Do Black Holes End up as Quark Stars?

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Abstract. The possibility of the existence of quark stars has been discussed by several authors since 1970. Recently, it has been pointed out that two putative neutron stars, RXJ 1856.5-3754 in Corona Australis and 3C58 in Cassiopeia are too small and too dense to be neutron stars; they show evidence of being quark stars. Apart from these two objects, there are several other compact objects which fit neither in the category of neutron stars nor in that of black holes. It has been suggested that they may be quark stars. In this paper it is shown that a black hole cannot collapse to a singularity, instead it may end up as a quark star. In this context it is shown that a gravitationally collapsing black hole acts as an ultrahigh energy particle accelerator, hitherto inconceivable in any terrestrial laboratory, that continually accelerates particles comprising the matter in the black hole. When the energy $E$ of the particles in the black hole is $\geq 10^2$ GeV, or equivalently the temperature $T$ of the matter in the black holes is $\geq 10^{15}$ K, the entire matter in the black hole will be converted into quark-gluon plasma permeated by leptons. Since quarks and leptons are spin 1/2 particles, they are governed by Pauli’s exclusion principle. Consequently, one of the two possibilities will occur; either Pauli’s exclusion principle would be violated and the black hole would collapse to a singularity, or the collapse of the black hole to a singularity would be inhibited by Pauli’s exclusion principle, and the black hole would eventually explode with a mini bang of a sort. After explosion, the remnant core would stabilize as a quark star.

Key words. black hole, gravitational collapse, space-time singularity, quark star

1. Introduction

The possibility of the existence of the quark stars, i.e. the stars composed of the fundamental constituents of matter, viz., quarks is being discussed for more than three decades (Itoh 1970, Bodmer 1971, Collins and Perry 1975, Brecher and Caporaso 1976, Chaplin and Nauenberg 1978, Witten 1984, Alcock et al. 1986, Haensel et al. 1986, Li et al. 1995, Bombaci 1997, Cheng et al. 1998, Xu et al. 1999). It has been suggested that such an object would have an approximately thermal spectrum (Xu 2002, Pons et al. 2002). Moreover, in this context it may be noted that there are several compact objects, e.g., Her - X1, 4U 1820 - 30 (Bombaci 1997, Dey et. al. 1998), SAX J 1808.4 - 3658 (Li et al. 1999 a), 4U1728 - 34 (Li et al. 1999 b), PSR 0943+10 (Xu et al. 1999), which fit neither in the category of neutron stars nor in that of black holes. The apparent compactness of these objects could be explained if they are composed of quarks.

Recently, two teams – one led by David Helfand of Columbia University, New York (Slane et al. 2002), and another led by Jeremy Drake of Harvard-Smithsonian Center for Astrophysics, Cambridge, Masss., U.S.A. (Drake et al. 2002) – studied independently two objects, 3C58 in Cassiopeia, and RXJ1856.5 - 3754 in the outskirts of the RCrA dark molecular cloud in Corona Australis respectively by combining data from NASA’s Chandra X-ray Observatory, and the Hubble Space Telescope. These objects, at first, seemed to be ordinary neutron stars. However, when observed more carefully, each of them showed evidence of being an even smaller and denser object, a quark star or strange star.

The team led by David Helfand failed to detect the expected X- radiation from the hot surface of 3C 58, a putative neutron star, believed to be the remnant core of a supernova explosion witnessed by Chinese and Japanese astronomers in A.D. 1181. This led the team to conclude that 3C 58 has a surface temperature less than $10^6$ K, a value far below the predicted value, assuming that the object is a neutron star.

The group led by Drake analyzed deep Chandra Low Energy Transmission Grating and High Resolution Camera Spectroscopic observations of the isolated putative neutron star RX J1856.5 − 3754 with a view to searching for metallic and resonance cyclotron spectral features and for pulsation behaviour. The group found that the X-ray spectrum is well represented by an $\sim 60$ eV ($7\times10^9$ K) blackbody. It did not find any unequivocal evidence of spectral line or edge features which argues against the metal dominated models. The group also found that the data did not contain any evidence for pulsation. The "radiation radius" $R_\infty$ was found to be $3.8 - 8.2$ km, where

$$R_\infty = \frac{R}{(1 - 2GM/Rc^2)^{1/2}}$$ (1)
R being the true radius of the star of mass M. The group is of the view that the combined observational evidence – a lack of spectral and temporal features, and an implied radius $R_{\odot} = 3.8 \sim 8.2$ km that is too small for current neutron star models – points to a more compact object, a quark star, rather than a neutron star. According to Drake et al.(2002), of the existing quark star candidates, RX J 1856.5-3754 presents the strongest and the most direct case.

