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Characteristics of Spinning Black Holes

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Authors' contributions

This work was carried out in collaboration among both authors. Author DM collected the materials and designed the study and plotted the graphs with statistical data analysis. He wrote the first draft of the manuscript and managed literature searches. Author AR managed the analyses of the study and literature searches. Both authors read and approved the final manuscript.

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ABSTRACT

Aims: The present paper derives an expression for the frequency or wavelength of Hawking radiation emitted by spinning black holes in terms of the event horizon ($\lambda = 16\pi R_s$ & $\nu = c/16\pi R_s$), when the quantum theory of radiation ($E = h\nu$), energy of Hawking radiation and event horizon of the spinning black holes ($R_s = GM/c^2$) are used. This frequency or wavelength of Hawking radiation may be regarded as the characteristics of spinning black holes and this work is extended to derive an expression for the change in the frequency of Hawking radiation with respect to radius of event horizon ($\delta\nu / \delta R_s = -c/16\pi R_s^2$).
Study Design: The secondary data for the frequencies and wavelengths of Hawking radiation has been calculated from the primary data of rest masses for stellar – mass black holes (M ~ 5 - 20 $M_\odot$) in XRBs and (M ~ 10^6 – $10^{9.5}$ $M_\odot$) in AGN resulting the wavelength($\lambda = 16\pi R_s$) & and frequency ($\nu = c/16\pi R_s$). Our result corresponds to the result of research work entitled: Frequency of

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Hawking radiation from black holes by Mahto et al. published in International Journal of Astrophysics and Space Science (2013).

Place and Duration of Study: This work has been completed in the department of Physics of Marwari College under T.M.B.U. Bhagalpur from Jan 2016 to Aug 2016.

Methodology: This research work is completely theoretical and the total work has been doneusing Laptop at Marwari College Bhagalpur and University Department of Physics, T.M.B.U. Bhagalpur.

Results: The astrophysical objects which emit the radiations of wavelengths (3.707x10^5 m to 14.828x10^5m) or frequencies (8.092x10^2Hz to 2.023x10^2Hz)in XRBs and wavelengths (7.414×10^{10} m to 37.070×10^{13} m) or frequencies (4.046×10^{-3} Hz to 0.809×10^{-6} Hz) in AGN may be classified as spinning as well as non-spinning black holes.

Conclusion: The frequencies/wavelengths of Hawking radiation either emitted from spinning black holes or non-spinning black holes are the same and only depends on their mass. This may be also regarded as the characteristics of spinning black holes in addition to the mass, spin and charge. The mass of black holes are mainly responsible for their identification and characterization and independent from spinning character.

Keywords: Radius of event horizon; XRBs and AGN.

1. INTRODUCTION

A new solution of the Einstein-Maxwell equations as proposed by E. T. Newman et al., represents a rotating mass & charge in some sense and has certain characteristics that correspond to a rotating ring of mass and charge [1]. The no-hair theorem states that once the black hole achieves a stable condition after formation, a black hole has only three independent physical properties: mass, charge and angular momentum [2]. In addition to the mass, spin and charge, Kanak Kumari et al. have used the Schwarzschild radius for characterization of the non-spinning as well as spinning black holes [3]. Classically, black holes are perfect absorbers, but do not emit anything; their temperature is absolute zero can only absorb and not emit particles [4]. The quantum mechanical effects cause black holes to create and emit particles as if they were hot bodies having temperature $\kappa/2\pi$, where κ is surface gravity of black holes [5]. On the basis of general relativity, the black hole is defined as the solution of Einstein's gravitational field equations in the absence of matter that describes the space time around a gravitationally collapsed star [6,7] and its gravitational pull is so abnormally high that even light cannot escape from it. Mahto et al. proposed a model for the frequency and wavelength of Hawking radiation emitted by non-spinning black holes in terms of event horizon and this model may be regarded as the characteristics of non-spinning black holes [8].

In the present paper, we also have proposed a model for the frequency and wavelength of Hawking radiation($\lambda = 16\pi R_s$ & $\nu = c/16\pi R_s$) emitted by spinning black holes in terms of the event horizon using quantum theory of radiation ($E = h\nu$), energy of Hawking radiation and the radius of event horizon of the spinning black holes ($R_s = GM/c^2$), which may be regarded as the characteristics of spinning black holes.

