Black holes: do they exist?

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Abstract

Black holes entered scientific literature as early as at the end of eighteenth century. They had been known at that time as dark stars, but their concept did not find its way to physics or astronomy, and had been abandoned for more than one hundred years. I shall sketch historical developments and discuss present mathematical and observational status of black holes.

Keywords

black holes, history of physics, history of black holes, first observations of black holes, present status of black holes in physics.

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1. Introduction

What would do a general relativist who is asked one day in spring 2017 to give a talk at a methodological conference *on what exists in physics*? He would try – I guess – to find out what kind of a story is expected by philosophers. I have gone through that, and I decided after meticulous considerations that black holes constitute the right concept, that should be of interest. They originated in late 18th century in a work by an almost forgotten English scholar. They had been abandoned by Laplace, in interesting circumstances. Schwarzschild gave them in 1915 new life, without knowing about their primordial existence, but the next half of a century had to pass before the mathematical and physical status of black holes had been explained and accepted. The astronomical evidence for their existence has accumulated since 1960s and there are many new observational projects concerning important properties of black holes. I shall sketch this developments in what follows.

2. Prehistory (1783-1806)

Reverend John Michell, a rector in one of Yorkshire parishes, sent in 1783 a paper to his friend Henry Cavendish, under a title: *On the Means of discovering the Distance, Magnitude, &c. of the fixed Stars, in consequence of the Diminution of the Velocity of their Light, in case such a Diminution should be found in any of them, and such other data should be procured from Observations, as would be further necessary for that Purpose* (Michell, 1784).

There had been discussed a number of ideas, one of which is particularly interesting to us. Michell states (without analytic calculations, using geometric arguments), that a star of a radius exceeding 500 solar radii and density not less than that of the Sun, would appear dark. It is easy to convert that statement into modern concepts: such a star would be hidden entirely under its Schwarzschild radius; it would be a black hole. Thus we know now that Michell was right!

We should add, that Michell was one of leading scientific figures in England in the third quarter on 17^{th} century. He made important contributions to geophysics and astronomy. The idea of the Cavendish measurement of the gravitational constant and of the torsion balance instrument was devised by Michell (Israel, 1987).

Thirteen years later Pierre Simon de Laplace discussed, without detailed explanations, the concept of dark stars in the first two editions of his book *Exposition du Système du Monde* (Laplace, 1796). He had been asked by the editor Franz Xaver von Zach to explain his reasoning and he did so in the paper entitled *Beweis des Satzes, daß die anziehende Kraft bey einem Weltkörper so groß seyn könne, daß das Licht davon nicht ausströmen kann,* published in the German journal *Allgemeine Geographische Ephemeriden* (Laplace, 1799). There is essentially a modern type reasoning and a (Newtonian) calculation, that shows that if the escape velocity V of a spherical star is equal to (or exceeds) the speed of light c,

$$V^2 = \frac{2GM}{R} > c^2,$$

then corpuscules of light cannot leave the star's surface. Thus the star becomes dark to an external observer. Above G is the gravitational constant, M is the mass and R is the radius of the star. Let us add, that it is quite likely, that Laplace did not know the work of Michell, because "there was little scientific contact between England and France during this extremely troubled time in French history." (Montgomery, Orchiston and Whittingham, 2009). For the next nearly two centuries there is no reference to the work of Michell, and Laplace is mentioned in this context (by Eddington) quite late – in 1926 (see Israel, 1987) and then in 1973 (Hawking and Ellis, 1973).

There emerges this interesting question: Why this primordial idea of black stars had been forgotten? In order, to find the clue, let us quote from Michell:

> Let us now suppose the particles of light to be attracted in the same manner as all other bodies with which we are acquainted; that is, by forces bearing the same proportion to

> their *vis inertiae* (or mass), of which there can be no reasonable doubt, gravitation being, as far as we know, or having any reason to believe, an universal law of nature.