2. Transition from Hadrons to Quarks

If indeed the quark stars exist, the pertinent question is: How are they formed? The answer to this question lies in understanding the physical process that leads to the transition of ordinary matter consisting of hadrons (i.e. baryons and mesons) and leptons into quark-gluon plasma (QGP) permeated by leptons. In this context it may be noted that though actual existence of quarks – the up(u), down(d) charm(c), strange(s), top(t), bottom(b) – has been only indirectly confirmed by experiments that probe hadronic structure by means of electromagnetic and weak interactions, and by production of various quarkonia ($\bar{q}q$), the bound states of quarks (q) and antiquarks ($\bar{q}$), in high-energy collisions made possible by various high energy particle accelerators, no free quark has, so far, been detected in experiments at these accelerators. This fact has been attributed to the phenomenon called infrared slavery of quarks, i.e. to the nature of the interaction between quarks responsible for their confinement inside hadrons. On the contrary, the results of deep inelastic scattering experiments reveal an altogether different feature of the interaction between quarks. If one examines quarks at very short distances ($< 10^{-13}$ cm) by observing the scattering of a nonhadronic probe, e.g., an electron, or a neutrino, one finds that quarks move almost freely inside baryons and mesons as though they are not bound at all. This phenomenon is called asymptotic freedom of quarks. In fact, Gross and Wilczek (1973 a,b), and Politzer (1973) have shown that the running coupling constant of the interaction between two quarks vanishes in the limit of infinite momentum (or, equivalently, in the limit of zero separation). Consequently, in order to liberate quarks from infrared slavery, i.e. for quark deconfinement, very large energy, more than what is available in the existing terrestrial particle accelerators, is required. In fact, it has been shown theoretically that when the energy $E$ of the particles $\sim 10^2$ GeV, the separation $s$ between the particles $\sim 10^{-16}$ cm, corresponding to a temperature $T \sim 10^{15}$ K, all interactions are of the Yang-Mills type with $SU(3) \times SU(2) \times U(1)$ gauge symmetry, where $c$ stands for colour, $I_W$ for weak isospin, and $Y_W$ for weak hypercharge, and at this stage quarks are liberated from infrared slavery, and acquire asymptotic freedom, i.e. quark deconfinement occurs as a result of which matter now consists of its fundamental constituents: spin 1/2 leptons, viz., the electrons, the muons, the tau leptons, and their neutrinos, which interacts only through electro-weak interaction (i.e. the unified electromagnetic and weak interactions), and the spin 1/2 quarks; $u,d,c,s,t,b$, which interact electroweakly as well as through the colour force generated by gluons (G) (Ramond 1983). In other words, when $E \geq 10^2$ GeV ($s \leq 10^{-16}$ cm) corresponding to $T \geq 10^{15}$ K, the entire matter is converted into quark-gluon plasma permeated by leptons.

3. Experimental Evidence for Existence of QGP

It may be emphasized here that the notion of QGP is not just a theoretical speculation, or conjecture. There are positive indications of its existence as revealed by the series of experiments performed at CERN, the European Organization for Nuclear Research at Geneva, and at RHIC, the Relativistic Heavy Ion Collider, the world’s newest and largest particle accelerator for nuclear research, at Brookhaven National Laboratory in Upton, New York (Heinz 2001). Programmes to create QGP in terrestrial laboratories are already in progress at CERN and RHIC.

Recently, a team of 350 scientists from 20 countries almost succeeded in creating QGP at CERN by smashing together lead ions at temperatures $\sim 10^{12}$ K, and densities $\sim 20$ times that of nuclear matter. A report released by CERN on February 10, 2000 said, “A series of experiments using CERN’s lead beam have provided compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up in more complex particles such as protons and neutrons, are liberated to roam freely.”

On the other hand, RHIC’s goal is to create QGP by head-on collisions of two beams of gold ions at energies 10 times that of CERN’s, and densities 30 times that of nuclear matter, which is expected to produce QGP with higher temperature and longer lifetime, thereby allowing much clearer and direct observation. The programme at RHIC began in the summer of 2000, and later, Thomas Kirk, Brookhaven’s Associate Laboratory Director for High Energy Nuclear Physics, remarked, “It is too early to say that we have discovered the quark-gluon plasma, but not too early to mark the tantalizing hints of its existence.”