2. DATA FOR THE MASS OF BLACK HOLES IN XRBs AND AGN

There are some astrophysical objects in universe with masses greater than 3$M_\odot$, the likely maximum mass of a neutron star identified as "black hole candidates". Some of these candidates have masses ∽5 – 20$M_\odot$ in X-ray binaries (XRBs) and masses ∽10^6-$10^{9.5}M_\odot$ in Active Galactic Nuclei (AGN) [8,9,10]. The equations for the measurement of mass of black hole can be seen in reference [8,10].

3. DATA FOR THE MEASUREMENT OF SPIN (a_*)

For maximum spin of the spinning black hole, the spin parameter is a_*= +1, if the orbit co-rotates and a_*= - 1, if the orbit counter-rotates [10]. The spin of black hole is given by the equation $a_* = M^2/J$ [11], where M and J indicate the mass & angular momentum of spinning black hole respectively.

4. CHARGE CONCEPT REGARDING THE BLACK HOLES

The Reissner-Nordstrom space-time for an electrically charged black hole is given by equations:

$$ds^2 = -V(r)dt^2 + \frac{dr^2}{V} + r^2 d\Omega^2 \quad \text{(i)}$$

Where

$$V(r) = 1 - \frac{2M}{r} + \frac{Q^2}{r^2} \quad \text{(ii)}$$

The space-time (i) describes a black hole for which there is a horizon, when M>Q. For M<Q, there is no horizon and the space-time has a naked singularity. The case for M=Q is called an extremal black hole [12]. In the case of non-spinning black holes, the charge is zero, i.e. $Q = 0$ [10].

5. DATA IN SUPPORT OF SCHWARZSCHILD RADIUS

The Schwarzschild radius/radius of the event horizon of spinning black holes for stellar – mass black holes in X-ray binaries are 7375 metre to 29500 metre and for the super massive black holes in the active galactic nuclei are 1.475×10^9 metre to 1.475×10^{13} metre [3].

6. EXPRESSION FOR THE CHANGE IN FREQUENCY / WAVELENGTH

The energy of a photon of Hawking radiation is given by the following equation [13]

$$E = \frac{hc^3}{16\pi GM} \quad (1)$$

When the virtual particles (electron and a positron) are formed on the event horizon, then one virtual particle falls into the black hole and other escapes as Hawking radiation. The energy of radiated photons is given by [9]

$$E = h\nu \quad (2)$$

Comparing the equation (1) and (2), we get

$$\nu = \frac{c^3}{16\pi GM} \quad (3)$$

There are three fundamental constants of nature like the gravitational constant (G), Planck constant (h) and velocity of light (c) in the equations (1) and (2). These constants have their own significances discussed with the help of reference [6].

Planck's constant governs the laws of the quantum world and has a more pervasive influence on twentieth century physics. The speed of light *c* is the cornerstone of the special theory of relativity. It is fact that light is an electromagnetic wave travelling at the speed of light (c) is a consequence of Maxwell's equations for the electromagnetic field. The mass-energy equivalence relation $E = mc^2$ has immortalized in popular imagination.

The gravitational constant G, derived from Newton's laws of gravitation, belongs to the general theory of relativity, is the greatest achievements of Albert Einstein. In the case of General theory of relativity, According to Newton, the gravitational constant (G) is the proportionality constant appearing in the inverse square law of gravitation, while the gravitational constant (G) in relativity is the constant determining the degree to which a given distribution of matter warps space-time.

Regarding the special theory of relativity, Einstein harmonized Maxwell's electrodynamics with Newton's mechanics introducing *c* into mechanic, while in the general relativity, he further harmonized this structure with Newton's law of gravitation, which brings together the both constants G and c.

The frequency of radiation is given by the following equation

$$\nu = \frac{c}{\lambda} \quad (4)$$

From equations (3) and (4), and solving, we obtain the following relation

$$\lambda = 16\pi \frac{GM}{c^2} \quad (5)$$

For spinning black holes, the radius of event horizon is given by [10].

$$R_s = \frac{GM}{c^2} \quad (6)$$

Putting the equation (6) into equation (5), we have

$$\lambda = 16\pi R_s \quad (7)$$

$$\delta\lambda = 16\pi\delta R_s \quad (8)$$

$$\delta\lambda / \delta R_s = 16\pi \quad (9)$$

$$\delta\lambda / \delta R_s = Constant \quad (10)$$

$$\delta\lambda \alpha \delta R_s \quad (11)$$

The equation (11) shows that the change in wavelength of Hawking radiation emitting from the spinning black holes is directly proportional to the change in the radius of event horizon.

