Irreversible gravitational collapse: black stars or black holes?

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Abstract

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It is well known that the concept of black hole has been considered very fascinating by scientists even before the introduction of Einstein’s general relativity. They should be the final result of an irreversible gravitational collapse of very massive bodies.

However, an unsolved problem concerning such objects is the presence of a space-time singularity in their core. Such a problem was present starting by the first historical papers concerning black holes. It is a common opinion that this problem could be solved when a correct quantum gravity theory will be, finally, constructed.

In this work we review a way to remove black hole singularities at a classical level i.e. without arguments of quantum gravity. By using a particular non-linear electrodynamics Lagrangian, an exact solution of Einstein field equations is shown. The solution prevents the collapsing object to reach the gravitational radius, thus the final result becomes a black star, i.e. an astrophysical object where both of singularities and event horizons are removed. Such solution is not only a mathematical artifice. In fact, this kind of Lagrangian has been recently used in various analysis in astrophysics, like surface of neutron stars and pulsars. The authors also recently adapted the analysis on a cosmological context by showing that the big-bang singularity can be removed too.

Keywords: Black holes; singularity, nonlinear electrodynamics, extremely electromagnetic compact objects.

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This paper is dedicated to the Memory of Professor Darryl Jay Leiter, February 25, 1937 - March 4, 2011. Professor Leiter gave a fundamental contribution in evolving an alternate explanation of black holes, the theory of MECOs or magnetic eternally collapsing compact objects.

1 Introduction

The concept of black-hole (BH) has been considered very fascinating by scientists even before the introduction of general relativity (see [1] for an historical review). A BH is a region of space from which nothing, not even light, can escape out to infinity. It is the result of the deformation of spacetime caused by a very compact mass. Around a BH there is an undetectable surface which marks the point of no return. This surface is called an event horizon. It is called ”black” because it absorbs all the light that hits on it, reflecting nothing, just like a perfect black body in thermodynamics [2]. However, an unsolved problem concerning such objects is the presence of a space-time singularity in their core. Such a problem was present starting by the first historical papers concerning BHs [3][4][5]. It is a common opinion that this problem could be solved when
a correct quantum gravity theory will be, finally, obtained, see [6] for recent developments in this direction.

On the other hand, fundamental issues which dominate the question about the existence or non-existence of BH horizons and singularities and some ways to avoid the development of BH singularities within the classical theory, which does not require the need for a quantum gravity theory, have been discussed by various authors in the literature, see references from [7] to [10]. In fact, by considering the exotic nature of BHs, it may be natural to question if such bizarre objects could indeed exist in nature or rather to suggest that they are merely pathological solutions to Einstein’s equations. Einstein himself thought that BHs would not form, because he held that the angular momentum of collapsing particles would stabilize their motion at some radius [17].

Let us recall some historical notes. In 1915, A. Einstein developed his theory of general relativity [18]. A few months later, K. Schwarzschild gave the solution for the gravitational field of a point mass and a spherical mass [3]. After Schwarzschild, J. Droste, a student of H. Lorentz, independently gave an apparently different solution for the point mass and wrote more extensively about its properties [19]. In such a work Droste also claimed that his solution was physically equivalent to the one by Schwarzschild. In the same year, 1917, H. Weyl re-obtained the same solution by Droste [20]. This solution had a peculiar behaviour at what is now called the Schwarzschild radius, where it became singular, meaning that some of the terms in the Einstein equations became infinite. The nature of this surface was not quite understood at the time, but Hilbert [21] claimed that the form by Droste and Weyl was preferable to that in [3] and ever since then the phrase “Schwarzschild solution” has been taken to mean the line-element which was found in [19, 20] rather than the original solution in [3].