Later, on June 18, 2003 a special scientific colloquium was held at Brookhaven National Laboratory (BNL) to discuss the latest findings at RHIC. At the colloquium, it was announced that in the detector system known as STAR (Solenoidal Tracker at RHIC) a head-on collision between two beams of gold nuclei of energies of 130 GeV per nucleon resulted in the phenomenon called “jet quenching”. STAR as well as three other experiments at RHIC viz., PHENIX, BRAHMS, and PHOBOS, detected suppression of “leading particles”, highly energetic individual particles that emerge from nuclear fireballs, in gold-gold collisions. Jet quenching and leading particle suppression are signs of QGP formation. The findings of the STAR experiment were presented at the BNL colloquium by Berkeley Laboratory’s NSF (Nuclear Science Division) physicist Peter Jacobs.

However, the experimental evidence of the QGP is indirect and leaves much to be done to definitively confirm the existence of QGP. In view of this, CERN will start a new experiment ALICE, soon (around 2007-2008 at its Large Hadron Collider (LHC) in order to definitively and conclusively create QGP.

Obviously, the lack of complete success in creating QGP in terrestrial laboratories is due to the fact that these laboratories fall short of the threshold energy required for creating QGP. However, in the universe we have already naturally occurring
ultrahigh energy particle accelerators, as will be shown in section 5, in the form of gravitationally collapsing black holes, wherein not only this threshold of energy, but even much more can be reached.

4. Internal Dynamics of a Gravitationally Collapsing Black Hole

Attempts have been made, using the general theory of relativity (GTR), to understand what happens inside a gravitationally collapsing black hole. In doing so, various simplifying assumptions have been made. In the simplest treatment of Oppenheimer and Snyder (1939) a black hole is considered to be a ball of dust with negligible pressure, uniform density \( \rho = \rho(t) \), and at rest at \( t = 0 \). These assumptions lead to the unique solution of the Einstein field equations, and in the comoving co-ordinates the metric inside the black hole is given by

\[
\begin{align*}
  ds^2 &= dt^2 - R^2(t) \left[ \frac{dr^2}{1 - kr^2} + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2 \right] \\
  \text{in units in which } c, \text{ the speed of light in vacuum, is } 1, \text{ and where } k \text{ is a constant (Weinberg 1972a). The requirement of energy conservation implies that } \rho(t) R^3(t) \text{ remains constant. On normalizing the radial co-ordinate } r \text{ so as to have } R(0) = 1, \text{ on gets } \rho(t) = \rho(0) R^{-3}(t). \text{ Furthermore, since the fluid is assumed to be at rest at } t = 0, \text{ i.e., } \dot{R}(0) = 0, \text{ the field equations give } k = 8\pi G\rho(0)/3. \text{ Finally, the solution of the field equations is given by the parametric equations of a cycloid:}
  \\
  t &= \left( \frac{\psi + \sin \psi}{2 \sqrt{k}} \right) \\
  R &= \frac{1}{2} (1 + \cos \psi) \\
  \text{Equation (4) implies that when } \psi = \pi, \text{i.e. when}
  \\
  t &= t_s = \frac{\pi}{2 \sqrt{k}} = \frac{\pi}{2} \left( \frac{3}{8\pi G\rho(0)} \right)^{\frac{1}{2}} \\
  \text{a space time singularity occurs; the scale factor } R(t) \text{ vanishes. In other words, a black hole of uniform density having the initial value } \rho(0), \text{ and zero pressure collapses from rest to a point in 3-space, i.e., to a 3-subspace of infinite curvature and zero proper volume, in a finite time } t_s; \text{ the collapsed state being a state of infinite proper energy density.}