Putting equation (7) in the equation (4), we have

$$\nu = \frac{c}{16\pi R_s} \quad (12)$$

$$\delta\nu = -\frac{c}{16\pi R_s^2}\delta R_s \quad (13)$$

$$\frac{\delta\nu}{\delta R_s} = -\frac{c}{16\pi R_s^2} \quad (14)$$

$$\left|\frac{\delta\nu}{\delta R_s}\right| = \frac{c}{16\pi R_s^2} \quad (15)$$

Equation (15) shows that the magnitude of change in the frequency of Hawking radiation with respect to the event horizon is inversely proportional to the square of event horizon of spinning black holes, while the relation (12) indicates that the frequency of Hawking radiation emitted by the spinning black holes is inversely proportional to the event horizon of black holes. From the relation (7), it is obvious that the wavelength of the same radiation emitted by the spinning black holes is directly proportional to the event horizon of the spinning black holes. This also means that heavier spinning black holes will emit the Hawking radiation of lower frequency or longer wavelength and vice-versa.

7. RESULTS AND DISCUSSION

In the present paper, we have proposed an model for the wavelength/change in wavelength represented by equation (7)/(8) and frequency/ change in frequency represented by equation (12)/(13) of Hawking radiation emitted by spinning black holes in terms of the radius of event horizon with the help of energy of radiated photons of black holes ($E = h\nu$), the energy of a photon of Hawking radiation ($E = \frac{hc^3}{16\pi GM}$) and the event horizon of the spinning black holes ($R_s = \frac{GM}{c^2}$) with proper mathematical operation. It is clear from the data of Tables 1 and 2 that the radiations emitted by spinning black holes are within the range of frequencies from 8.092x102Hz to 2.023x102Hz or wavelengths

Table 1. Wavelength and frequency of spinning black holes in XRBs

S. no	Mass of BH_s (M)	R_{bh}=1475(M/M$_\odot$) (in metre)	Wavelength $\lambda = 16\pi R_s$ metre.	Frequency $\nu = \frac{c}{16\pi R_s}$ Hz
1	5 M$_\odot$	7375	3.707x10^5	8.092x10^2
2	6 M$_\odot$	8850	4.448 x10^5	6.744 x10^2
3	7 M$_\odot$	10325	5.189 x10^5	5.781 x10^2
4	8 M$_\odot$	11800	5.913 x10^5	5.073 x10^2
5	9 M$_\odot$	13275	6.672 x10^5	4.496 x10^2
6	10 M$_\odot$	14750	7.414 x10^5	4.046 x10^2
7	11 M$_\odot$	16225	8.155 x10^5	3.678 x10^2
8	12 M$_\odot$	17700	8.996 x10^5	3.334 x10^2
9	13 M$_\odot$	19175	9.638 x10^5	3.112 x10^2
10	14 M$_\odot$	20650	10.379 x10^5	2.890 x10^2
11	15 M$_\odot$	22125	11.121 x10^5	2.697 x10^2
12	16 M$_\odot$	23600	11.862 x10^5	2.529 x10^2
13	17 M$_\odot$	25075	12.604 x10^5	2.380 x10^2
14	18 M$_\odot$	26550	13.345 x10^5	2.248 x10^2
15	19 M$_\odot$	28025	14.086 x10^5	2.129 x10^2
16	20 M$_\odot$	29500	14.828 x10^5	2.023 x10^2

