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Regular black hole solution surrounded by PFDM to explain the radiative efficiency of A0620-00

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In the work I show that static and regular black hole solution surrounded by perfect fluid dark matter (PFDM) can be used to explain the radiative efficiency of the source A0620-00. This black hole solution has two extra spacetime parameters besides mass being the magnetic charge of a black hole and parameter that describes the properties of dark matter around a black hole. I demonstrate that combination of these two extra spacetime parameters is able to interpret the observational radiative efficiency of the source A0620-00.

I. INTRODUCTION

The very first image of the black hole (BH) in the center of galaxy M87* [1, 2] obtained by Event Horizon Telescope (EHT) together with the detection of the gravitational waves detected by LIGO-VIRGO collaboration [3, 4] played an important role in the test of General Relativity (GR) of Einstein in the strong regime developed about century ago. But GR suffers from some fundamental problems like physical singularity in the solutions obtained in the framework of the theory. However, Bardeen in his work [5] has showed that the physical singularity can be avoided with the use of GR coupled with nonlinear electrodynamics. Several black hole solutions without physical singularity have been obtained in the works [6–9]. In the works [10–12] the spinning versions of such solutions have been derived.

Existence of dark matter and dark energy in the Universe [13] motivates to take into account BH solutions surrounded by dark matter and quintessence which is a hypothetical form of dark energy [14, 14–20]. Kiselev in his works [14, 20] has shown the models for dark matter that considered to be as perfect fluid and black hole solution surrounded by PFDM has been studied in [21]. Properties of spacetime around several black hole solutions has been investigated in our preceding works (see e.g. [22–26]).

In this work I am aimed to show how well the regular Bardeen BH with PFDM around can explain the radiative efficiency of the black hole source A0620-00. The work has the following structure: in Sect. II the brief description of the spacetime around regular Bardeen BH with PFDM around has been presented. In Sect. III the main steps to get the constraints between spacetime parameters from the observed radiative efficiency of the source A0620-00 has been presented. In Sect. IV the main points of the work has been discussed. In the work I use geometrized units $G = c = 1$, the signature of the spacetime is taken as (-,+,+,+), and Greek indices run 0,1,2,3.

II. SPACETIME METRIC AROUND REGULAR BARDEEN BH WITH PFDM

In the work [27] it has been shown the derivation of spacetime metric around regular Bardeen BH surrounded by PFDM which has the following expression

$$\begin{aligned} ds^2 &= -f(r)dt^2 + f(r)^{-1}dr^2 + r^2 d\Omega^2 \,, \\ f(r) &= 1 - \frac{2Mr^2}{(r^2+g^2)^{\frac{3}{2}}} + \frac{\alpha}{r}\log\frac{r}{|\alpha|} \,. \end{aligned} \tag{1}$$

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Here, g is the magnetic charge of central black hole and α stands for the density and pressure of PFDM. One can recover the Schwarzschild spacetime for the vanishing values of these two extra spacetime parameters. In this solution the energy-momentum tensor of the PFDM can be written as

$$T^{\mu}_{\nu} = \mathrm{diag}(-\rho, p_r, p_\theta, p_\phi)\,, \tag{2}$$

where the distribution of the PFDM is given by the following relation between the pressure and the density of the PFDM

$$\rho = -p_r = \frac{\alpha}{8\pi r^3} \quad \text{and} \quad p_\theta = p_\phi = \frac{\alpha}{16\pi r^3}\,. \tag{3}$$

Here I take $\alpha > 0$ as in our preceding work [25].

III. CONSTRAINTS FROM THE RADIATIVE EFFICIENCY PROFILE OF THE ACCRETION DISC OF A BLACK HOLE

In this section I investigate how well the given spacetime can be used to interpret the observed radiative efficiency of astrophysical black hole candidate. I use Novikov-Thorne model for the structure of accretion disk formed around central gravitating object which considers the disk to be geometrically thin but optically thick [28]. The effective potential of massive particle moving in the equatorial plane of the central object can be written as [28–30]

$$V_{eff}(r) = \frac{E^2 g_{\phi\phi} + 2ELg_{t\phi} + L^2 g_{tt}}{g_{t\phi}^2 - g_{tt}g_{\phi\phi}} - 1, \tag{4}$$

where E is a specific energy and L is a specific angular momentum of a test particle. In terms of metric components these two quantities can be written as

$$E = \frac{-g_{tt} - \Omega g_{t\phi}}{\sqrt{-g_{tt} - 2\Omega g_{t\phi} - \Omega^2 g_{\phi\phi}}}\,, \tag{5}$$

and

$$L = \frac{\Omega g_{\phi\phi} + g_{t\phi}}{\sqrt{-g_{tt} - 2\Omega g_{t\phi} - \Omega^2 g_{\phi\phi}}}\,. \tag{6}$$

