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SOME PREDICTIONS OF SCALING RELATIONS: THE CASE OF THE BLACK HOLE IN M87

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ABSTRACT

In the context of supermassive black holes and their host galaxies, we consider two scaling relations: $M_\bullet - R_e\sigma^3$ and $M_\bullet - M_G\sigma^2$, to derive three fundamental parameters for the supermassive black hole at the center of M87. In this paper we will get predictions for the efficiency and mass of the black hole, and the temperature of its accretion disk, by comparing them with the respective experimental values.

RESUMEN

En el contexto de los hoyos negros supermasivos y sus galaxias anfitrionas consideramos dos relaciones de escala: $M_\bullet - R_e\sigma^3$ y $M_\bullet - M_G\sigma^2$, para obtener tres parámetros fundamentales del hoyo negro supermasivo en el centro de M87. En este trabajo, al compararlas con los valores experimentales respectivos, obtenemos predicciones para la eficiencia y la masa del hoyo negro, así como para la temperatura del disco de acreción.

Key Words: accretion, accretion discs — black hole physics — galaxies: individual: M87 — quasars: supermassive black holes

1. INTRODUCTION

Today, it is increasingly evident that local galaxies of different morphological types host a supermassive black hole (SMBH) at their center (Kormendy and Richstone 1995; Richstone et al. 1998; Ferrarese and Ford 2005). In the literature, it is possible to find many correlations to understand the link between the mass of a supermassive black hole with the properties of the galaxy, such as the brightness or mass of the bulge, the scattering speed, the effective radius, the Sérsic index, etc. (Magorrian et al. 1998; Tremaine et al. 2002; Marconi and Hunt 2003; Haring and Rix 2004; Aller and Richstone 2007; Graham 2008; Hu 2008; Kisaka et al. 2008; Beifiori et al. 2009; Gültekin et al. 2009a), but also the correlations between the process of accretion of SMBHs and the formation and evolution of their galaxies (Silk and Rees 1998; Burkert and Silk 2001; Cavaliere and Vittorini 2002; King 2003; Wyithe and Loeb 2003; Granato et al. 2004; Haiman et al. 2004; Begelman and Nath, 2005; Murray et al. 2005; Sazonov et al. 2005; Croton et al. 2006; Hopkins et al. 2007a; Sijacki et al. 2007; Pipino et al. 2009a, b). There are numerous scaling relations found between the mass of the supermassive black hole and the different properties of the host spheroidal component, such as the bulge luminosity, mass, effective radius, central potential, dynamical mass, concentration, Sérsic index, binding energy, X-ray luminosity, momentum parameter, etc. (Ferrarese and Merritt 2000; Gebhardt et al. 2000; Laor 2001; Merritt and Ferrarese 2001; Wandel 2002; Graham and Driver 2005; Hopkins et al. 2007b; Gultekin et al. 2009b; Soker and Meiron 2011).

Among the various scaling relations, we consider $M_\bullet - R_e\sigma^3$ (Feoli and Mancini, 2011) and $M_\bullet - M_G\sigma^2$ (Feoli and Mele, 2005), where R_e, M_G and σ are the effective radius of the host spheroidal component, the mass and the velocity dispersion of the host galaxy, respectively.

The aim of this paper is, using these two scaling relations, to predict three particularly interesting parameters concerning the giant elliptical galaxy M87, which has been well studied in detail by Event Horizon Collaboration: the mass of the black hole, its efficiency and the temperature of the black hole accretion disk.

2. EFFICIENCY OF THE BLACK HOLE

The first parameter that we propose to derive is the efficiency ϵ of the black hole in the conversion of the matter captured into emitted radiation. This parameter has been obtained using Feoli and Mancini's model (2011).

