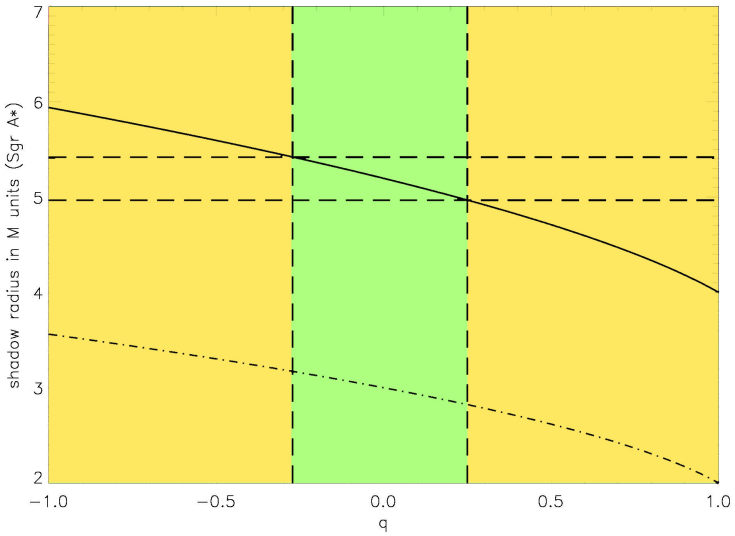


Figure 1 Shadow (mirage) radius (solid line) and radius of the last circular unstable photon orbit (dot-dashed line) in M units as a function of q. We adopt a shadow diameter $\theta_{\rm sh\ Sgr\ A*} \approx (51.8 \pm 2.3)\,\mu$as at 68% confidence levels as it was given by Event Horizon Telescope Collaboration: Akiyama et al. (2022a). Horizontal dashed lines correspond to constraints on shadow radius in M units. Light green vertical strip corresponds to q parameter ($-0.27 < q < 0.25$) which are currently consistent with the shadow size estimate done by the EHT collaboration for Sgr A* while yellow vertical strips correspond to q parameters which are not consistent with the shadow size estimate.

et al. (2021b) (polarization is connected with synchrotron radiation of electrons accelerating in magnetic fields near M87*).

Based on the results of these studies Event Horizon Telescope Collaboration: Kocherlakota et al. (2021) constrained charges of several metrics including Reissner–Nordström, Frolov, Kazakov–Solodukhin and several others. We would like to note that the blue dotted line in the left panel of Fig. 2 shown by Event Horizon Telescope Collaboration: Kocherlakota et al. (2021) corresponds to an analytical expression for the shadow size as a function of charge and Fig. 2 as it was shown by Zakharov et al. (2005a).

6 Shadow sizes for RN black holes with a tidal charge

In Zakharov et al. (2005a) an analytical expression for shadow radius has been obtained as a function of a black hole charge and in the derivation we used an algebraic condition of vanishing discriminant which was used earlier by Zakharov (1991, 1994). However, cosmic plasma is neutral we do not expect to find significant electric charge for astrophysical black holes, but in the framework of theories with extra dimension there are solutions which look very similar to Reissner–Nordström ones. For instance, Dadhich et al. (2000) showed that if we consider the Randall–Sundrum II braneworld scenario, the Reissner–Nordström metric may be a black hole solution in the model.

Later, this solution was called the Reissner–Nordström with a tidal charge. Similar solutions may exist in the scalar–tensor theories which are called now Horndeski theories as it was shown by Babichev et al. (2017).

An expression for the Reissner–Nordström metric may be written in the form in natural units ($G = c = 1$)

$$ds^2 = -\left(1 - \frac{2M}{r} + \frac{\mathcal{Q}^2}{r^2}\right) dt^2 + \left(1 - \frac{2M}{r} + \frac{\mathcal{Q}^2}{r^2}\right)^{-1} dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2), \quad (1)$$

where M is the mass of a black hole and $\mathcal{Q}$ is its charge (in the case of electric charge we have the ordinary Reissner–Nordström metric, while Dadhich et al. (2000) showed $\mathcal{Q}^2$ may be negative and it is called a tidal charge).

