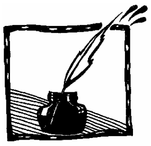

How do we know what we see is a black hole?

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> A black hole is perhaps the most fantastic of all conceptions of the human mind.
> *Igor Novikov*

1. Introduction

Nowadays, at the beginning of XXI century, we can see more than our ancestors tens of years ago. This is due mainly to the dynamical development of technology. Before the invention of the telescope people observed stars and other celestial bodies by the "naked" eye. We perceive only a small fraction of what comes to us in the form of electromagnetic waves. There are different waves around us. The human eye is sensitive only to a narrow range of electromagnetic spectrum – the so called optical range $\left(\lambda_{opt} \in (4\cdot 10^{-7},\ 8\cdot 10^{-7})\,[\mathrm{m}]\right)$.

Even now, equipped with modern telescopes which investigate our Universe in the full range of electromagnetic spectrum from the Earth or its orbit, we still do not see everything.

Nobody has seen a black hole and I am sure that nobody will do so. Not long ago nobody had any observational proof for the existence of such objects in nature, which were investigated by using theoretical physics long ago.

The concept of a body so massive that not even light could escape it was put forward by John Michel in a 1783 paper submitted to the Royal Society. However, this idea was forgotten. People reconsidered it when Albert Einstein (1915) better understood gravity than Izaak Newton (1687).

Today we have convincing observational proofs for the existence of several dozen black holes and we suppose that their number is very large [1]. One can observe black holes only in an indirect way. They interact with the environment through the gravitational field. And the idea is to observe the environment and then guess what the reason for this behavior is. Before we think how to "see" a black hole, let's say something more about these amazing objects. In our Universe one can find two kinds of black holes:

Stellar black holes – the final step in the evolution of massive stars.

Supermassive black holes are believed to exist in the centers of most galaxies, including our own Milky Way. This type of black hole contains millions to billions of solar masses. It is supposed that they are "born" in the gravitational collapse of matter in the nuclei of forming galaxies.

It is worth noting the possibility of the existence of the so-called micro black holes (with the size smaller than an atomic nucleus and mass lower then mass of a star). Some people believe that one can observe a micro black hole as a product of the certain reactions in the LHC[1] accelerator.

Let's say again, the black hole is an area of space-time from which it is impossible to send any information (we neglect here quantum effects like Hawking radiation) or a particle outside where intercommunication usually exists. The boundary of a black hole is called the **event horizon**. The possibility of the existence of black holes in nature has been predicted by the General Theory of Relativity.

The first strict solution of equations of this theory (Einstein equations) was found by Karl Schwarzschild. He analyzed the gravitational field of a static, isotropic object of a big mass. For a nonrotating black hole of a mass M, the radius of an event horizon is given by a formula derived by Schwarzschild:

$$R_S = \frac{2GM}{c^2} = 2{,}95\ (M/M_\odot)\ [\text{km}]$$

where $M_\odot$ – the mass of the Sun.

2. The binary star systems – the calculations of the component masses

Stars very often exist in systems composed of at least two stars[2]. They interact gravitationally with each other and in effect they move around the center of gravity. If we know orbital periods and radial velocities and additionally we know the inclination of the orbit with respect to the observer, then using Kepler's laws, we can calculate their masses. However, when there are only the lines of one component in the spectrum of the binary, we can calculate the so-called mass function:

$$f(M) \equiv \frac{\sin^3 i}{(1+M_2/M_1)^2} M_1 = \frac{P_{orb} K_2^3}{2\pi G} \tag{1}$$

where: M_1 and M_2 are the masses of the compact primary and the secondary, respectively,

P_{orb} – orbital period of the secondary component,

K_2 – semi-amplitude of the secondary's line-of-sight velocity,

i – inclination angle of the binary orbit

If, in addition, we know the mass of the second component, then using the mass function we can calculate the mass of the first component. Let us investigate

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[1] LHC is the contraction of *Large Hadron Collider* – the accelerator in CERN in Geneva.