For the sake of completeness we recall that, based on new translations of Schwarzschild’s original work, there are researchers who invoke the non-existence of BHs by claiming that the Schwarzschild’s original work [3] gives a solution which is physically different from the one derived by Droste [19] and Weyl [20]. The new translations of Schwarzschild’s original work can be found in ref. [22, 23]. These works commented on Schwarzschild’s original paper [3]. In particular Abrams [22] claimed that the line-element (we use natural units in all this paper)

\[ ds^2 = (1 - \frac{r_g}{r})dt^2 - r^2 \sin^2 \theta d\varphi^2 + d\theta^2 - \frac{dr^2}{1 - \frac{r_g}{r}} \]  (1)

i.e. the famous and fundamental solution to the Einstein field equations in a vacuum, gives rise to a space-time that is neither equivalent to Schwarzschild’s original solution in [3]. In a following work [24] Abrams further claimed that “Black Holes are The Legacy of Hilbert’s Error” as Hilbert’s derivation used a wrong variable. Thus, Hilbert’s assertion that the form of (1) was preferable to the original one in [3] should be misleading. Based on this, there are plenty of authors who agree with Abrams by claiming that the work of Hilbert was
wrong and Hilbert’s mistake spawned the BHs and the community of theoretical physicists continues to elaborate on this falsehood, with a hostile shouting down of any and all voices challenging them, see for example references [23, 25]. In any case, this issue has been ultimately clarified in [26] where it has been shown that “the original Schwarzschild solution” [3] results physically equivalent to the solution [1] enabled like the correct one by Hilbert in [21], i.e. the solution that is universally known like the “Schwarzschild solution” [1]. The authors who claim that the original Schwarzschild solution leaves no room for the science fiction of the BHs (see references from [22] to [25]) give the wrong answer [26]. The misunderstanding is due to an erroneous interpretation of the different coordinates [26]. In fact, arches of circumference appear to follow the law $dl = r d\phi$, if the origin of the coordinate system is a non-dimensional material point in the core of the BH, while they do not appear to follow such a law, but to be deformed by the presence of the mass of the central body $M$ if the origin of the coordinate system is the surface of the Schwarzschild sphere, see [26] for details.

After this clarification, let us return on historical notes. In 1924, A. Eddington showed that the singularity disappeared after a change of coordinates (Eddington coordinates [27]), although it took until 1933 for G. Lemaître to realize, in a series of lectures together with Einstein, that this meant the singularity at the Schwarzschild radius was an unphysical coordinate singularity [28].

In 1931, S. Chandrasekhar calculated that a non-rotating body of electron-degenerate matter above 1.44 solar masses (the Chandrasekhar limit) would collapse [5]. His arguments were opposed by many of his contemporaries like Eddington, Lev Landau and the same Einstein. In fact, a white dwarf slightly more massive than the Chandrasekhar limit will collapse into a neutron star which is itself stable because of the Pauli exclusion principle [1]. But in 1939, J. R. Oppenheimer and G. M. Volkoff predicted that neutron stars above approximately 1.5 - 3 solar masses (the famous Oppenheimer-Volkoff limit) would collapse into BHs for the reasons presented by Chandrasekhar, and concluded that no law of physics was likely to intervene and stop at least some stars from collapsing to BHs [29]. Oppenheimer and Volkoff interpreted the singularity at the boundary of the Schwarzschild radius as indicating that this was the boundary of a bubble in which time stopped. This is a valid point of view for external observers, but not for free-falling observers. Because of this property, the collapsed stars were called "frozen stars" [30] because an outside observer would see the surface of the star frozen in time at the instant where its collapse takes it inside the Schwarzschild radius. This is a known property of modern BHs, but it must be emphasized that the light from the surface of the frozen star becomes redshifted very fast, turning the BH black very quickly. Originally, many physicists did not accept the idea of time standing still at the Schwarzschild radius, and there was little interest in the subject for lots of time. But in 1958, D. Finkelstein, by re-analysing Eddington coordinates, identified the Schwarzschild surface $r = 2M$ (in natural units, i.e. $G = 1$, $c = 1$ and $\hbar = 1$, i.e where $r$ is the radius of the surface and $M$ is the mass of the BH) as an event horizon, "a perfect unidirectional membrane: causal influences can
cross it in only one direction” [31]. This extended Oppenheimer’s results in order to include the point of view of free-falling observers. Finkelstein’s solution extended the Schwarzschild solution for the future of observers falling into the BH. Another complete extension was found by M. Kruskal in 1960 [32].