We introduce notations $\hat{r} = r/M, \xi = L/(ME)$ and $\hat{\mathcal{Q}} = \mathcal{Q}/M$. Below we omit the hat symbol for these quantities. We also introduce $l = \xi^2, q = \mathcal{Q}^2$. The polynomial $R(r)$ describes a motion along r-coordinate and it has a multiple root r_{crit} if and only if the polynomial discriminant is vanishing and as it was shown by Zakharov (2014) we found the polynomial $R(r)$ has a multiple root for $r \geq r_+$ if and only if

$$l^2(1-q) + l(-8q^2 + 36q - 27) - 16q^3 = 0. \quad (2)$$

If $q = 1$, then $l = 16$, or $\xi_{cr} = 4$ as it was noted by Zakharov et al. (2005a); Zakharov (2014). These values also correspond to the blue curve shown in Fig. 2 presented by Event Horizon Telescope Collaboration: Kocherlakota et al. (2021) since at this curve we can see that for $\mathcal{Q} = 1$ we have $\xi_{cr}(\mathcal{Q}) = 4$. From Eq. (2), we have

$$l_{\rm cr} = \frac{(8q^2 - 36q + 27) + \sqrt{(9-8q)^3}}{2(1-q)}. \quad (3)$$

Therefore, we see from the last relation that there are circular unstable photon orbits only for $q \leq \frac{9}{8}$. For $1 < q \leq \frac{9}{8}$ we have naked singularities and we have unstable photon circular orbits but there are no shadows for these tidal parameters. As it was shown by Zakharov et al. (2005a) a set of Chandrasekhar's parameters ξ, η corresponding to the photon unstable circular orbits separates capture and scatter regions for Kerr–Newman black hole solutions but for generalizations of these solutions including naked singularity cases this statement may be wrong as it was noted for naked singularities of Reissner–Nordström metric with $1 < q \leq \frac{9}{8}$ there are unstable circular photon orbits but shadows are not formed for these metrics. Interesting cases of the naked singularities forming shadows were considered by Shaikh et al. (2018). As it was first noted many years ago, the photon capture cross section for a charged black hole has to be considerably smaller than the capture cross section of a Schwarzschild black hole as one can see in corresponding figures presented by Zakharov et al. (2005b); Zakharov (2014); Event Horizon Telescope Collaboration: Kocherlakota et al. (2021). The critical value of the impact parameter, characterizing the capture cross section for a Reissner–Nordsröm black hole, is determined by equation (3), since $\xi = \sqrt{l}$. As it was shown by Zakharov et al. (2005b); Zakharov (2014, 2022) we can calculate the radius of the unstable circular photon orbit (which is the same as the minimum

periastron distance for all orbits which are scattered). Namely,

$$r_{\rm crit} = 2\sqrt{\frac{l_{\rm cr}}{6}}\cos\frac{\alpha}{3}, \tag{4}$$

where

$$\cos\alpha = -\sqrt{\frac{27}{2l_{\rm cr}}}. \tag{5}$$

7 Constraints on a tidal charge

Based on estimates of shadow size for M87* done by Event Horizon Telescope Collaboration: Kocherlakota et al. (2021) in a paper by Zakharov (2022) it was estimated a tidal charge using analytical expressions done in Zakharov (2014), namely $q \in [-1.22, 0.814]$ at 68% C. L. and the upper bound ($q_{upp} = 0.814$) of the interval corresponds to the upper limit $\mathcal{Q}_{upp} = \sqrt{q_{upp}} \approx 0.902$ which corresponds to the value shown by blue curve in Fig. 2 of paper by Event Horizon Telescope Collaboration: Kocherlakota et al. (2021).

Zakharov (2022) found constraints on a tidal charge $-0.25 < q$ for Sgr A* based on preliminary estimates of a ring width done by Lu et al. (2018). Below we improve an upper limit estimate for tidal charge using new EHT estimates for shadow size in Sgr A*. Similarly to Event Horizon Telescope Collaboration: Akiyama et al. (2022a) we adopt a shadow diameter $\theta_{\rm sh\ Sgr\ A^*} \approx (51.8 \pm 2.3)\mu$as at 68% confidence level. In Fig. 1 we show an allowed region for a tidal charge. Horizontal dashed lines correspond to constraints on shadow radius in M units. Light green vertical strip corresponds to q parameter ($-0.27 < q < 0.25$) which are currently consistent with the shadow size estimate obtained by the EHT collaboration for Sgr A* while yellow strips correspond to q parameters which are not consistent with the shadow size estimate.