[2] It is estimated that about 60% of stars are members of multiple stellar systems.

the two types of binaries in which the spectral lines of the first component are absent:

1. light visible companion – heavy invisible
2. heavy visible companion – light invisible

In the first type of systems we can assume $M_2 << M_1$. Then from (1):

$$M_1 \sin^3 i = \frac{P_{orb} K_2^3}{2\pi G} = \text{const} \tag{2}$$

In addition, assuming $i = \frac{\pi}{2}$ we obtain the minimal value of the mass of the first component. The second type of binaries is more difficult to analyze. The visible companion is heavy therefore the determination of its mass has a bigger measuring error, which amplifies the inaccuracy in the calculation of the mass of the invisible component.

2.1. Soft X-ray Transient

Many excellent black hole candidates have been discovered in a class of objects called X-ray binaries. These are double stars in which a compact primary star, either a neutron star or a black hole, accretes mass from a normal secondary companion star (see Section **3**.). The accretion process induces X-ray, ultraviolet and optical radiation.

A particular class of X-ray binaries, called soft X-ray transients or SXTs for short, has turned out to be especially helpful in the hunt for black holes. In these binaries, the mass accretion rate varies with time.

Most of the time, an SXT is in a very low luminosity state with $L_{acc} \approx (10^{-6} \div 10^{-8}) L_{Edd}$.

Eddington luminosity is the largest luminosity that can pass through a layer of gas in hydrostatic equilibrium, assuming spherical symmetry. If the luminosity of a star exceeds the Eddington luminosity of a layer on the stellar surface, the gas layer is ejected from the star. This limit is obtained by equating the radiation pressure with gravitational forces.

$L_{Edd} = 1{,}3 \times 10^{38}\, M/M_\odot \left[\frac{\text{erg}}{\text{s}}\right]$ where: M is the mass of the accreting star.

Sometimes the system goes into an accretion outburst and becomes very bright, achieving luminosity almost equal to Eddington luminosity. After the outburst, the luminosity slowly declines over a period of several months.

Observations indicate that a typical black hole mass in SXT falls in the range 5 $M_\odot$ to 15 $M_\odot$.

2.2. Is the determination of the mass a sufficient proof?

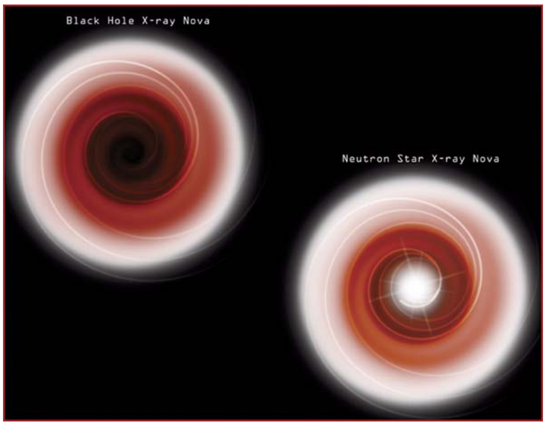
Astronomers have certainly discovered many compact stars that are too massive to be neutron stars. *Can we therefore claim victory in the search for black holes*? In the opinion of many astrophysicists, it would be premature.

It is true that a compact star with $M > 3\,M_\odot$ cannot be a neutron star and must therefore be a black hole. However, we should look for independent evidence that could confirm it. Let's think what is the most characteristic property of a black hole. It is the event horizon that makes the black hole so special. It makes a black hole so unique in the Universe. That is why we should verify whether black hole candidates posses event horizons.

How to acquire such evidence? In brief, we need an observed phenomenon (or lack of it) that is a unique signature of an event horizon. Ideally, we should compare black hole candidates to a control sample of objects, say neutron stars, that are known to have surfaces. We should show that some observable characteristic is distinctly different in the two classes of objects, and that the difference is consistent with the notion that one class (black hole candidates) has event horizons and the other class (neutron stars) has surfaces. Moreover, the difference should not have any other plausible explanation.