Here

$$\Omega = \frac{d\phi}{dt} = \frac{-g_{t\phi,r} \pm \sqrt{\{-g_{t\phi,r}\}^2 - \{g_{\phi\phi,r}\}\{g_{tt,r}\}}}{g_{\phi\phi,r}}\,. \tag{7}$$

The ISCO location can be found from the following conditions

$$\begin{aligned} V_{eff}(r) &= 0\,, \\ V'_{eff}(r) &= 0\,, \\ V''_{eff}(r) &= 0\,. \end{aligned} \tag{8}$$

The radiative efficiency of the disk around black hole can be found from the following relation

$$\eta = 1 - E_{isco}\,, \tag{9}$$

with E_{isco} being the specific energy of a test particle orbiting at ISCO. Since E_{isco} depends on spacetime parameters one can now get the constraint for these parameters using the data for the black hole source A0620-00. This black hole candidate corresponds to X-ray binary source with K-Type main-sequence star and stellar mass BH with mass $6.61M_\odot$ [31]. In [32] it has been shown that the distance between the source and Earth is $1.06 \pm 0.12kpc$ with the angle of inclination $51 \pm 0.9°$. Assuming that the source is defined by the Kerr spacetime in the work [33] it has been shown using the continuum-fitting method (CFM) that the spin of the source aligns in the range $-0.59 < a < 0.49$ and the best fitting value is $a = 0.12 \pm 0.19$. For this best fitting values of the spin the corresponding values of the radiative efficiency of the source is $\eta = 0.061^{+0.009}_{-0.007}$. I use this value to get the desired constraints between the spacetime parameters g and α as presented in Fig. 1. One can see from the figure that the magnetic charge parameter itself (i.e. in the absence of the PFDM) can explain the radiative efficiency of the source in the range $0 < g < 0.77$. One can also see that with the increase in the values of the parameter α the range of g to explain the observed radiative efficiency of the source becomes narrow.

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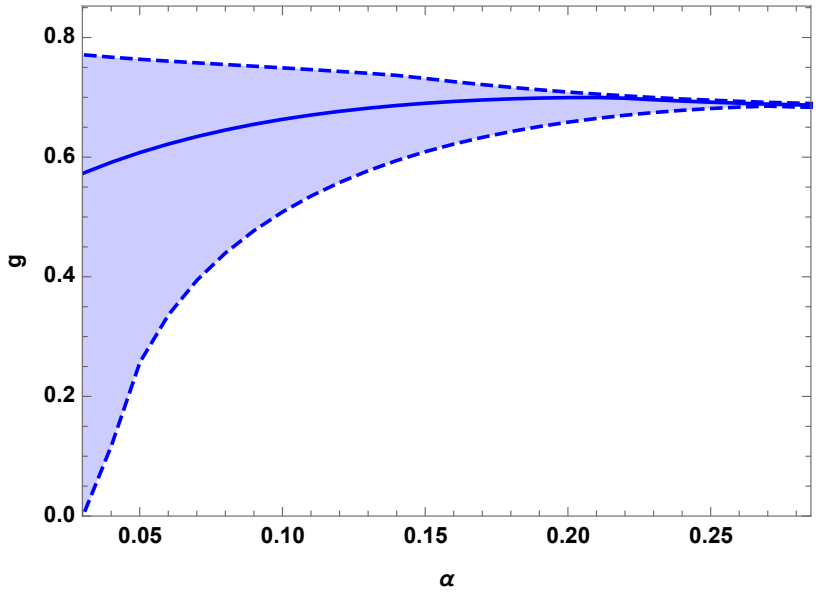


FIG. 1: The values of spacetime parameters g and α to explain the radiative efficiency of the source A0620-00. The upper dashed lines corresponds to the value of $\eta = 0.061^{+0.009}$ while the down one to $\eta = 0.061_{-0.007}$ and the central one to $\eta = 0.061$. The shaded region gives the values of parameters that can explain the radiative efficiency in the given error band.

IV. DISCUSSION

In this paper I tried to show that static black hole solutions can be used to explain the observational results for astrophysical black hole sources which originally adjusted for the Kerr spacetime. I have demonstrated that based on the simple idea of imitation of the radiative efficiency of the source A0620-00 from the Kerr spacetime to Bardeen solution surrounded by PFDM it is possible to get constraints between the spacetime parameters of the latter for the matching values of the radiative efficiency. I have shown that even in the case of the absence of the PFDM the magnetic charge itself can replace the spin of the Kerr solution to describe the observed radiative efficiency of the chosen source. For the future prospects I plan to extend this work for the cases of other black hole candidates like GROJ1655-40, XTEJ1550-564, H1743-322, and GRS1124-683 to see if the given spacetime is able to explain the radiative efficiency of those sources as well.

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