The core of the model is the transformation of the angular momentum of the matter falling into the black hole, into the angular momentum of the radiation emitted during the process. Further details can be found in Feoli and Mancini (2011), Feoli (2014a) and Beltramonte et al. (2019). This model works better for the early-type galaxies, as can be observed in Feoli and Iannella (2019) and in Beltramonte et al. (2019).

Feoli and Mancini's model (2011) allows an estimate of ϵ for each single black hole, through the following relation:

$$\epsilon = \frac{R_e \sigma^3}{2 M_\bullet c G}, \tag{1}$$

where G is the gravitational constant and c the speed of light.

From this relation, by entering the parameters of the galaxy M87, we obtain $\epsilon = 0.007 \pm 0.003$. The effective radius $R_e = 0.82 \pm 0.07$ in Log(kpc) and the velocity dispersion $\sigma = 2.42 \pm 0.02$ in Log(km s^{-1}) have been taken from van den Bosch (2016) and the black hole mass $M_\bullet = 9.813 \pm 0.047$ in $Log(M_\odot)$ from the EHT Collaboration (VI, 2019). The value of the obtained efficiency is in good agreement with the value found in the EHT Collaboration (VIII, 2021), i.e. $\epsilon \lesssim 1\%$.

Of course, the model based on the conservation of angular momentum can also be used in a different way, i.e. if we know the efficiency of the black hole we can calculate the angular momentum of the matter orbiting around the hole, but not the spin of the black hole itself. The argument of angular momentum has been faced in a series of papers cited in Feoli (2014a), Feoli and Mancini (2011), and Beltramonte et al. (2019).
An interesting and more recent discussion of the angular momentum problem in an accretion disc can be found in Blandford and Globus (2022).

3. PREDICTION OF THE BLACK HOLE MASS

Feoli and Mele (2005) proposed a correlation between the mass of a supermassive black hole and the kinetic energy of the host galaxy. This correlation was tested with many different samples and fitting methods (Feoli and Mele, 2007; Feoli and Mancini, 2009; Mancini and Feoli, 2012; Benedetto et al. 2013; Iannella and Feoli, 2020) and a theoretical background was proposed in Feoli (2014b). Furthermore, in Iannella et al. (2021), the predictive power of the relation has been analysed and the statistical elaboration done previously has been enhanced. Finally, this relation proved to be very competitive with its very low intrinsic scatter (Saglia et al. 2016).

The relation can be very useful to understand the evolution of galaxies, just like the HR diagram is for the evolution of stars (Feoli and Mancini 2009), and allows good predictions of the masses of some black holes, so we decided to use it to predict the mass of the galaxy M87.

We have used the relation of Feoli and Mele (2005) to infer the mass of the black hole of M87:

$$Log M_\bullet = (m \pm se(m)) \left(Log \frac{M_G \sigma^2}{c^2} \pm se\left(Log \frac{M_G \sigma^2}{c^2} \right) \right) + (b \pm se(b)), \tag{2}$$

where m and b are respectively the slope and the intercept of the linear relation with the corresponding uncertainties.

We have considered the regression coefficients, which are the slope m and the intercept b for the $M_\bullet - M_G \sigma^2$ and $M_\bullet - \sigma$ relations, of the five samples taken from Iannella and Feoli (2020).

The predictions are reported in Table 1, and they are compared with those inferred by the correlation $M_\bullet - \sigma$ in Table 2 and with the experimental value of the EHT Collaboration (VI, 2019), that we indicate in logarithmic scale $Log\, M_\bullet = 9.813 \pm 0.047$ and in units of $M_\odot$.

It is evident that the $M_\bullet - M_G \sigma^2$ relation deduces in almost all cases a mass value closer to the experimental one than the one predicted by $M_\bullet - \sigma$, also having a narrower range of values. The only case in which this does not happen is in van den Bosch_174's sample, for which the intrinsic scatter of the linear relation is the highest (Iannella and Feoli, 2020).