These results generated a new interest on general relativity, which, together with BHs, became mainstream subjects of research within the Scientific Community. This process was endorsed by the discovery of pulsars in 1968 [33] which resulted to be rapidly rotating neutron stars. Until that time, neutron stars, like BHs, were regarded as just theoretical curiosities; but the discovery of pulsars showed their physical relevance and spurred a further interest in all types of compact objects that might be formed by gravitational collapse.

In this period more general BH solutions were found. In 1963, R. Kerr found the exact solution for a rotating BH [34]. Two years later E. T. Newman and A. Janis found the asymmetric solution for a BH which is both rotating and electrically charged [35]. Through the works by W. Israel, B. Carter and D. C. Robinson the no-hair theorem emerged [1], stating that a stationary BH solution is completely described by the three parameters of the Kerr–Newman metric; mass, angular momentum, and electric charge [1].

For a long time, it was suspected that the strange features of the BH solutions were pathological artefacts from the symmetry conditions imposed, and that the singularities would not appear in generic situations. This view was held in particular by Belinsky, Khalatnikov, and Lifshitz, who tried to prove that no singularities appear in generic solutions [1]. However, in the late sixties R. Penrose and S. Hawking used global techniques to prove that singularities are generic [1].

The term “black hole” was first publicly used by J. A. Wheeler during a lecture in 1967 [36] but the first appearing of the term, in 1964, is due to A. Ewing in a letter to the American Association for the Advancement of Science [37], verbatim: “According to Einstein’s general theory of relativity, as mass is added to a degenerate star a sudden collapse will take place and the intense gravitational field of the star will close in on itself. Such a star then forms a ‘black hole’ in the universe.”

In any case, after Wheeler’s use of the term, it was quickly adopted in general use.

Today, the majority of researchers in the field is persuaded that there is no obstacle to forming an event horizon. On the other hand, there are other researchers who demonstrated that various physical mechanisms can, in principle, remove both of event horizon and singularities during the gravitational collapse [7] - [16]. In particular, in [7] an exact solution of Einstein field equations which removes both the event horizon and singularity has been found by constructing the right-hand side of the field equations, i.e. the stress-energy tensor, through a non-linear electrodynamics Lagrangian which was previously used in studying super-strongly magnetized compact objects, in particular neutron stars and pulsars [38, 39]. In the next Section we will discuss this important issue.
2 Non-singular gravitational collapse

In Einstein’s General Theory of Relativity the Einstein equation relates the curvature tensor of spacetime on the left hand side to the energy-momentum tensor in spacetime on the right hand side [1, 40]. Within the context of the Einstein equation the strong principle of equivalence (SPOE) requires that special relativity must hold locally for all of the laws of physics in all of spacetime as seen by time-like observers ([10] and Section 2.1 of [11]). Hence, in the context of the SPOE this implies that the frames of reference of co-moving observers within a gravitationally collapsing object are required to always be able to be connected to the frame of reference of stationary observers by special relativistic transformations with physical velocities which are less than the speed of light in a vacuum [40]. Recently plausible arguments have been made which support the idea that physically acceptable solutions to the Einstein equation will only be those which preserve the SPOE as a law of nature in the universe [7, 8, 16, 40].