Table 2. Wavelength and frequency of spinning black holes in AGN

S. no.	Mass of BH_s (M)	Rbh=1475x (M/ M⊙) (m)	log(R$_{bh}$) (m)	$\lambda = 16\pi R_s$ (in metre)	$\log(\lambda)$	$\nu = \frac{c}{16\pi R_s}$ Hz	$Mod \log(\nu)$
1	1 x 10^6 M⊙	1.475 x10^9	9.1687	7.414×10^{10}	10.8700	4.046×10^{-3}	3.6070
2	2 x 10^6 M⊙	2.950 x10^9	9.4698	14.953×10^{10}	11.1747	2.006×10^{-3}	3.3023
3	3 x 10^6 M⊙	4.425 x 10^9	9.6459	22.242×10^{10}	11.3471	1.348×10^{-3}	3.1296
4	4 x 10^6 M⊙	5.900 x 10^9	9.7708	29.656×10^{10}	11.4721	1.011×10^{-3}	3.0047
5	5 x 10^6 M⊙	7.375 x 10^9	9.8677	37.070×10^{10}	11.5690	0.809×10^{-3}	3.0920
6	6 x 10^6 M⊙	8.850 x 10^9	9.9469	44.448×10^{10}	11.6478	0.674×10^{-3}	3.1713
7	7 x 10^6 M⊙	1.032 x 10^{10}	10.0136	51.899×10^{10}	11.7151	0.578×10^{-3}	3.2380
8	8 x 10^6 M⊙	1.180 x 10^{10}	10.0718	59.313×10^{10}	11.7731	0.505×10^{-3}	3.2967
9	9 x 10^6 M⊙	1.327 x 10^{10}	10.1228	66.727×10^{10}	11.8243	0.449×10^{-3}	3.3477
10	1 x 10^7 M⊙	1.475 x10^{10}	10.1687	7.414×10^{11}	11.8700	4.046×10^{-4}	4.6070
11	2 x 10^7 M⊙	2.950 x10^{10}	10.4698	14.953×10^{11}	12.1747	2.006×10^{-4}	4.3023
12	3 x 10^7 M⊙	4.425 x 10^{10}	10.6459	22.242×10^{11}	12.3471	1.348×10^{-4}	4.1296
13	4 x 10^7 M⊙	5.900 x 10^{10}	10.7708	29.656×10^{11}	12.4721	1.011×10^{-4}	4.0047
14	5 x 10^7 M⊙	7.375 x 10^{10}	10.8677	37.070×10^{11}	12.5690	0.809×10^{-4}	4.0920
15	6 x 10^7 M⊙	8.850 x 10^{10}	10.9469	44.448×10^{11}	12.6478	0.674×10^{-4}	4.1713
16	7 x 10^7 M⊙	1.032 x 10^{11}	11.0136	51.899×10^{11}	12.7151	0.578×10^{-4}	4.2380
17	8x 10^7 M⊙	1.180 x 10^{11}	11.0718	59.313×10^{11}	12.7731	0.505×10^{-4}	4.2967
18	9 x 10^7 M⊙	1.327 x 10^{11}	11.1228	66.727×10^{11}	12.8243	0.449×10^{-4}	4.3477
19	1 x 10^8 M⊙	1.475 x10^{11}	11.1687	7.414×10^{12}	12.8700	4.046×10^{-5}	5.6070
20	2 x 10^8 M⊙	2.950 x10^{11}	11.4698	14.953×10^{12}	13.1747	2.006×10^{-5}	5.3023
21	3 x 10^8 M⊙	4.425 x 10^{11}	11.6459	22.242×10^{12}	13.3471	1.348×10^{-5}	5.1296
22	4 x 10^8 M⊙	5.900 x 10^{11}	11.7708	29.656×10^{12}	13.4721	1.011×10^{-5}	5.0047
23	5 x 10^8 M⊙	7.375 x 10^{11}	11.8677	37.070×10^{12}	13.5690	0.809×10^{-5}	5.0920
24	6 x 10^8 M⊙	8.850 x 10^{11}	11.9469	44.448×10^{12}	13.6478	0.674×10^{-5}	5.1713
25	7 x 10^8 M⊙	1.032 x 10^{12}	12.0136	51.899×10^{12}	13.7151	0.578×10^{-5}	5.2380
26	8 x 10^8 M⊙	1.180 x 10^{12}	12.0718	59.313×10^{12}	13.7731	0.505×10^{-5}	5.2967
27	9 x 10^8 M⊙	1.327 x 10^{12}	12.1228	66.727×10^{12}	13.8243	0.449×10^{-5}	5.3477
28	1 x 10^9 M⊙	1.475 x10^{12}	12.1687	7.414×10^{13}	13.8700	4.046×10^{-6}	6.6070
29	2 x 10^9 M⊙	2.950 x10^{12}	12.4698	14.953×10^{13}	14.1747	2.006×10^{-6}	6.3023
30	3 x 10^9 M⊙	4.425 x 10^{12}	12.6459	22.242×10^{13}	14.3471	1.348×10^{-6}	6.1296