Actually, the internal dynamics of non-idealized, real black hole is very complex. Even in the case of a spherically symmetric collapsing black hole with non zero pressure the details of interior dynamics are not well understood, though major advances in the understanding are being made by means of numerical computations and analytic analyses. But in these computations and analyses no new features have emerged beyond those that occur in the simple uniform-density, free fall collapse considered above (Misner, Thorne, and Wheeler 1973). However, using topological methods Penrose (1965, 1969), Hawking (1966a, 1966b, 1967a, 1967b), Hawking and Penrose (1970), and Geroch (1966, 1967, 1968) have proved a number of singularity theorems purporting that if an object of mass \( M \) contracts to dimensions smaller than the gravitational radius \( r_g = 2GM/c^2 \), i.e., if it crosses the event horizon, and if other reasonable conditions — namely, validity of the GTR, positivity of energy, ubiquity of matter, and causality — are satisfied, its collapse to a singularity is inevitable. But the question is: Has the validity of the GTR been established experimentally in the case of strong fields? The answer is: Certainly not. Actually, the GTR has been experimentally verified only in the limiting case of weak fields. Moreover, it has been demonstrated theoretically that when curvatures exceed the critical value \( C_\kappa = 1/L_\kappa^4 \), where \( L_\kappa = (\hbar G/c^3)^{1/2} = 1.6 \times 10^{-53} \text{cm} \) corresponding to the critical density \( \rho_\kappa = 5 \times 10^{33} \text{gcm}^{-3} \), the GTR is no longer valid; quantum effects must enter the picture (Zeldovich and Novikov 1971). Therefore, it is clear that the GTR breaks down before a gravitationally collapsing object could collapse to a singularity. Consequently, the conclusion based on the GTR that any gravitationally collapsing object of mass greater than the Oppenheimer-Volkoff limit (~ 3M_\odot) in general, and a black hole in particular, collapses to a singularity need not be held sacrosanct, actually it may not be correct at all.

It may also be noted that while arriving at the singularity theorems attention has been focused mostly on the space-time geometry and geostromodynamics; matter has been tacitly treated as a classical fluid, remaining entirely unchanged structurally even on being crushed heavily during the gravitational collapse. This is not tenable. To begin with, when the density of matter in a collapsing object reaches the value \( \rho \sim 10^{17} \text{gcm}^{-3} \), the process of neutronization sets in; the electrons and protons in the object combine into neutrons through the reaction

\[
p + e^{-} = n + \nu_e
\]

The electron neutrinos \( \nu_e \) so produced escape from the object. During the gravitational contraction when the density reaches the value \( \rho \sim 10^{14} \text{gcm}^{-3} \), the object consists almost entirely of neutrons. Of course, enough electrons and protons must remain in the object so that Pauli’s exclusion principle prevents neutron beta decay

\[
n \rightarrow p + e^{-} + \bar{\nu}_e
\]

where \( \bar{\nu}_e \) is the electron antineutrino (Weinberg 1972b). Therefore, when a black hole collapses to a density \( \rho \sim 10^{14} \text{gcm}^{-3} \), it would consist almost entirely of neutrons apart from traces of protons and electrons. However, neutrons as well as protons and electrons are fermions, and as such they obey Pauli’s exclusion principle. If a black hole collapses to a singularity, i.e., to a point in 3-space, then all the neutrons in the black hole would be crammed into just two quantum states available at that point, one for spin up, and another for spin down neutron. This would violate Pauli’s exclusion principle according to which no more than one fermion of a given species can occupy any quantum state. So would be the case with the protons and the electrons in the black hole. Consequently, either Pauli’s exclusion principle would be violated, or a black hole would not collapse to a singularity in contravention to
Pauli’s exclusion principle. It may be recalled, however, that
Pauli’s exclusion principle has a profound theoretical basis, it
is a consequence of the microcausality in local quantum field
theory (Huang 1982). In addition to this, it has been experiment-
ally validated in the realms of atomic, subatomic, nuclear, and
subnuclear physics, both at low energies, and at high and ultra-
high energies. On the contrary, this is not the case with the GTR

5. Gravitationally Collapsing Black Hole: An
Ultrahigh Energy Particle Accelerator
For creating QGP we need an ultrahigh energy particle ac-
celerator which can accelerate particles to energies $E \geq 10^2 \text{ GeV}$
corresponding to temperatures $T \geq 10^{15} \text{ K}$. At present such an
accelerator does not exist in any terrestrial laboratory. But as
mentioned towards the end of section 3, the universe has such
ultrahigh energy particle accelerators in the form of gravita-
tionally collapsing black holes.

To see this we consider a gravitationally collapsing black
hole. On neglecting mutual interactions the energy $E$ of any
one of the particles comprising the black hole is given by
$E^2 = p^2 + m^2 > p^2$, in units in which the speed of light in vac-
cum, $c = 1$, and where $p$ is the magnitude of the 3-momentum of
the particle, and $m$ its mass. But $p = h/\lambda$, where $\lambda$ is the
de Broglie wavelength of the particle, and $h$ Planck’s constant
of action. Since all lengths in the collapsing black hole scale
down in proportion to the scale factor $R(t)$ in equation (2), it
is obvious that $\lambda \propto R(t)$. Therefore, $p \propto R^{-1}(t)$, and hence
$p = a R^{-1}(t)$, where $a$ is the constant of proportionality. This
implies that $E > a/R$. Consequently, $E$ as well as $p$ increases
continually as $R$ decreases. It is also obvious that $E$ and $p \to \infty
as R \to 0$. Thus, in effect, we have an ultrahigh energy particle
accelerator in the form of a gravitationally collapsing black
hole, which can, in the absence of any physical process inhib-
itng the collapse of the black hole to a singularity, accelerate
particles to an arbitrarily high energy and momentum without
any limit.