The observable consequence of preserving the SPOE as a law of nature would be that compact objects which emerge from the process of gravity collapse could not have event horizons (EHs) because their existence would prevent co-moving observers within a gravitationally collapsing object from being able to be connected to the frame of reference of stationary observers by special relativistic transformations with physical velocities which are less than the speed of light [40]. Hence, as a result of the SPOE, objects having EHs with non-zero mass would be physically prohibited [7, 8, 16, 40]. In particular, the preservation of the SPOE in the Einstein equation would put an overall constraint on the nature of the non-gravitational physical elements which go into the energy-momentum tensor on the right hand side of the Einstein equation. However this constraint would not uniquely determine the specific form of the non-gravitational dynamics of the energy-momentum tensor [7, 8, 16, 40]. For this reason many different theories can be constructed (e.g. eternally collapsing objects (ECO), magnetospheric eternally collapsing objects (MECO), nonlinear electrodynamics (NLED) extremely compact objects, which preserve the SPOE and hence can generate highly redshifted compact objects without EHs [7, 8, 9, 16, 40]. Since each of these different SPOE preserving theories have unique observational predictions associated with the interaction of their non-gravitational components with the environment of their highly redshifted compact objects without EHs, the specific one chosen by Nature can only be determined by astrophysical observations which test these predictions [7, 8, 16, 40]. In the following, we will review the NLED model in [9].

NLED Lagrangian has been used in various analysis in astrophysics, like the surface of neutron stars [38] and pulsars [39], and also on cosmological context to remove the big-bang singularity [12, 43].

The effects arising from a NLED become quite important in super-strongly magnetized compact objects, such as pulsars and particular neutron stars [38, 39]. Some examples include the so-called magnetars and strange quark magnetars. In particular, NLED modifies in a fundamental basis the concept of gravitational redshift as compared to the well established method introduced
by standard treatments [38]. The analyses proved that, unlike using standard linear electrodynamics, where the gravitational redshift is independent of any background magnetic field, when a NLED is incorporated into the photon dynamics, an effective gravitational redshift appears, which happens to depend decidedly on the magnetic field pervading the pulsar. An analogous result has also been obtained for magnetars and strange quark magnetars [39]. The resulting gravitational redshift tends to infinity as the magnetic field grows larger [22, 23], as opposed to the predictions of standard analyses which involve linear electrodynamics. What is important here is that the gravitational redshift of neutron stars is connected to the mass–radius relation of the object [38, 39]. Thus, NLED effects turn out to be important as regard to the mass–radius relation, which is maximum for a BH.

Following this approach, in [9] a particular non singular exact solution of Einstein field equation has been found adapting to the BH case the cosmological analysis in [43]. In fact, the conditions concerning the early era of the Universe, when very high values of curvature, temperature and density were present [1, 9], and where matter should be identified with a primordial plasma [1, 9], are similar to the conditions concerning BH physics. This is exactly the motivation because various analyses on BHs can be applied to the Universe and vice versa [1, 9].

The model works on a homogeneous and isotropic star (a collapsing "ball of dust") supported against self-gravity entirely by radiation pressure. Let us consider the Heisenberg-Euler NLED Lagrangian [9, 42, 43]

$$
\mathcal{L}_m \equiv -\frac{1}{4} F + c_1 F^2 + c_2 G^2,
$$

where $G = \frac{1}{2} \eta_{\alpha\beta\mu\nu} F^{\alpha\beta} F^{\mu\nu}$, $F \equiv F_{\mu\nu} F^{\mu\nu}$ is the electromagnetic scalar and $c_1$ and $c_2$ are constants. Through an averaging on electric and magnetic fields [9, 42, 43], the Lagrangian (2) enables a modified radiation-dominated equation of state ($p$ and $\rho$ are the pressure and the density of the collapsing star)

$$
p = \frac{1}{3} \rho - \rho_\gamma,
$$

where a quintessential density term $\rho_\gamma = \frac{4}{3} c_1 B^4$ is present together with the standard term $\frac{1}{3} \rho$ [9, 42, 43]. $B$ is the strength of the magnetic field associated to $F$. The interior of the star is represented by the well-known Robertson–Walker line-element [1, 9]

$$
ds^2 = -dt^2 + a(t)(d\chi^2 + \sin^2 \chi (d\theta^2 + \sin^2 \theta d\phi^2)).
$$