Conclusions

We recall that the contributions of Russian scientists in the development of synchrotron radiation and its astrophysical applications to explain spectra of astronomical objects. We also noted Matveenko's contribution in the development of the VLBI method for astronomical observations. Recent remarkable results of the EHT for reconstructions of shadows for black holes in Sgr A* and M87* showed a high efficiency of this technique. As we noted there are analytical expressions for dependence of shadow sizes on (tidal) charge and this parameter can be evaluated from shadow size estimates done with VLBI observations and data analysis.

Considerations of Randall–Sundrum theories with extra dimension led to conclusions on existence of Reissner–Nordström solutions with a tidal charge. Based on our analytical expressions for shadow sizes as a function of charge we constrained tidal charge for Sgr A* and improved our previous results obtained by Zakharov (2022). Similar constraints on electric charge were obtained recently by Event Horizon Telescope Collaboration: Akiyama et al. (2022b).

Acknowledgements

The author thanks the organizers of ICRAnet–Isfahan Astronomy Meeting for their kind invitation to present a contribution for this activity.

References

Artsimovich L. A., Pomeranchuk I. (1945) J. Phys. USSR 2, 267
Babichev E., Charmousis C., Lehebel A. (2017) JCAP 4, 27
Bardeen J. (1973) in Black Holes (Les Astres Occlus), eds. B. S. DeWitt and C. DeWitt-Morette, New York: Gordon & Breach, p. 215
Batchelor R., Jauncey D. L., Johnson K. J. et al. (1976) SvAL 2, 181
Bisnovatyi-Kogan G. S. (1999) in Synchrotron Radiation Theory and Its Development, ed. V. A. Bordovitsyn, World Scientific, Singapore, p. 385
Blewett J. P. (1946) Phys. Rev. 69, 87
Bohr N. (1913) Phil. Mag. 26, 1
Broderick J. J., Vitkevich V. V., Jauncey D. L. el al. (1971) SvA **14**, 627
Burke B. F., Johnston K. J., Efanov V. A. et al. (1972) SvA 16, 379
Chandrasekhar S. (1983) Mathematical Theory of Black Holes, Oxford: Clarendon Press
Connerade J.-P. (2021) The Planetary Atom: A Fictional Account of George Adolphus Schott the Forgotten Physicist World Scientific, Singapore
Dadhich N., Maartens R., Papadopoulos P., Rezania V. (2000) Phys. Lett. B 487, 1
Elder F. R., Gurewitsch A. M., Langmuir R. V., Pollock H. C. (1947) Phys. Rev. 71, 829
Eckart A., Genzel R. (1996) Nature 383, 415
Event Horizon Telescope Collaboration: Akiyama K., Alberdi A., Alef W. et al., (2019) ApJL 875, L1
Event Horizon Telescope Collaboration: Akiyama K., Alberdi A., Alef W. et al. (2021a) ApJL 910, L12
Event Horizon Telescope Collaboration: Akiyama K., Alberdi A., Alef W. et al. (2021b) ApJL 910, L13
Event Horizon Telescope Collaboration: Akiyama K., Alberdi A., Alef W. et al. (2022) ApJL 930, L12
Event Horizon Telescope Collaboration: Akiyama K., Alberdi A., Alef W. et al. (2022) ApJL 930, L17
Event Horizon Telescope Collaboration: Kocherlakota P., Rezzolla L., Falcke H. et al. (2021) Phys. Rev. D 103, 104047
Falcke H., Melia F., Agol E. (2000) ApJL 528, L13
Ghez A. M., Klein B. L., Morris M., Becklin E. E. (1998) ApJ 509, 678
Ginzburg V. L. (1984) in The early years of radio astronomy. Reflections fifty years after Jansky's discovery, ed. W. T. Sullivan III, Cambridge University Press, p. 289
Ginzburg V. L. (1985) in The early years of cosmic ray studies, ed. Y. Sekido and H. Elliot, D. Reidel Publishing Company, Dordrech, p. 411
Ginzburg V. L., Syrovatskii S. I. (1965) ARAA 3, 297
Ginzburg V. L., Zheleznyakov V. V. (1958) SvA 2, 653

