TESTING THE NATURE OF ASTROPHYSICAL BLACK HOLE CANDIDATES

Cosimo Bambi[§], *Ludwig-Maximilians-Universität München (Munich, Germany)*

Abstract

It is thought that the final product of the gravitational collapse is a Kerr black hole and astronomers have discovered several good astrophysical candidates. For the time being, all the black hole candidates are objects so compact and heavy that cannot be explained otherwise without introducing new physics, but there is no evidence that the geometry of the space-time around them is really described by the Kerr metric. Future space-based gravitational wave detectors will be able to test the nature of the black hole candidates with high precision. In this talk, I will show that the measurement of the radiative efficiency of individual AGN may test the Kerr black hole hypothesis at a similar level of accuracy, but before the advent of gravitational wave astronomy.

1. Introduction

General Relativity (GR) has been tested and verified to high precision for distances in the rage ~1 mm to ~1 pc and for weak gravitational fields (Will 2006). The research is now moving to check the validity of the theory at cosmological scales, sub-millimeter distances, and for strong gravitational fields. One of the most intriguing predictions of GR is that the collapsing matter inevitably produces singularities in the space-time. According to the weak cosmic censorship conjecture, singularities of gravitational collapse must be hidden within black holes (BHs) (Penrose 1969). In 4-dimensional GR, BHs are described by the Kerr solution, which is completely specified by two parameters, the mass, M, and the spin angular momentum, J (Carter 1972, Robinson 1975). The condition for the existence of the event horizon is that the spin parameter $a = |J/M^2|$ cannot exceed 1. When $a > 1$, there is no horizon and the central singularity is naked, violating the weak cosmic censorship conjecture.

Astronomers have discovered at least two classes of BH candidates (for a review, see e.g. Narayan 2005): stellar-mass objects in X-ray binary systems ($M \sim 5 - 20$ Solar masses) and super-massive objects in galactic nuclei ($M \sim 10^5 - 10^9$ Solar masses). The estimates of the masses of these objects are robust, because obtained via dynamical measurements and without any assumption about the nature of the massive body. The stellar-mass objects in X-ray binary systems are too heavy to be neutron or quark stars for any reasonable matter equation of state, while the super-massive objects at the centers of galaxies are too heavy, compact, and old to be clusters of non-luminous bodies. All these objects are therefore thought to be the BHs predicted by GR, as they cannot be explained otherwise without introducing new physics. However, there is no indication that the geometry around these objects is described by the Kerr metric.

Testing the Kerr BH hypothesis is thus the next step to progress in this research field and several authors have indeed suggested possible ways to do it using present and future data (for a review, see e.g. Bambi 2011a). A very promising approach is the detection of extreme mass ratio inspirals (EMRIs, i.e. systems consisting of a stellar-mass compact object orbiting a super-massive BH candidate) with future space-based gravitational wave antennas. Missions like LISA will be able to follow the stellar-mass compact object for millions of orbits around the central super-massive BH candidate, and therefore deviations from the Kerr geometry will lead to a phase difference in the gravitational waveforms that grows with the number of observed cycles (Ryan 1995; Glampedakis et al. 2006; Barack et al. 2007; Apostolatos et al. 2009; etc.). However, these data will not be available shortly, as the first mission will be launched, at best, in the early 2020's. This fact has motivated the study of alternative approaches to test the nature of BH candidates, such as the X-ray continuum fitting method (Bambi et al. 2011a), observations of quasi-periodic oscillations (Johannsen et al. 2011) and measurements of the cosmic X-ray background (Bambi 2011b,c). These methods can in principle be applied even with present data, provided that the systematic errors are properly understood. Future observations of the shadow of nearby super-massive BH candidates are another exciting possibility to test the Kerr BH paradigm (Bambi et al. 2009, 2010, 2011d).