Using sin $\chi$ we choose the case of positive curvature, which is the only one of interest because it corresponds to a gas sphere whose dynamics begins at rest with a finite radius [1, 9]. Considering Eq. (2) together with the stress-energy tensor of a relativistic perfect fluid [1, 9, 42, 43]

$$
T = \rho u \otimes u - pg,
$$

7
where \( u \) is the four-vector velocity of the matter and \( g \) is the metric, the Einstein field equation gives the relation \[9, 43\]

\[
t = \int_{a(0)}^{a(t)} dz \left( \frac{B_0^2}{6z^2} - \frac{8c_1 B_0^4}{6z^6} - 1 \right)^{-\frac{1}{2}},
\]

being \( B_0 = a^2 B \). The expression \[6\] is not singular for values of \( c_1 > 0 \) in Eq. \[2\] \[9, 43\]. In fact, the presence of the quintessential density term \( \rho_\gamma \) permits to violate the reasonable energy condition \[1\] of the singularity theorems. By using elliptic functions of the first and second kind, one gets a parabolic trend for the scale factor near a minimum value \( a_f \) in the final stages of gravitational collapse \[9\].

In concrete terms, by calling \( l, m, n \) the solutions of the equation

\[
8c_1 B_0^4 - B_0^2 x + 3x^3 = 0,
\]

reads \[9, 43\]

\[
t = \left[ -(m - l)^{\frac{1}{2}} \beta_1(\arcsin \sqrt{\frac{z - l}{m - l}}, \arcsin \sqrt{\frac{1 - m}{1 - n}}) \\
+ n(m - l)^{-\frac{1}{2}} \beta_2(\arcsin \sqrt{\frac{z - l}{m - l}}, \arcsin \sqrt{\frac{1 - m}{1 - n}}) \right]_{z = a(t)} \Bigg|_{z = a^2(0)},
\]

where

\[
\beta_1(x, y) \equiv \int_0^{\sin x} dz \left[ (1 - z^2)^{-\frac{1}{2}} (1 - y^2 z^2)^{-1} \right]
\]

is the elliptic function of the first kind and

\[
\beta_2(x, y) \equiv \int_0^{\sin x} dz \left[ (1 - z^2)^{-\frac{1}{2}} (1 - y^2 z^2)^{-1} \right]^{\frac{1}{2}}
\]

is the elliptic function of the second kind.

Then, recalling that the Schwarzschild radial coordinate, in the case of the BH geometry \[4\], is \( r = a \sin \chi_0 \) \[1, 9\], where \( \chi_0 \) is the radius of the surface in the coordinates \[4\], one gets a final radius of the star, if \( B_0 \) has an high strength \[9\]

\[
r_f = a_f \sin \chi_0 > 2M
\]

where \( M \) is the mass of the collapsed star and \( 2M \) the gravitational radius in natural units \[1, 9\]. Thus, we find that the mass of the star generates a curved space-time without EHs.

### 3 Conclusion remarks

Black holes should be the final result of an irreversible gravitational collapse of very massive bodies. An unsolved problem, which was present starting by the first historical papers concerning black holes, is the presence of a space-time singularity in their core. It is a common opinion that this problem could be solved when a correct quantum gravity theory will be, finally, constructed.
In this paper we reviewed a way to remove black hole singularities at a classical level i.e. without arguments of quantum gravity. By using a particular non-linear electrodynamics Lagrangian, an exact solution of Einstein field equations has been shown. The solution prevents the collapsing object to reach the gravitational radius, thus the final result becomes an extreme electromagnetic compact object exhibiting an utterly extreme gravitational redshift $z \rightarrow \infty$, i.e., a black star, that is nothing else than an astrophysical object where both singularities and event horizons were removed. Such solution is not a mathematical artifice. In fact, this kind of Lagrangian has been recently used in various analysis in astrophysics, like surface of neutron stars and pulsars. The authors also recently adapted the analysis on a cosmological context by showing that the big-bang singularity can be removed too [12].

Potential removal of BH horizons and singularities is an exciting and rapidly advancing field of research on theoretical, observational and experimental fronts. We take the chance to signal some recent results [44, 45].

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