We also want to compare our results with Nokhrina et al. (2019). They propose a method of estimating BH mass for core-jet AGN, following the theoretical model by Beskin et al. (2017) and obtaining the different values of BH mass for different magnetizations, reported in Table 3b. It is possible to observe that, within the errors, the black hole masses of Nokhrina et al. (2019) for different magnetizations are comparable with the results of this paper, reported in Table 3a.

TABLE 1

PREDICTIONS OF BLACK HOLE MASS WITH $M_\bullet - M_G\sigma^2$

Sample (1)	m (2)	b (3)	*Log* $M_\bullet$ (4)	*Log* $M_{\bullet,low}$ (5)	*Log* $M_{\bullet,high}$ (6)
1st Sample: Cappellari	0.99 ±0.09	3.76 ±0.42	9.32	8.30	10.37
2nd Sample: van den Bosch_174	1.02 ±0.05	3.21 ±0.26	8.93	8.25	9.64
3rd Sample: van den Bosch_108	0.92 ±0.05	3.93 ±0.24	9.09	8.44	9.76
4th Sample: de Nicola-Saglia	0.72 ±0.04	5.19 ±0.17	9.46	8.97	9.97
5th Sample: Saglia	0.73 ±0.04	5.16 ±0.17	9.49	9.00	10.00

Columns: (1) Sample. (2)-(3) The regression coefficients taken from Iannella and Feoli (2020). (4) M87 predicted black hole mass. (5) Black hole mass predicted minimal value. (6) Black hole mass predicted maximal value.

TABLE 2

PREDICTIONS OF BLACK HOLE MASS WITH $M_\bullet - \sigma$

Sample (1)	m (2)	b (3)	*Log* $M_\bullet$ (4)	*Log* $M_{\bullet,low}$ (5)	*Log* $M_{\bullet,high}$ (6)
1st Sample: Cappellari	5.20 ±0.46	-3.44 ±1.05	9.15	6.89	11.44
2nd Sample: van den Bosch_174	5.10 ±0.25	-3.39 ±0.56	8.95	7.69	10.22
3rd Sample: van den Bosch_108	4.94 ±0.26	-2.92 ±0.60	9.03	7.71	10.37
4th Sample: de Nicola-Saglia	4.99 ±0.26	-3.11 ±0.61	9.41	8.01	10.84
5th Sample: Saglia	5.05 ±0.27	-3.24 ±0.62	9.44	8.01	10.88

Columns: (1) Sample. (2)-(3) The regression coefficients taken from Iannella and Feoli (2020). (4) M87 predicted black hole mass. (5) Black hole mass predicted minimal value. (6) Black hole mass predicted maximal value.

3.1. *Temperature of the Black Hole Accretion Disk*

To better explain the experimental relation proposed in Feoli and Mele (2005), a simple model that links the mass of a supermassive black hole and the kinetic energy of the corresponding galactic bulge has been presented in Feoli (2014b). Feoli's approach starts by considering that the accretion process of the SMBH involves a thermodynamic transformation of the gas falling inside the radius of influence of the hole, describing the process with a simple model. Starting from considering an ideal and relativistic gas that flows from the outer parts of the spheroidal component (bulge) of a galaxy, with volume V_G and radius R_G, to the sphere of influence of a central SMBH, having volume $V_\bullet$ and radius R_{inf}, we can write the following conservation equation, which connects two equilibrium states:

$$T_\bullet V_\bullet^{\gamma-1} = T_{GAS} V_G^{\gamma-1}, \tag{3}$$

where $T_\bullet$ is the temperature inside the region of influence of the black hole, and T_{GAS} is the temperature of the gas in the galaxy. We can write the previous equation in this way

$$T_\bullet = T_{GAS}\left(\frac{R_G}{R_{inf}}\right)^{3(\gamma-1)}, \tag{4}$$

and we assume:

$$R_{inf} \simeq \frac{GM_\bullet}{\sigma^2}, \tag{5}$$

$$R_G = \frac{GM_G}{\sigma^2}, \tag{6}$$

$$T_{GAS} = \frac{m_H\sigma^2}{k}, \tag{7}$$

and that $T_\bullet$ is of the order of the electron temperature T_e near the black hole:

$$T_\bullet = \delta\, T_e = \delta\frac{m_e c^2}{k} = \delta(5.9\times 10^9)K, \tag{8}$$

where m_H is the mass of the hydrogen atom, k the Boltzmann constant, m_e is the electron mass and δ a parameter. Considering that the adiabatic index