Previous studies have clearly pointed out that “rapidly-rotating” objects are the best candidates to test the Kerr BH hypothesis: if the object rotates fast, even a small deviation from the Kerr background can cause significant differences in the properties of the electromagnetic radiation

---

[§] Email: Cosimo.Bambi@physik.uni-muenchen.de emitted by the gas of the accretion disk and peculiar features, otherwise absent in the Kerr geometry, may show up (Bambi et al. 2011b,c,d). In this talk, I will consider the most massive BH candidates in AGN. I will show that the measurement of their radiative efficiency may soon provide stringent constraints on possible deviations from the Kerr geometry, comparable to the ones that may be obtained with future space-based gravitational wave detectors. The talk is based on a work in preparation (Bambi 2011f).

2. Standard accretion disk model

The Novikov-Thorne (NT) model is the standard model for accretion disks (Novikov et al. 1973). It describes geometrically thin and optically thick disks and it is the relativistic generalization of the Shakura-Sunyaev model (Shakura et al. 1973). The disk is thin in the sense that the disk opening angle is $h = H/r \ll 1$, where H is the thickness of the disk at the radius r. Magnetic fields are ignored. In the Kerr background, there are four parameters (BH mass, BH spin parameter, mass accretion rate, and viscosity parameter), but the model can be easily extended to any (quasi-)stationary, axisymmetric, and asymptotically flat space-time. Accretion is possible because viscous magnetic/turbulent stresses and radiation transport energy and angular momentum outwards. The model assumes that the disk is on the equatorial plane and that the disk's gas moves on nearly geodesic circular orbits. Heat advection is ignored (it scales as h^2) and energy is radiated from the disk surface.

The key-ingredient of the NT model is that the inner edge of the disk is at the innermost stable circular orbit (ISCO), where viscous stresses are assumed to vanish. When the gas's particles reach the ISCO, they quickly plunge into the BH, without emitting additional radiation. Neglecting the radiation emitted by the disk and captured by the BH, the maximum value for the radiative efficiency is

$$\eta = 1 - E_{ISCO} \, , \tag{1}$$

where E_{ISCO} is the specific energy of the gas at the ISCO radius and depends uniquely on the background geometry. Eq. (1) provides the maximum value for η because a fraction of the gas's gravitational energy may be converted to kinetic energy of jet/wind outflows. In what follows, I will assume the conservative hypothesis that all the gravitational energy of the gas is converted to radiation and η is given by Eq. (1).

As a consequence of the accretion process, the BH spin parameter evolves. Since the gas particles arriving at the ISCO plunge quickly into the central object, without emission of additional radiation, the BH changes its mass by $\delta M = E_{ISCO} \delta m$ and its spin angular momentum by $\delta J = L_{ISCO} \delta m$, where L_{ISCO} is the specific angular momentum of the gas at the ISCO, while δm is the gas rest-mass. The evolution of the spin parameter of the BH, a, turns out to be governed by the following equation:

$$d\,a / d\,\ln M = (1/M)\, L_{ISCO} / E_{ISCO} - 2\,a \, . \tag{2}$$

If the right hand side of Eq. (2) is positive, the accretion process spins the BH up. If it is negative, the BH is spun down. The equilibrium spin parameter a_{eq} is reached when the right hand side of Eq. (2) vanishes and its value depends on the geometry of the space-time.

For non-magnetized and weakly-magnetized disks, there is a common consensus that the NT model describes correctly thin disks, $h \ll 1$, when the viscosity parameter is small (Afshordi et al. 2003). In the case of magnetized disks, the issue is more controversial, as it is not yet possible to perform GRMHD simulations of thin disks (see e.g. Penna et al. 2010 and Noble et al. 2010). Here, I will assume that the NT model works, as it is commonly supposed in most studies discussed in the literature. At the observational level, a common criterion to select sources with thin disks is that the bolometric luminosity of the source does not exceed 30% of its Eddington luminosity (McClintock et al. 2006).

