No observational proof of the black-hole event-horizon

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Abstract. Recently, several ways of obtaining observational proof of the existence of black-hole horizons have been proposed. We argue here that such proof is fundamentally impossible: observations can provide arguments, sometimes very strong ones, in favour of the existence of the event horizon, but they cannot prove it. This applies also to future observations, which will trace very accurately the details of the spacetime metric of a body suspected of being a black hole.

1. Introduction

It is generally believed that the compact component in X-ray binary systems is either a star possessing a material surface (a neutron star or a quark star) or a black hole, i.e. an object whose surface is formed by an event horizon. The evidence of the presence of a material surface is obtained from two types of observations. First, stable periodic pulsations of the X-ray emission indicate the presence of a strong ($10^9 - 10^{15}$ G) magnetic field, which by the virtue of the “no-hair” theorem excludes the presence of a black hole in the system. Second, observations of X-ray bursts - thermonuclear explosions occurring in matter accumulated at the surface of the compact object are an obvious proof of the absence of an event horizon.

Although X-ray pulsations or X-ray bursts indicate the presence of a solid surface, their absence does not prove the presence of an event horizon. “Absence of evidence is not evidence of absence”. However, there is direct evidence that compact bodies in X-ray binaries form (at least) two types of objects: their masses show a bimodal distribution (see Miller, Shahbaz & Nolan 1998). Neutron star masses are all concentrated around the “canonical” value of 1.4 M\(_\odot\), whereas the second class of bodies, usually called “black hole candidates” have higher masses in the range of \(\sim 5\) to \(18\ M_\odot\) (see e.g. Narayan, Garcia & McClintock 2001 and Greiner, Cuby & McCaughrean 2001). The reason for suspecting the more massive bodies of being black holes is that their masses are higher than the maximum mass of a neutron (or quark) star, which is never larger than \(\sim 3\ M_\odot\) (see e.g. Salgado et al. 1994).

In general, the maximum mass of a compact body can be expressed as \(8.4 (\varepsilon_0/10^{14}\text{g cm}^{-3})^{-1/2}\ M_\odot\), where \(\varepsilon_0\) is the fiducial density above which the equation of state is taken to be described by a causality-limit equation of state (Rhoades & Ruffini 1974; Friedmann & Ipser 1987). Bahcall, Lynn & Selipsky (1990) showed that stars with a material surface can have masses as high as 10 M\(_\odot\), if one is willing to entertain configurations of sub-nuclear density. These are the so-called “Q-stars.” The mean-field description of nuclear interactions given by Bahcall et al. (1990) allows baryonic matter to have densities this low. Although, as shown by Miller et al. (1998), it is unlikely that bodies with masses larger than 10 M\(_\odot\) are Q-stars—because this would require unrealistically low densities at which hadronic bulk matter would persist—“unlikely” is not a very satisfactory argument in favour of the black-hole existence. One would rather wish a “positive” proof of the event-horizon’s existence. This has been attempted by Ramesh Narayan and collaborators. The claim is that properties of Advection Dominated Accretion Flows (ADAFs; Abramowicz et al. 1995; Narayan & Yi 1994, 1995a,b) can be used to prove the existence of event-horizons.

2. Proof by ADAFs

ADAFs describe accretion with very low radiative efficiency in which energy released by viscous torques removing angular momentum from the accreting matter is not radiated away but stored in the flow. If an ADAF forms around a black hole, the stored energy will be lost forever.
under the event horizon, whereas if the accreting body is a “star” this energy must be radiated away once matter lands on its surface. Therefore, the argument runs, black holes should be dimmer than neutron stars, quark stars, etc., if in both cases an ADAF is present.