X-ray binaries are particularly good for such investigations since some X-ray binaries contain black hole candidates and some contain neutron stars.

Ramesh Narayan with his collaborators [3] have compared black hole and neutron star X-ray binaries and showed that quiescent black hole SXTs are very much dimmer than quiescent neutron star SXTs (see the picture below[3]).



This large luminosity difference is a natural consequence if black hole candidates have event horizons.

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[3] http://imagine.gsfc.nasa.gov

3. Accretion of gas onto compact objects

The process by which compact stars gravitationally capture the ambient matter is called accretion. However, this process doesn't necessarily involve conversion of gravitational energy into radiation. For example the accretion of a non-interacting particle increases only the mass of the central object and doesn't lead to radiation.

In real situations, both neutron stars and black holes are surrounded by clouds of gas. The problem of the accretion of gas onto a spherically symmetric body in the Newtonian theory of gravitation was investigated by Bondi (1952). He considered the adiabatic process of a gas satisfying the equation of state $p = K\rho^{\gamma}$. Bondi's considerations were later generalized to the relativistic case.

Spherically symmetric accretion is an inefficient converter of rest-mass energy into radiation. Allowing the motion of the gas cloud relative to the centre makes no substantial difference. If the velocity of the motion of a neutron star or a black hole is greater than the speed of sound in the gas, a shock wave will develop in front of the star. It will be a weak shock, and the efficiency of the transformation of the particle kinetic energy into radiation will be very low [2]. It became necessary to find a different, more efficient model of accretion. Attention was drawn to close binary systems. In such a system the matter flowing through the Lagrange point will be captured by the black hole. The process of accretion will differ from that occuring in the spherical symmetric case. The falling matter will have non-zero angular momentum. It will form a disc, gradually lose its angular momentum owing to dissipative processes, and approach the horizon, to be eventually drawn in by the black hole.

Lagrangian point – place where the gravitational force of a first body exactly balance the gravitational force of the second body.

When gas accretes on the surface of a neutron star, it is compressed by the strong surface gravity of the star, becomes denser and hotter, until the conditions are sufficient for igniting thermonuclear reactions leading to a burst of X-ray emission.

4. X-ray bursts

Bursts of X-ray emission from X-ray binaries were first discovered by Jonathan Grindlay (1976) and were immediately identified with thermonuclear explosions on the surface of a neutron star. These explosions are known as Type I bursts (to be distinguished from Type II bursts, which are not thermonuclear in origin).

In a typical Type I burst, the luminosity of the neutron star increases to nearly the Eddington limit. The time interval between two bursts is usually several hours to perhaps a day or two.

Type I bursts are very common and have been seen in many neutron star X-ray binaries. However, it is a remarkable fact that no black hole candidate in any X-ray binary has ever had a Type I burst. In some sense, this is obvious. A Type I burst requires a surface where matter is compressed and heated until a thermonuclear instability is triggered.

A black hole has no surface; matter simply falls in through the event horizon and disappears. Therefore, a black hole cannot have Type I bursts.
Since black hole candidates are indeed observed not to have bursts, does it then prove that they have event horizons? The answer is, unfortunately, No!

An object that has a Type I burst must have a surface and therefore cannot be a black hole. This statement is uncontroversial. However, an object that does not have Type I bursts does not necessarily lack a surface and therefore is not necessarily a black hole. For instance, most X-ray pulsars do not exhibit bursts and they certainly have surfaces.

5. Why do black hole candidates not emit Type I bursts?

What else [3], apart from the event horizon, could cause the lack of bursts?
Could rapid rotation somehow eliminate bursts? Rotation has the effect of introducing a variation in the effective surface gravitational acceleration **g** as a function of latitude. However, even a maximally rotating compact star has only a factor of **2** variation in **g** between the equator and the pole. Such a modest variation does not have a serious effect on the burst instability.