3. Radiative efficiency in Kerr and non-Kerr backgrounds

In the NT model, the maximum value of the radiative efficiency can be immediately inferred from Eq. (1) and depends only on the background geometry. In the Kerr space-time, there is a one-to-one correspondence between a and η. For corotating disks, the radiative efficiency increases monotonically with the spin parameter, from about 0.057 (Schwarzschild BH, $a = 0$) to about 0.42 (extreme Kerr BH, $a = 1$). If a compact object is a Kerr BH, a measurement of its radiative efficiency can potentially be used to estimate its spin parameter.

To test the Kerr BH hypothesis, we have to consider a more general background that includes the Kerr solution as special case. Roughly speaking, the object will be specified by its mass, its spin angular momentum, and one or more “deformation parameters”, measuring deviations from the Kerr geometry. The Kerr metric will be recovered when all the deformation parameters vanish. The idea is to study the properties of the accretion process in this more general space-time and then compare the theoretical predictions with the observational data. If the latter demand that the deformation parameters must vanish, then the Kerr BH hypothesis is verified and our astrophysical BH candidates are really the BHs predicted by GR.

In Fig. 1, I show the radiative efficiency η for a subclass of Manko-Novikov space-times (Manko et al. 1992; Manko et al. 2000a,b) characterized by one deformation parameter, the anomalous quadrupole moment q (for more details, see Bambi 2011f). q is related to the mass-quadrupole moment of the compact object by the relation:

$$Q = (1 + q)\, Q_{KERR} \,, \tag{3}$$

where $Q_{KERR} = - a^2M^3$ is the mass-quadrupole moment of a Kerr BH with mass M and spin parameter a. The compact object is thus more oblate than a Kerr BH with the same spin when $q > 0$, and it is more prolate when $q < 0$. Because of the introduction of a new parameter, there is now a degeneracy in η and, in general, a certain value of the radiative efficiency cannot be associated with a unique value of the spin parameter and of the anomaous quadrupole moment.

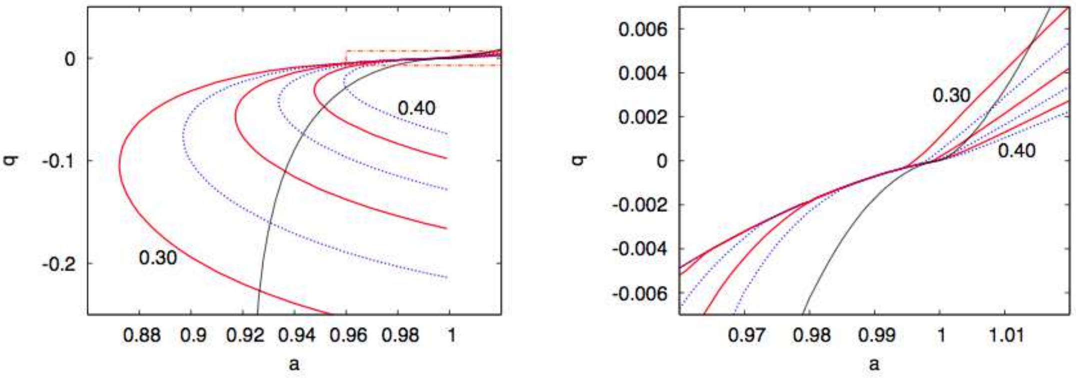

Figure 1: Manko-Novikov space-time with deformation parameter q. Contour plots of the radiative efficiency $\eta = 1 - E_{ISCO}$: η = 0.30 (red solid curve), 0.32 (blue dotted curve), 0.34 (red solid curve), 0.36 (blue dotted curve), 0.38 (red solid curve), 0.40 (blue dotted curve). The black solid curve is the equilibrium spin parameter a_{eq} as inferred from Eq. (2). If $a < a_{eq}$, the accretion process spins the compact objects up; if $a > a_{eq}$, the accretion process spins the compact object down. The right panel is simply the enlargement of the area inside the orange box in the left panel. From Bambi 2011f.