The best systems in which this hypothesis could be tested are the so-called Soft X-ray Transients (SXTs) which are close binary systems undergoing rare and powerful outbursts but spending most of their life in a low luminosity quiescent state (see Tanaka & Shibazaki 1996 for a review). In SXTs, like in Low-Mass X-Ray Binaries (LMXBs) in general, a compact body accretes matter lost by a Roche-lobe filling low-mass stellar companion. The accreting matter forms a disc whose instabilities trigger outbursts (see Lasota 2001 for a review of the instability model). Narayan, McClintock & Yi (1996) see also Lasota, Narayan & Yi 1996 and Narayan, Barret & McClintock 1997) proposed that quiescent SXT discs are truncated and that the inner accretion flow forms an ADAF. This hypothesis has been recently vindicated from the theoretical point of view by Dubus, Hameury & Lasota 2001 and is supported by observations (see Done 2002 for a review).

Narayan, Garcia & McClintock 1997 compared quiescent luminosities of SXTs supposed to contain black holes with those of neutron-star SXTs and realized that, in accordance with the prediction of the ADAF model, systems containing black-hole “candidates” are dimmer. They came to the conclusion that they found evidence for the presence of event horizons.

This conclusion has been challenged by Chen et al. 1998 who argued that the relative dimness of black-hole candidate systems was due solely to Narayan et al. 1997 comparison method. Things were clarified by Lasota & Hameury 1998 who suggested comparing systems with similar orbital period on the assumption such systems would have similar accretion rates – the ADAF model asserting only that accreting black holes should be dimmer than neutron stars for the same accretion rate. The new method showed, however, the same effect (Lasota & Hameury 1998; Menou et al. 1999, recently confirmed by Garcia et al. 2001): black holes (candidates) are dimmer than systems known to contain neutron stars, or at least stars with surface.

This is a very strong argument in favour of the presence of event horizons, in fact this is the most conservative conclusion. However, it is not a proof.

3. Arguments against evidence based on relative dimness of black hole candidates

The arguments against the claim that the relative dimness of black-hole candidates is the proof of existence of event horizons are of two, not unrelated, types. First, it has been argued that the accretion flow in quiescent SXTs are not represented by ADAFs. Narayan & Yi 1995a and Blandford & Begelman 1999 argued (see however Paczyński 1998 and Abramowicz, Lasota & Igumenshchev 2001 for criticism of the argument) that ADAFs are subject to mass loss and therefore the dimness of quiescent SXTs could result from the low accretion rate onto the compact object - most of the matter being lost with the wind. However, as shown by Menou et al. 1999, such wind models do not offer an explanation of the luminosity difference between neutron-star systems and those presumed to contain black holes. In fact, these authors also pointed out that the quiescent luminosity of neutron-star binaries is not consistent with the assumption of a ~ 10% radiative efficiency. Since the attempt to apply to these systems the windy-ADAF model of Quataert & Narayan 1999 failed, they proposed that the action of a magnetic propeller could be answer. However, a compelling signature of this effect has yet to be found.

Despite of this, Abramowicz & Igumenshchev 2001 suggested that the observed differences between quiescent luminosities of accreting black holes and neutron stars is well explained by the occurrence in such systems of a CDAF (Convexion Dominated Accretion Flow; see Narayan, Igumenshchev & Abramowicz 2000) instead of an ADAF. They found that for low viscosities accretion flows around compact bodies form ADAFs only in their innermost regions but are convectively dominated at radii \( R \gtrsim 10^2 R_S \) (where \( R_S = 2GM/c^2 \) is the Schwarzschild radius). In such flows emission comes mostly from the convective region; the radiative efficiency is independent of accretion rate and equals \( \varepsilon_R = 10^{-3} \). Assuming that the efficiency of accretion onto a neutron star is \( \varepsilon_{NS} \approx 0.1 \) one obtains the observed ratio between black-hole and neutron-star luminosities. Unfortunately this cannot be the correct explanation of the luminosity difference (Lasota 2002) because, as mentioned above, neutron stars in quiescent transient systems do not seem to accrete with a 0.1 efficiency.

Another class of argument asserts that X-rays in quiescent SXTs are not emitted by the accretion flow.