Could black hole candidates have very strong magnetic fields and thereby avoid bursts? Then we should observe the X radiation beam modulated at the rotation period of the star, from the magnetic field (this is, in fact, the explanation for the modulations seen in X-ray pulsars). If black hole candidates have strong magnetic fields, they ought to exhibit X-ray pulsations. None of these objects have ever shown coherent pulsations.

5.1. Science fiction: "exotic stars"

Conventional physics tells us that black hole candidates cannot be normal compact stars such as white dwarfs or neutron stars. It is therefore reasonable to suppose that, if they are not black holes, then they must be exotic stars of some kind. Could they be exotic in such a manner as to prevent Type I bursts when they accrete gas? The nature of matter deep in the core of a neutron star is unknown.

Could black hole candidates have cores made of some very exotic material, and could this prevent bursts? No, because bursts are very much a surface phenomenon (with the density of about $10^6\,\mathrm{g\,cm^{-3}}$).

The unusual kinds of matter that are invoked for neutron star interiors typically occur at very high pressure, when the density exceeds the nuclear density $(>10^{15}\,\mathrm{g\,cm^{-3}})$. Such changes in the interior have no effect on bursts at the surface.

Is there any form of exotic matter that instantly converts infalling baryonic matter into exotic matter even at densities below $< 10^6\,\mathrm{g\,cm^{-3}}$? If a star were to be made of such material, there would be no bursts since there would be no nuclei on the surface to undergo thermonuclear burning. No such matter is presently known.

Finally, the black hole candidate may consist of some kind of dark matter that does not interact with baryonic gas other than via gravity (just like the dark matter in the universe). Then such a compact object would be completely porous to ordinary matter. Infalling gas would fall freely through the dark matter and gather at the center. Would such an object have Type I bursts? To answer this question, we need to do some calculations it.

5.1.1. Would-be black holes (Gravastars)

In 2001 Emil Mottola and Paweł Mazur proposed the model which describes objects consisting of very dense and rigid matter. The space-time outside them is described by the Schwarzschild solution. Their interior is filled with matter which satisfies the following equation of state $p = -\rho$ (de Sitter phase). Their rigid surface is located close to the Schwarzchild radius:

$$R_* = R_S + 2\lambda_P$$

where λ_P is the Planck length.

$\lambda_P = 1{,}6 \times 10^{-33}\,\mathrm{cm}$ the smallest length in classical physics – hypothetical threshold, below which there are only quantum fluctuations.

This means that gravastars do not have horizon and singularity, which are the characteristics of a black hole. Nevertheless there is no observational method to distinguish them from black holes. Currently we have no means to tell whether these exotic objects exist in our Universe.

6. Gravitational waves

Does any phenomenon exist to uniquely identify the black holes?

Classically speaking a black hole does not radiate and it interacts with ambient matter only via gravitational field. Therefore searching for gravitational waves seems to be a natural way of detecting black holes [4]. It turns out that a black hole produces universal signals. Disturbing black hole space-time geometry may result in the appearance of an oscillating, damped radiation – the so-called quasi-normal modes. Their periods of oscillations and damping coefficients carry unique information about global black hole characteristics: mass, charge and angular momentum, which would allow one to identify the source of the gravitational field. So the appearance of quasi-normal modes would allow for unique identification of black holes. However, similar effect would be associated with gravastars. Therefore the observer wouldn't be able to decide as to whether he or she "sees" a black hole or its would-be "sister".

7. Conclusions

The lack of Type I bursts in black hole candidates is an important clue to the nature of these compact stars. If these objects possess surfaces, they should exhibit widespread burst activity. Why do we not see Type I bursts in black hole candidates? The most plausible explanation [3] for the lack of bursts in black hole candidates is that the objects simply have no surface (existence of an event horizon) which is a characteristic property of black holes.

Detection of gravitational waves should uniquely solve the problem whether black hole candidates are really black holes.

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The picture from the French comic book about black holes (there are also English and German translations) Jean-Pierre Petit, *Les aventures d'Anselme Lanturlu: La trou noir*, Editions Belin, 1980–1981.

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