TABLE 3

BLACK HOLE MASSES OF M87 IN COMPARISON

TABLE 3a. Data from this paper

Sample	$Log\ M_\bullet$
(1)	(2)
1st Sample: Cappellari	9.32 ±1.04
2nd Sample: van den Bosch_174	8.93 ±0.70
3rd Sample: van den Bosch_108	9.09 ±0.66
4th Sample: de Nicola-Saglia	9.46 ±0.50
5th Sample: Saglia	9.49 ±0.50

Columns: (1) Sample. (2) The predicted black hole mass.

TABLE 3b. Data from Nokhira et al. (2019)

σ_M	$Log\ M_\bullet$
(1)	(2)
5	9.89 ±0.15
10	9.82 ±0.14
20	9.72 ±0.13

Columns: (1) Michel's magnetization parameter. (2) Estimated black hole mass.

for an ideal relativistic gas is $\gamma = 4/3$, we obtain (for more details see Feoli, 2014b):

$$M_\bullet = \frac{m_H}{\delta m_e}\left(\frac{M_G\sigma^2}{c^2}\right), \qquad (9)$$

where M_G is the bulge mass. Taking the logarithm of the previous equation and measuring the black hole masses and galaxy masses in solar units, we find:

$$Log\, M_\bullet = Log\left(\frac{m_H}{m_e}\right) - Log\,\delta + Log\left(\frac{M_G\sigma^2}{c^2}\right), \qquad (10)$$

that is,

$$Log\, M_\bullet = 3.264 - Log\,\delta + Log\left(\frac{M_G\sigma^2}{c^2}\right). \qquad (11)$$

We obtain the scaling relation proposed by Feoli and Mele (2005):

$$Log\, M_\bullet = b + m\, Log\left(\frac{M_G\sigma^2}{c^2}\right), \qquad (12)$$

where $b = 3.264 - Log\,\delta$ is a normalization and $m = 1$ is the slope.

The model is able to recover the right order of magnitude for the temperature near the SMBH. We apply the relation found in Feoli (2014b) to the experimental data of M87 contained in Saglia's sample and we find the temperature of the black hole accretion disk $T = (1.44 \pm 0.57) \times 10^9 K$, which is of the same order of magnitude given by the EHT Collaboration (V, 2019), i.e. $T \approx 6 \times 10^9 K$ for the peak brightness of the ring. Our prediction can also be compared with the values estimated by Kim et al. (2018) ($T = (1-3) \times 10^{10} K$) and by Akiyama et al. (2015) ($T = 1 \times 10^{10} K$). Many determinations of temperature exist. In particular, the problem of the X-ray flux of M87 has been well studied by different researchers (Di Matteo et al. 2003; Imazawa et al. 2021) but the derived temperatures are, of course, lower than the one measured at the peak brightness of the ring.

4. CONCLUSIONS

In this paper we have proposed to derive three important parameters for the supermassive black hole of the elliptical galaxy M87: the efficiency of the black hole, its mass and the temperature of the accretion disk. These three parameters were obtained by applying two models that we have proposed in Feoli and Mancini (2011), Feoli and Mele (2005) and Feoli (2014b), managing to make correct predictions. The results we have obtained are very interesting and promising; therefore, by improving the experimental data with increasingly precise tools and testing our relationships accordingly, it will be possible to make increasingly reliable predictions.

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