Brown, Bildsten, & Rutledge 1998 suggested that, in neutron-star systems, most (or all) of the quiescent X-ray luminosity is not due to accretion but results from cooling of the neutron-star crust heated by nuclear reactions. This crust-cooling model does not seem to be in perfect agreement with observations showing two spectral components and a variable flux (see Rutledge et al. 2002 and references therein). If the crustal-cooling model were right it would imply different X-ray emission mechanisms for the two classes of quiescent SXTs. However, luminosity variations observed also in quiescent black-hole systems (see e.g. García et al. 2001) would rather suggest a common origin. Attempts to ascribe quiescent X-ray luminosity in black-hole systems to active stellar companions (Bildsten & Rutledge 2000) are not based on a sound theoretical foundation (Lasota 2001) and have been refuted by observations (García et al. 2001).

Menou 2001 presented an argument based on the settling-flow model of Medvedev & Narayan 2001 in which the accretion flow arrives with very low angular momentum at the surface of a rapidly rotating compact ob-
ject. The X-ray luminosity is then due to rotation-energy loss by the accreting body. This requires viscous contact between this body and the accreting matter. Menou (2001) pointed out that if black-hole candidates had, contrary to neutron stars, radii smaller than the inner-most stable orbit the accretion flow would be supersonic and viscous contact impossible. Black-hole candidates would be dimmer because unable to lose their rotational energy.

Finally, we note that very compact objects with a surface would be dimmer than less compact objects, simply because of redshift and light bending. If the surface is below the photon orbit, the fraction of “outward moving” photons which escape to infinity is in the Schwarzschild metric

\[ \frac{\Delta \Omega}{2\pi} = 1 - \left[ 1 - \frac{27}{4} \left( \frac{1 - R_S/R}{(R/R_S)^2} \right) \right]^{1/2}. \]  

For the lowest possible value for a causality-limit equation of state \( R/R_S = 9/8 \), this factor and the redshift squared yield a luminosity at infinity which is equal to only 0.040 of the luminosity at the source.

4. Absence of X-ray bursts

Three of the SXTs show millisecond pulsations, and two of them are X-ray bursters. They all have very short orbital periods, 2 hr in the case of SAX J1808.4-3658 (Wijnands and van der Klis 1998), Chakrabarty and Morgan 1998, 43.6 min for XTE J1751-305 (Markwardt et al. 2002), and 42 min for XTE J0929-314 (Galloway et al. 2002). It is perfectly well understood that occurrence of coherent pulsations or of type I X-ray bursts is incompatible with the presence of an event horizon, so none of these sources can be found on the list of black hole candidates, even though their masses are unknown.

However, it is true, as pointed out by Narayan & Heyl (2002), that none of the longer (binary) period SXTs, with a measured mass function greater than \( 3M_\odot \) is a type I burster. Narayan & Heyl (2002) compute instability of accretion onto a hypothetical \( 10M_\odot \) star with a surface of radius between \( (9/8)R_S \) and \( 3R_S \), and report that for a range of accretion rates compatible with observations of X-ray novae, the star is expected to give rise to an X-ray burst if the accreted column density is \( 10^9 \) g/cm\(^2\) \( < \Sigma \leq 10^{11} \) g/cm\(^2\). From this, the authors conclude that black hole candidates cannot have a surface, as they do not exhibit X-ray bursts.

One concern is that the authors do not present the results separately for the lowest column density considered, \( 10^9 \) g/cm\(^2\), and the higher values \( 10^{10} \) g/cm\(^2\) and \( 10^{11} \) g/cm\(^2\)——for a \( 10M_\odot \) star with a 3\( R_\odot \) radius, the mass transferred in the transient outburst ~ \( 6 \times 10^{24} \) g/cm\(^2\) corresponds to \( 6 \times 10^6 \) g/cm\(^2\), so the X-ray burst expected at one of the higher column densities may, in fact, not occur during a SXT outburst. However, there is a more fundamental doubt as to the relevance of the result.

Since the minimum radius of Q-star is 1.4 \( R_\odot \) (Miller et al. 1998), Narayan & Heyl (2002) consider not only objects composed of matter whose properties have been described by Bahcall et al. (1990) but also more compact configurations whose microscopic properties are not known at all. Therefore there is no reason to assume that the surface of such objects is composed of ordinary matter and is in the temperature range required for X-ray bursts to occur. The stellar surface could be too cold to support a thermonuclear runaway. As a matter of fact, the accreted matter could be converted right away to a more exotic form, as it would be on contact with quark matter in the color-locked phase (Alford, Rajagopal & Wilczek 1998, Rapp et al. 1998), or with the skin of a gravastar (Mazur & Mottola 2001, see below). This could happen even at zero density, contrary to the hypothesis advanced by Narayan & Heyl (2002). No nuclei, no bursts.