4. Constraining deviations from the Kerr geometry

At the observational level, the radiative efficiency is defined as the ratio between the bolometric luminosity of the source and the mass accretion rate of the BH candidate. The latter, however, is usually difficult to measure. The Soltan's argument provides an elegant way to determine the mean radiative efficiency of AGN from the mean BH mass density in the contemporary Universe and the AGN luminosity per unit volume integrated over time (Soltan 1982). There are several sources of uncertainty in the final result, but current estimates suggest a high radiative efficiency (see e.g. Elvis et al. 2003; Wang et al. 2006).

Recently, Davis and Laor (Davis et al. 2011) proposed a way to estimate the radiative efficiency of individual AGN. The mass accretion rate can indeed be determined from the low frequency region of the thermal spectrum of the accretion disk of these objects, if the mass of the BH candidate is known. Such a radiation is mainly emitted at large radii, where gravity is Newtonian and the details of all the complicated astrophysical processes, like the viscosity mechanism, are not important. The authors found a strong correlation of η with M, raising from $\eta \sim 0.03$, when $M \sim 10^7$ Solar masses and the bolometric to Eddington luminosity ratio is $L_{bol}/L_{Edd} \sim 1$, to $\eta \sim 0.4$, when $M \sim 10^9$

Solar masses and L_{bol}/L_{Edd} ~ 0.3. For our discussion, the crucial point is that the most massive BH candidates in AGN seem to have a high radiative efficiency, η ~ 0.4, and a moderate mass accretion rate, L_{bol}/L_{Edd} ~ 0.3. The high radiative efficiency suggests that they are very rapidly-rotating objects. The moderate luminosity could be interpreted as the indication that their accretion disk is geometrically thin: if this is the case, the measurement of radiative efficiency could provide the specific energy of the gas at the ISCO via Eq. (1).

Interestingly, in the case of super-massive BH candidates, we can deduce an upper bound on their spin parameter. These objects must have $a < a_{eq}$, where a_{eq} the equilibrium spin parameter in case of accretion from a thin disk. The point is that the super-massive BH candidates have increased their mass by several orders of magnitude from its original value, the value of the spin parameter at the time of the formation of the object is irrelevant, while other processes (chaotic accretion, minor and major mergers) more likely spin the BH down (Bambi 2011c,d,e,f). On the other hand, the process of accretion from a thin disk is the most efficient mechanism to spin these objects up (and it spins them down if $a > a_{eq}$).

If observations can provide a robust lower bound on the radiative efficiency of a source, and we then combine such a measurement with the requirement $a < a_{eq}$, we can obtain interesting constraints on possible deviations from the Kerr background. For instance, for $\eta > 0.30$, we can deduce the bound $-0.20 < q < 0.005$, see Fig. 1. The observation of gravitational waves emitted by an EMRI with future space-based gravitational wave detectors like LISA will be able to constrain the quadrupole moment of the super-massive BH candidates with a precision of order 0.01 – 0.001 (Barack et al. 2007). For $q > 0$, the measurement of the radiative efficiency can likely provide similar results of LISA. Let us also notice that a self-gravitating fluid with reasonable equations of state has q positive and significantly larger than 0.01. For a neutron star, $q > 1$. The constraint in the region $q < 0$ is much weaker with our approach. However, these objects might be excluded from theoretical arguments: their ISCO is marginally unstable along the vertical direction, which means that there are two “centers of attraction”, one above and one below the equatorial plane. It is not clear if a similar object can exist and be stable, as it may be necessary a repulsive force between the two centers of attraction in order to balance their gravitational force and maintain them at a fixed distance. On the other hand, if we discovered a BH candidate with $\eta > 0.32$ accreting from a thin disk, the Kerr BH hypothesis may be rejected and the existence of objects with $q < 0$ may be necessary to explain the observation. Astrophysical Kerr BHs can unlikely have a radiative efficiency higher than 0.32 (Thorne 1974).