from 3.707x10^5 m to 14.828x10^5m in XRBs and frequencies from 4.046×10^{-3} Hz to 0.809×10^{-6} Hz or wavelengths from 7.414×10^{10} m to 37.070×10^{13} m in AGN. The observations from the Tables 1 and 2, it is also clear that the wavelength of radiations emitted by black holes increases with increase the radius of event horizon of the spinning black holes and vice-versa in the case of XRBs as well as AGN, but the frequency of radiations emitted by spinning black holes decreases with increase the radius of event horizon of the spinning black holes. These two parameters like wavelength and frequency may be regarded as the characteristics of spinning black holes, because

other characteristics of the spinning black holes can be estimated with the help wavelength and frequency. Hence the astrophysical objects emitting the radiations of frequencies ($8.092 x 10^2$Hz to $2.023 x 10^2$Hz) or wavelengths ($3.707 x 10^5$ m to $14.828 x 10^5$m) in X-ray binaries (XRBs) and frequencies (4.046×10^{-3} Hz to 0.809×10^{-6} Hz) or wavelengths (7.414×10^{10} m to 37.070×10^{13} m) in active galactic nuclei (AGN) may be identified as spinning black holes.

To know the variation in the wavelength/ frequency of spinning black holes with corresponding change in the event horizon, the graphs have been plotted between:

(i) The event horizon of different spinning black holes and their corresponding wavelength in XRBs in Fig. 1.
(ii) The event horizon of different spinning black holes and their corresponding frequency in XRBs in Fig. 2.
(iii) The event horizon of different spinning black holes and their corresponding wavelength in AGN in Fig. 3.
(iv) The event horizon of different spinning black holes and their corresponding frequency in AGN in Fig. 4.

The nature of graph as plotted in the Figs. 1 and 3 are in a straight line in the case of the radius of event horizon and corresponding wavelength of spinning black holes for XRBs and AGN respectively. The straight line nature of the graph shows that there is a linear relationship between the event horizon and wavelength of spinning black holes and justifies the validity of model ($\lambda = 16\pi R_s$).

The graph plotted between radius of event horizon and their corresponding frequency of spinning black holes in the Fig. 2 for XRBs shows that the frequency decreases gradually with increase of the radius of event horizon.

From the graph in the Fig. 4 with the help of the Table 2, it is obvious that the frequency of Hawking radiation emitted from spinning black holes decreases with the increase of radius of the event horizon of the spinning black holes and it has a peculiar nature in AGN. The frequency of Hawking radiation emitted from spinning black holes in AGN is so small that they are not easily detectable. So to outcome the difficulties, we have used the logarithmic scale and the modes of their negative values are taken into consideration for our convenience. On the basis of observation of the graph in the Fig. 4, the black holes can be categorized regarding their same order of mass or radius of event horizon as discussed below.