Michell and Laplace adopted the view, after Newton, that *light consists of particles*. In 1801 Thomas Young's experiments revealed interference – a phenomenon characteristic for waves. The reasoning of Michell and Laplace could not be applied to a wave. Interestingly, in the third edition of his *Exposition du Système du Monde* (1808) the passage about dark stars disappears; is that because Laplace realized, that Young experiments invalidate one of his basic assumptions? I leave that question as an open issue, that perhaps will never be conclusively answered.

The concept of dark stars required the universality of gravitation and corpuscular nature of light. We should stress again that the existence of dark stars within Newtonian gravity would not be compatible with the wave character of light.

There was not made any attempt, at that time, to confront theoretical predictions with astronomical observations. This confrontation was anyway impossible, with astronomical instruments available in 19^{th} century, but there exists this interesting possibility, that the main reason was the realization that there exists a conflict between notions of dark stars and the wave-like nature of light. I conclude this section by stating a conjecture, that the eighteen's century concept of dark stars was abandoned because of internal theoretical inconsistencies.

3. History (1916-1990)

Karl Schwarzschild (1916) published a paper with his famous solution to Einstein equations:

$$ds^2 = -(1 - \frac{2GM}{Rc^2})dt^2 + dR^2(1 - \frac{2GM}{Rc^2})^{-1} + R^2 dO^2.$$

Here dO denotes the line element on a unit sphere. Notice the emergence of an apparent "singularity" when the Michell-Laplace condition is saturated,

$$c^2 = v^2 = \frac{2GM}{R}.$$

Notice that this relation defines the critical radius $R_s = \frac{2GM}{c^2}$ – the same quantity as in Michell's or Laplace's works! If a star finds itself beneath a sphere of a radius R_s, then it becomes dark. The Schwarzschild's solution was regarded for almost 50 years as unphysical – albeit with notable exceptions like Landau and Lifszic (see discussion in Israel, 1987). Einstein presented a (correct) proof that no stationary system can be compacted within the Schwarzschild radius R_s. Schwarzschild has shown that a constant mass density spherical star must be larger than $9R/8$. Others would argue that stars squeezed within their Schwarzschild radius would be absurdly dense – a cubic centimeter of the Sun compacted to a ball of the radius 3 km would weigh more than 10^{16} grams.

Werner Israel (1987) describes in his review developments of the preceding 70 years. They proceeded in many directions.

There was a formal (theoretical) progress, in which were found regular representations of the horizon in the Schwarzschild metric (in non-polar slicing conditions) We shall mention here (see discussion in Israel, 1987) Painlevé, Gullstrand, Lemaître, Eddington, Finkelstein, Synge and Szekeresz. Interesting is the case of Lemaître, who explicitly stated that in his coordinates (coinciding with Painlevé and Gullstrand) the Schwarzschild solution is manifestly regular up to the horizon. Nevertheless, this information was not understood and it was somehow suppressed. It was only around 1960 when it was accepted, that there is nothing unusual from the analytic point of view at the sphere $R = R_s$; that the event horizon is located at R_S, that it can be freely traversed from the outside but that it is confining standard matter inside a black hole. In 1960 appeared a paper *Maximal extension of Schwarzschild metric* (Kruskal, 1960). We should mention in this context also Szekeresz and Synge. By mid-sixties (after the discovery of the Kerr and Kerr-Newman solutions and their maximal extensions) it was generally accepted that there do exist mathematically correct solutions of Einstein equations that could be regarded as dark stars. The name *"black hole"* appeared for the first time in print in 1968, in one of publications of John Wheeler, who evidently was the main driving force of the whole development in the years 1955-1965. I like to think that this resolution of theoretical difficulties had constituted the fundamental step in allowing the existence of the modern incarnation of dark stars.

There was a progress from the other – astrophysical – side. Theoretical models and observation of compact stars led to developments of models of white dwarves (Chandrasekhar) and neutron stars (Landau, Gamov and others), that would have quite dense interiors (up to $10^{\mathbf{15}}$ grams per cubic centimeter). That partially took away the odium of "absurdity" from black holes. Baade and Zwicky initiated before the second world war observational search for neutron stars, that led to first successful results in 1967 – discovery of pulsars, quickly rotating neutron stars.