5. Conclusions

There is some evidence that the most massive BH candidates in AGN have a high radiative efficiency and a thin accretion disk. In this case, they could be excellent candidates to test GR in the strong field regime and, in particular, the Kerr BH paradigm. For instance, the confirmation of the existence of BH candidates with $\eta > 0.30$ could test the Kerr BH hypothesis at the level of 0.5% for objects more oblate than a Kerr BH, and at the level of 20% for more prolate bodies. These bounds can be compared with the capabilities of future space-based gravitational wave detectors like LISA, which may be able to perform the same test with an accuracy of 0.1% – 1%. For the time being, there are a few issues to address before using the measurement of the radiative efficiency of individual AGN to test GR (the validity of the NT model for magnetized disk and the confirmation of the method proposed in Davis et al. 2011), but the approach seems to be promising and capable of providing interesting constraints on the nature of the super-massive BH candidates well before the advent of gravitational wave astronomy.

Acknowledgments

This work was supported by Humboldt Foundation.

References

Afshordi N and Paczynski B (2003) The Astrophysical Journal 592, 354-367
Apostolatos T A, Lukes-Gerakopoulos G and Contopoulos G (2009) Physical Review Letters 103, 111101
Bambi C (2011a) Modern Physics Letters A 26, 2453-2468
Bambi C (2011b) Physical Review D 83, 103003
Bambi C (2011c) Physics Letters B 705, 5-8
Bambi C (2011d) Europhysics Letters 94, 50002

Bambi C (2011e) JCAP 1105, 009
Bambi C (2011f) in preparation
Bambi C and Freese K (2009) Physical Review D 79, 043002
Bambi C and Yoshida N (2010) Classical and Quantum Gravity 27, 205006
Bambi C and Barausse E (2011a) The Astrophysical Journal 731, 121
Bambi C and Barausse E (2011b) Physical Review D 84, 084034
Bambi C and Modesto L (2011c) Physics Letters B 706, 13-18
Bambi C, Caravelli F and Modesto L (2011d) arXiv:1110.2768
Barack L and Cutler C (2007) Physical Review D 75, 042003
Carter B (1971) Physical Review Letters 26, 331-333
Davis S W and Laor A (2011) The Astrophysical Journal 728, 98
Elvis M, Risaliti G and Zamorani G (2002) The Astrophysical Journal Letters 565, L75-L77
Glampedakis K and Babak S (2006) Classical and Quantum Gravity 23, 4167-4188
Johannsen T and Psaltis D (2011) The Astrophysical Journal 726, 11
Manko V S, Mielke E W and Sanabria-Gomez J D (2000a) Physical Review D 61, 081501
Manko V S, Sanabria-Gomez, J D and Manko O V (2000b) Physical Review D 62, 044048
Manko V S and Novikov I D (1992) Classical and Quantum Gravity 9, 2477-2487
McClintock J E et al. (2006) The Astrophysical Journal 652, 518-539
Narayan R (2005) New Journal of Physics 7, 199
Noble S C, Krolik J H and Hawley J F (2010) The Astrophysical Journal 711, 959-973
Novikov I D and Thorne K S (1973) Black Holes (Les Astres Occlus), 343-450
Penna R F et al. (2010) Monthly Notices of the Royal Astronomical Society 408, 752-782
Penrose R (1969) Rivista del Nuovo Cimento, Numero Speciale 1, 252
Robinson D C (1975) Physical Review Letters 34, 905-906
Ryan F D (1995) Physical Review D 52, 5707-5718
Shakura N I and Sunyaev R A (1973) Astronomy & Astrophysics 24, 337-355
Soltan A (1982) Monthly Notices of the Royal Astronomical Society 200, 115-122
Thorne K S (1974) The Astrophysical Journal 191, 507-520
Wang J-M, Chen Y-M, Ho L C and McLure R J (2006) The Astrophysical Journal Letters, 642, L111-L114
Will C M (2006) Living Reviews in Relativity 9, 3