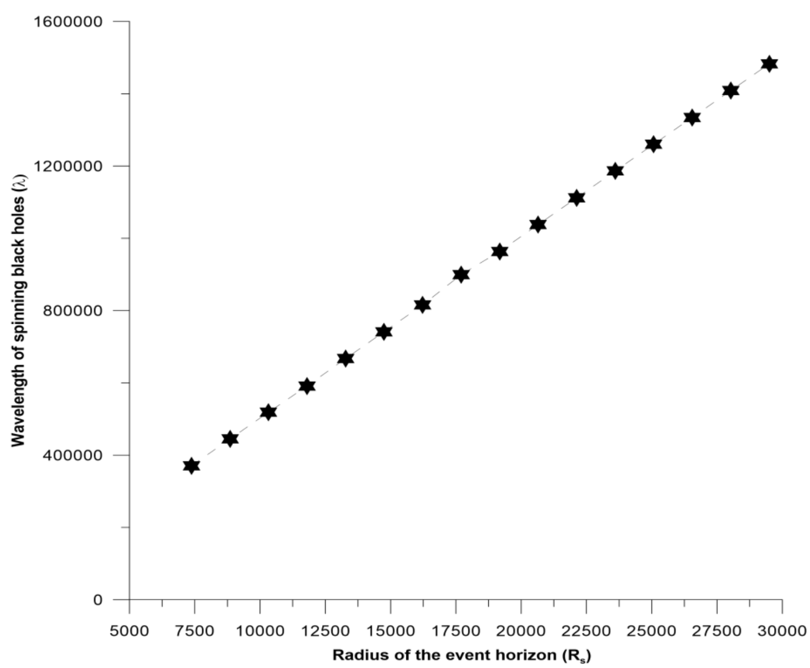

Fig. 1. The graph plotted between the event horizon and wavelength of the different test spinning black holes in XRBs

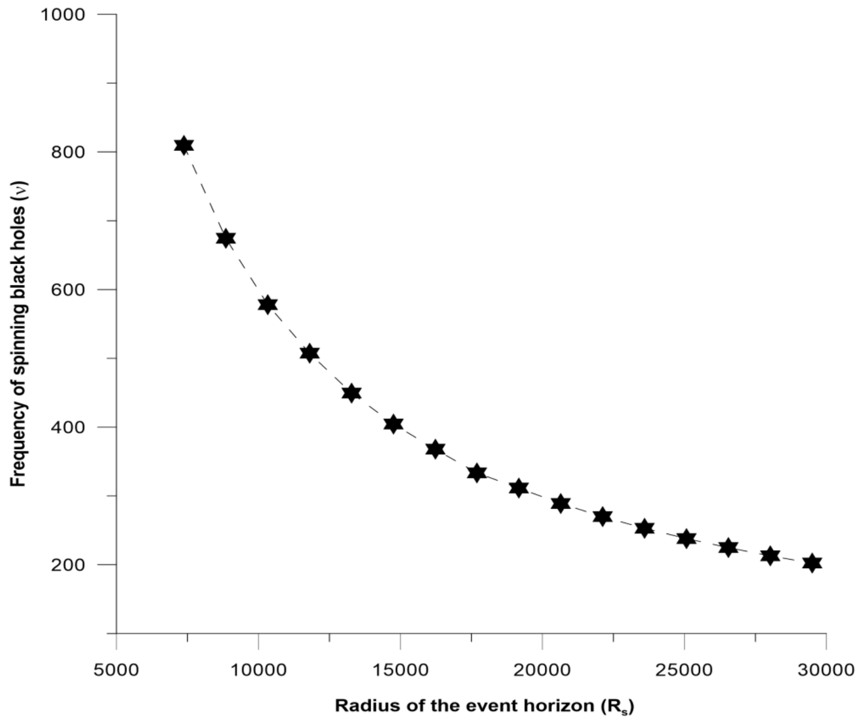

Fig. 2. The graph plotted between the event horizon and frequency of the different test spinning black holes in XRBs