Oppenheimer and Snyder (1939) presented a scenario for the gravitational collapse to a black hole. It required high symmetry and special matter, but singularity theorems of Penrose (Penrose, 1965) and others gave a chance to extend its validity in non-spherical systems

Analysis of accreting systems demonstrated that matter falling onto a black hole can be a very efficient source of electromagnetic energy – one teaspoon of water falling onto a black hole produces roughly the energetic equivalent of dozens of fuel tankers of petrol.

The compact component in a binary system Cygnus X-1, discovered in 1964, has been for a long time a black hole candidate, eventually confirmed a few years ago, to my knowledge.

Active galactic nuclei – sources of electromagnetic radiation, thought to contain giant black holes – have been discovered. Extremely distant and extremely bright sources of radiation – quasars – have conjectured in early 1970s to contain black holes. Accretion of matter onto these black holes would power quasars.

In conclusion: *by mid-1990s the hypothesis of (black holes)/(former dark stars) was firmly grounded theoretically and convincingly supported by observations.*

4. Present status of black holes (1990-2017)

We should acknowledge further formal developments – mathematical investigations of the collapse to black holes (Christodolou, Klainerman, Rodnianski, Dafermos and others) for simple physical models. In the last three decades Christodoulou, Klainerman and others have shown that gravitational collapse of material fields can lead to a black hole. Real astrophysical processes (from realistic stars to black holes, for instance) are not well studied, to my knowledge. The main obstacle is the complexity of nuclear and transport processes in interiors of heavy stars.

Let me address briefly a claim expressed in many popular books on black holes – that one needs to know the full *(infinite) history of* *a spacetime* in order to establish that it contains a black hole (an event horizon). On the other hand, astronomers explain many of their observations by the presence of black holes in the sky. There is no need to stress, that astronomers observe their objects only for a *finite time period*. The whole written history of astronomy can be compacted in the last 2-3 thousands years. Thus on what basis astronomers can claim, that they see black holes? The answer to that question is interesting, because it refers to real astronomical phenomena, but it also shows limitations in our understanding of Einstein equations. Unfortunately, the full discussion requires many technicalities (physical or mathematical) and each time must be adapted to a particular sort of astronomical observations. Let me consider just two particular cases. *It was established* – see the forthcoming example concerning the black hole in the Milky Way – that there is a huge mass that is contained in a volume that is perhaps only ten times larger than the volume within the Pluto orbit in the Solar system. This configuration is evidently stable; the simplest way to explains its stability is to accept the existence of a black hole. It should be noted that black holes have their specific signature – their event horizons are dark – that can be also tested in dedicated observations (see below information on projects of Rezzolla and Falcke et al.). The assertion, that there exists (*now and in the future*) a black hole in the center of Milky Way can be checked in a number of ways. *The other case* – the formation of a black hole in the gravitational wave detection (Abbott et al., 2016) – is of a different category. Its analysis involves a modeling (numerical and analytic, albeit approximate) of the coalescence of two black holes, and detecting in numerics the emergence of the so-called apparent horizon. Apparent horizons can be detected in local experiments (albeit indirectly, through modeling), but they signal – through the so-called cosmic censorship (Penrose, 1969) – the existence of the event horizon (and therefore *of the black hole, now and in the future*). This argument has a gap – the cosmic censorship is essentially a hypothesis, albeit supported by some important cases. The validity of the so-called Penrose inequality – stated in (Penrose, 1973) and proven (in the so-called Riemannian case) by Huisken and Ilmanen (2001) – is one of strongest arguments in favour of the cosmic censorship. Dynamical black holes, that are in the process of creation, can emit damped gravitational waves, suggesting the existence of event horizons; that was detected in the (Abbott et al., 2016) event, as discussed below. We see here a chain of observations, theoretical/mathematical arguments and philosophical ideas. Some of the latter can be in principle proven by clever manipulation of Einstein equations, assuming that the material content of the Universe obeys several ("energy") conditions.

There exists a multitude of observations, almost all collected after 1990, that confirm the existence of black holes. The most striking evidence is that concerning the center of the Milky Way.