5. Gravastars

Mazur and Mottola (2001) have recently found a new static, spherically symmetric, solution of Einstein’s field equations. A gravastar, as it is called, has the standard vacuum Schwarzschild exterior, and an interior filled with matter that has the equation of state \( \rho = -p \). The interior is described by the de Sitter solution, and is matched to the exterior vacuum solution in a very thin shell of thickness on the order of the Planck length, \( \lambda_P = 1.6 \times 10^{-33} \) cm. The gravastar has no horizon or singularity. Its rigid surface is located at a radius just slightly greater than the gravitational radius, \( R_+ = R_S + f \lambda_P \), \( f \sim 2 \).

There are several purely theoretical objections that one could raise against gravastars, none of them conclusive. For example, stellar-mass gravastars have entropy smaller than ordinary stars with the same masses and this would require extremely efficient cooling before gravastars could form during stellar collapse.

There is no observational way to distinguish what may seem to be a Schwarzschild black-hole from a gravastar. To see this, let us denote the surface redshift by

\[ \varepsilon = \left( 1 - \frac{R_S}{R_+} \right)^{1/2} = \left( \frac{f \lambda_P}{R_+} \right)^{1/2}. \]  

For astrophysically interesting gravastars, with mass greater than \( M_\odot \), i.e., \( R_S > 3 \times 10^5 \) cm, this quantity is very small,

\[ \varepsilon < 10^{-19} \ll 1. \]  

The power of any radiation emitted by the surface of a gravastar is greatly reduced because only the radiation within the solid angle \( 27\varepsilon^2/4 \) around the normal to the surface escapes to infinity. Further, because of gravitational redshift, the power of radiation received by a distant observer is only \( \varepsilon^2 \) of what was emitted at the gravastar’s surface. Therefore, the power emitted from the surface is reduced by

\[ \varepsilon^4 < 10^{-75} \]  

by the time it reaches a distant observer. One should conclude that a gravastar with mass greater than \( M_\odot \) is to a distant observer as black as a black hole.
6. Conclusions

We have shown that it is fundamentally impossible to give an observational proof for the existence of a black-hole horizon. One could argue that it is not necessary to give such a proof – a black hole is a specific space-time metric, whose properties can, in principle, be determined through observations. If so, no ‘direct’ proof would be necessary, assuming one could determine that the spacetime around a compact object corresponds to the Kerr solution of the Einstein equations.

One way to distinguish a black hole from a rotating star is through the study of orbital and other frequencies (e.g., epicyclic) of accreting matter moving in strong-field gravity (Kato 2001, Wagoner 2001, Abramowicz & Kluźniak 2001, 2002). Another method of determining the space-time geometry is by observation of the energy spectrum reflected from an accretion disc deep in the gravitational well of a compact object (Fabian et al. 1989, 2000). Finally, the capture of stellar-mass compact objects by supermassive black holes in galactic nuclei produces gravitational radiation whose properties reflect the structure of black-hole spacetime (Ryan 1995; Hughes 2001). Such gravitational radiation could be observed by the gravitational-wave antenna LISA.

The last method is the most powerful since it uncovers the compact body’s multipolar structure. Like the other methods, however, it suffers from a fundamental weakness because it assumes that only a black hole can be the ‘source’ of the (a ≠ 0) Kerr metric. Although it was shown that it is very unlikely that other sources exist (Abramowicz, Lasota & Muchotrzeb 1997), such a possibility cannot be excluded.

Nevertheless, the case for the existence of black holes in the Universe is very strong and the evidence very convincing. We think, however, that a shadow of doubt will always cast its pall on our certainty in this matter. But it is a fertile doubt: it has already inspired new ideas and will surely continue to do so.

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