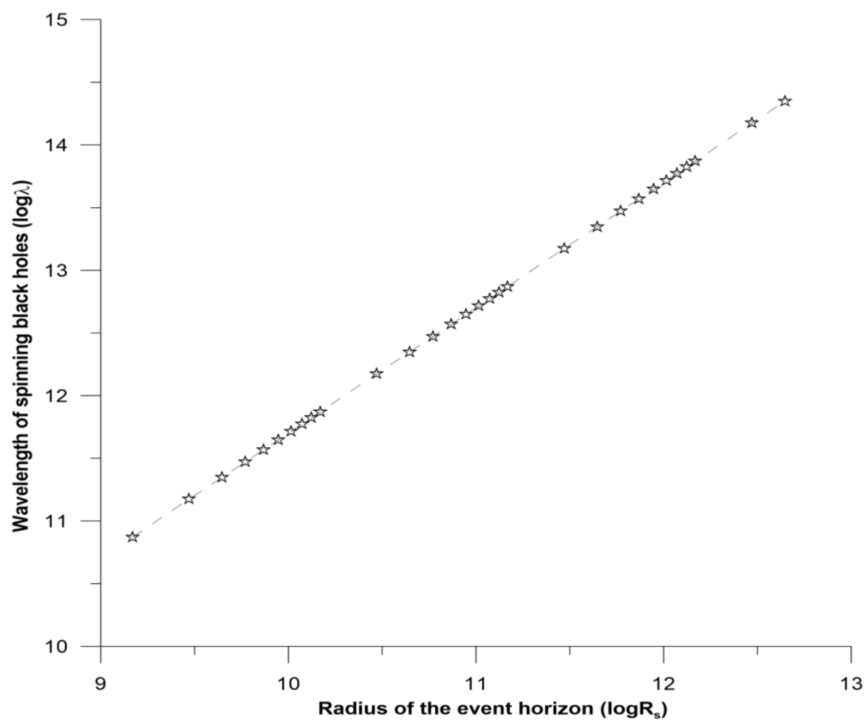

Fig. 3. The graph plotted between the event horizon and wavelength of the different test spinning black holes in AGN

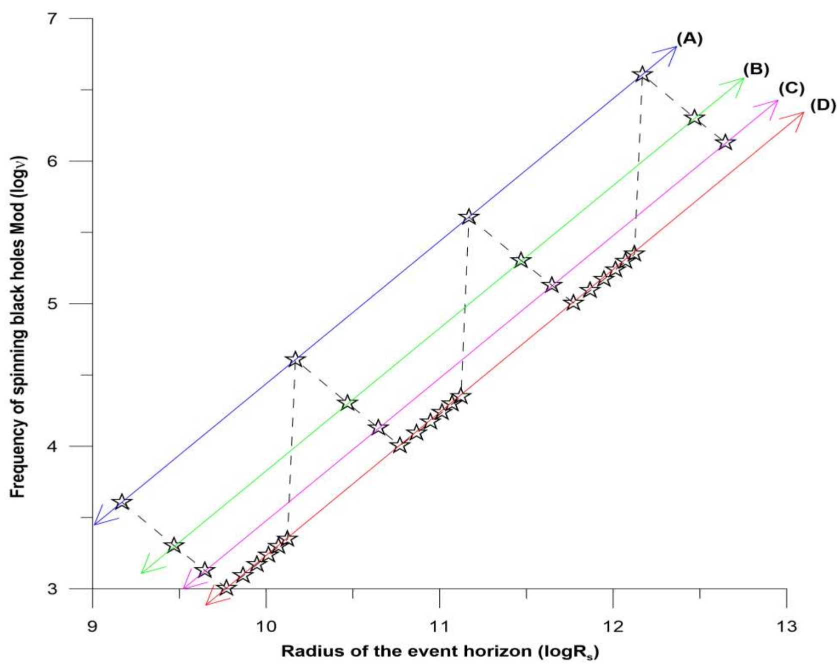

Fig. 4. The graph plotted between the event horizon and frequency of the different test spinning black holes in AGN

The spinning black holes of mass:

1. (1 x 10^6 M$_\odot$, 1 x 10^7 M$_\odot$,1 x 10^8 M$_\odot$,1 x 10^9 M$_\odot$),
2. (2 x 10^6 M$_\odot$, 2 x 10^7 M$_\odot$, 2 x 10^8 M$_\odot$,2 x 10^9 M$_\odot$),
3. (3 x 10^6 M$_\odot$, 3 x 10^7 M$_\odot$,3 x 10^8 M$_\odot$,3 x 10^9 M$_\odot$)

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and rest spinning black holes in AGN from Table 2 are in four categories. When the graph is plotted for each category in the same graph paper, four parallel lines are obtained.

When the results obtained from our research work is compared with that of the non-spinning black holes (Mahto et al. [8]), we see that the frequency/wavelength of spinning black holes is independent of their spinning character and only dependent on their masses. Hence, we may conclude that the mass of black holes are mainly responsible for the identification and characterization of black holes.

8. CONCLUSION

(1) The wavelength or frequency of Hawking radiation may be regarded as the characteristics of spinning black holes because they can be used for their identification.

(2) The frequencies of the Hawking radiation emitted from the spinning black hole decrease with the increase of the radius of event horizon of different test spinning black holes, while the wavelength increases with the corresponding increase in the event horizon.

(3) The graph plotted between the event horizon and corresponding wavelength is in a straight line which justifies the validity of model ($\lambda = 16\pi R_s$).

(4) The spinning black holes may be categorized in a group having exactly the same order of mass which follow the same character in AGN.

(5) Mass of black holes are mainly responsible for their identification and characterization and spinning character is independent.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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