There is something like two dozens of *observed stars* (Schoedel, Ghez) that circulate around a black hole (4 mln Solar masses!). Below (Figure 8) is an example – visualization (basing on real observations up to 2002) of the orbit of the best known star, S_2.

*The vicinity of Sagittarius A** will be investigated in two ongoing projects. Americans (*Event Horizon Telescope* – Doeleman) and Europeans (*Imaging the Event Horizon of Black Holes* – Falcke, Kramer and Rezzolla) attempt to "*construct the first accurate image of a black hole*." The main goal is to see directly the event horizon of the black hole.

A new class of data on black holes emerged in recent (2015-2017) detections of gravitational waves (Abbott et al., 2016; see also Królak and Patil, 2018). These waves resulted in the coalescence of binary

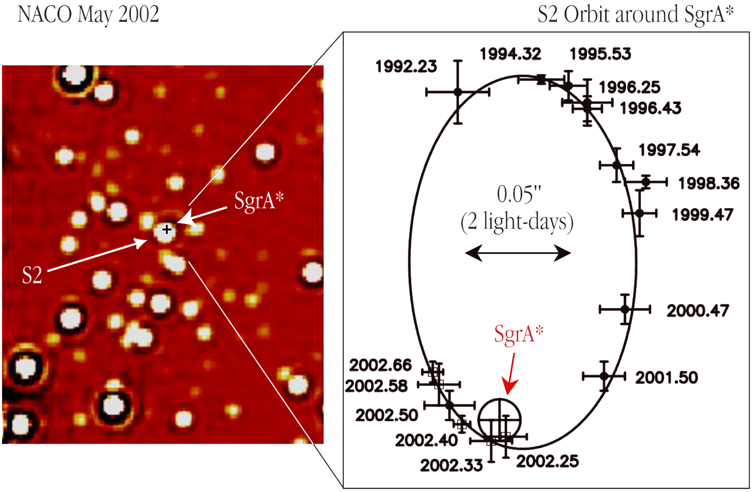

Figure 8: The motion of a star around the central black hole in the Milky Way. [Image credit: ESO]

systems, consisting exclusively of black holes. For not quite obvious reasons, their final collapse is associated with radiation of damped oscillating waves (quasinormal modes).

A comment on these quasinormal modes is needed in this place. They are related with black holes since 1970, when Vishveshwara found that radiation can scatter off a black hole, and that scattered radiation propagates as exponentially damped oscillations. Later investigation (Leaver and others) have shown, that periods of oscillations and damping characteristics allow one to identify uniquely global characteristic of black holes, such as mass and angular momentum. *It has been a common view since 1980s, that identification of quasinormal waves would be the strongest argument in favor of the existence of black holes.*

We should stress that parameters (mass and angular momentum) of the final black hole are determined from characteristics of the ringing pulses (their periods and damping rates). In a sense, the recent Nobel prize for the discovery of gravitational waves, can be regarded as recognition of the existence of black holes. At least by the Nobel Committee.

Important class of evidence is related to accretion of matter onto black holes. Almost all black holes of stellar origin and most of black holes in galactic centers are known due to accretion phenomena.

Astronomers (Ramesh Narayan and others) periodically publish lists of well documented objects purported to be black holes. Recent lists comprise about 3 dozens of black holes of stellar origin (https://en.wikipedia.org/wiki/Stellar_black_hole) and a significantly larger number of giant black holes that appear in galactic centers (see https://en.wikipedia.org/wiki/List_of_most_massive_black_holes).

5. Final remarks

I shall group them in two parts, each directed to a different category of potential readers.

Physicists probably would be content just to know that black holes exist in physics. They exist as well defined mathematical objects and there is a plethora of astronomical observational data.

Philosophers would probably be interested in the evolution of the notion and the history of black holes. I emphasize that black holes (dark stars) are invented in a theoretical speculation. They lost their brief theoretical existence after – I like that hypothesis – finding internal inconsistencies by Laplace. Black holes, revived after creation of general relativity, finally have been understood almost 200 years after invention. It is only at that stage that serious observations began. After next fifty years, evidence in favor of their existence have become compelling.

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