Ginzburg V. L., Zheleznyakov V. V. (1959) SvA 3, 235
Holz D., Wheeler J. A. (2002) ApJ 578, 330
Iwanenko D., Pomeranchuk I. (1944) Phys. Rev. 65, 343
Jansky K. (1933) Nature 132, 66
Kardashev N. S. (2001) in Quasars, AGNs and Related Research Across 2000: ESO Astrophysics Symposia, ed. G. Setti and J.-P. Swings, Springer-Verlag, p. 66
Kardashev N. S., Slysh V. I. (1988) in The Impact of VLBI on Astrophysics and Geophysics; Proceedings of the 129th IAU Symposium ed. M. J. Reid and J. M. Moran, Dordrecht: Kluwer Academic Publishers, p. 433
Kardashev N. S., Alakoz A. V., Andrianov A. S. et al. (2017) Solar System Research 51, 535
Kellermann K. I. (1992) in Astrophysics on the threshold of the 21st century, ed. N. S. Kardashev, Gordon & Breach, 1992, p. 37
Linden-Bell D., Rees M. J. (1971) MNRAS 152, 461
Lovell B. (1973) Out of the zenith; Jodrell Bank 1957-1970, Oxford University Press, London
Lu R.S., Krichbaum T.P., Roy A.L. et al. (2018) ApJ 859, 60.
Matveenko L. I. (1973) Nauka i Zhizn' (Science and Life) 10, 25 (in Russian)
Matveenko L. I. (2007a), The VLBI history: coming into being and developing, Preprint N 176 of Institute of Applied Astronomy fo Russian Academy of Sciences (in Russian)
Matveenko L. I. (2007b) Astron. Nachr. 328, 411
Matveenko L. I., Kardashev N. S., Sholomitskii G. B. (1965) Radiophysics 8, 651 (in Russian); Radiophysics 8, 461
Matveenko L. I., Kostenko V. I. (1982) Space Investigations (Kosmicheskie Issledovaniia) 20, 149 (in Russian).
Matveenko L. I., Moiseev I. G., Moran J. M. et al. (1978) SvAL 4, 26
Melia F., Falcke H. (2001) ARAA 39, 309
Okun L. B. (2004) in I. Ya. Pomeranchuk and Physics at the Turn of the Century, eds. A. Berkov, N. Narozhny and L Okun, World Scientific, Singapore, p. 3; arXiv:physics/0307123 [physics.hist-ph]
Papaleksi N. D. (1947) Soviet Physics – Uspekhi 31, 297
Pomeranchuk I. (1940) J. Exper. Theor. Phys. 9, 915 (in Russian); J. Phys. USSR 2, 356
Rees M. J. (1971) Nature 229, 312
Rees M. J. (1982) in AIP Conference Proceedings 83, 166
Schiff L. I. (1946) Rev. Scien. Instr. 17, 6
Schott G. A. (1912) Electromagnetic Radiation and the Mechanical Reactions Arising from it, Cambridge University Press
Schott G. A. (1939) Proc. R. Soc. Lond. A 171, 1
Schwinger J. (1949) Phys. Rev. 75, 1912
Shaikh R., Kocherlakota P., Narayan R., Joshi P.S. (2018) MNRAS 482, 52.
Shklovsky I. S. (1946) Astr. J. U.R.S.S. 23, 333
Shklovsky I. S. (1991) Five Billion Vodka Bottles to the Moon: Tales of a Soviet Scientist, W.W. Norton & Company
Shklovsky I. S., (1953) Akademiia Nauk SSSR Doklady 90, 983 (in Russian)
Shklovsky I. S., (1975) Sov. Astron. Lett. **1**, 135

Shklovsky I. S. (1976) Supernovae and Related Problems, Second Edition, Moscow: Nauka, in Russian
Shklovsky I. S. (1968) Supernovae, New York: Wiley–Blackwell
Zakharov A. F. (1986) Sov. Phys. JETP 64, 3
Zakharov A. F. (1991) SvA 35, 147
Zakharov A. F. (1994) CQG 11, 1027
Zakharov A. F. (2014) Phys. Rev. D 90, 062007
Zakharov A. F. (2022) Universe 8(3), 141
Zakharov A. F., Nucita A. A., De Paolis F., Ingrosso G. (2005a) New Astron., 10, 479
Zakharov A. F., De Paolis F., Ingrosso G., Nucita A. A. (2005b) A & A 442, 795