What has been concluded above can also be demonstrated
alternatively, without resorting to the GTR as follows. As an
object collapses under its selfgravitation, the interparticle dis-
tance $s$ between any pair of particles in the object decreases.
Obviously, the de Broglie wavelength $\lambda$ of any particle in the
object is less than, or equal to $s$, a simple consequence of
Heisenberg’s uncertainty principle. Therefore, $s \geq h/p$, where
$h$ is Planck constant of action, and $p$ the magnitude of the 3-
momentum of the particle. Consequently, $p \geq h/s$, and hence
$E \geq h/s$. Since during the collapse of the object $s$ decreases, the
energy $E$ as well as the momentum $p$ of each of the particles
in the object increases. Moreover, from $E \geq h/s$ and $p \geq h/s$ it
follows that $E$ and $p \to \infty$ as $s \to 0$. Thus, any gravitationally
collapsing object in general, and a black hole in particular, acts
as an ultrahigh energy particle accelerator.

It is also obvious that $\rho$, the density of matter in the black
hole, increases as it collapses. In fact, $\rho \propto R^{-3}$, and hence $\rho \to
\infty$ as $R \to 0$.

6. The End-Point and the End-product of a Black
Hole
If indeed a black hole collapses to a singularity, then the
most pertinent question is: What happens to a black hole af-

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possible, even if the passage of matter through infinite density is assumed.

A gravitationally collapsing black hole may also explode by the very same mechanism by which the big bang occurred in the universe, if indeed it did occur. This can be seen as follows. At the present epoch the volume of the universe is $\sim 1.5 \times 10^{85} \text{cm}^3$ and the density of the galactic material through out the universe is $\sim 2 \times 10^{-31} \text{gcm}^{-3}$ (Allen 1973). Hence a conservative estimate of the mass of the universe is $\sim 1.5 \times 10^{85} \times 2 \times 10^{-31} \text{g} = 3 \times 10^{53} \text{g}$ (actually it would be much more if the mass of the intergalactic matter as well as that of the dark matter in the universe is taken in to account).

However, according to Gamow’s big bang model, before the big bang, the entire matter in the universe was contained in the ylem which occupied very very small volume. The gravitational radius of the ylem of mass $3 \times 10^{54} \text{g}$ was $4.45 \times 10^{21} \text{km}$ (it would be much larger if the actual mass of the universe were taken into account which is greater than $3 \times 10^{54} \text{g}$ ). Obviously, the radius of the ylem was many order of magnitude smaller than its gravitational radius, and yet the ylem exploded with a big bang, and in due course of time, its expanding matter crossed the event horizon and expanded beyond it up to the present Hubble distance $c/H_0 \sim 1.5 \times 10^{23} \text{km}$ where $c$ is the speed of light in vacuum and $H_0$ the Hubble constant at the present epoch. Consequently, if the ylem could explode and its matter could cross the event horizon and expand beyond it in spite of Zeldovich and Novikov’s assertion to the contrary, why can’t a gravitationally collapsing black hole also explode, and much of the matter in it expand beyond the event horizon in due course of time ? However, the mechanism by which the ylem exploded is not definitively known and as such the mechanism by which a black hole would explode before collapsing to purported singularity is also not known.

Another way of looking at the problem is the following. It may not be unreasonable to assume that, during the gravitational collapse, the outward pressure $P$ inside a gravitationally collapsing black hole increases monotonically with the increase in the density of matter, $\rho$. Actually, it may be given by the polytrope, $P = K \rho^{n+1}$, where $K$ is a constant and $n$ is the polytropic index. Consequently, $P \to \infty$ as $\rho \to \infty$, i.e. $P \to \infty$ as the scale factor $R(t) \to 0$ ( or, equivalently $s \to 0$ ). In view of this, during the gravitational collapse of a black hole, at a certain stage when the density of matter $\rho = \rho_c$, the outward pressure $P = K \rho_c^{n+1}$, inside the black hole may be large enough to withstand the inward gravitational force, and the object may become gravitationally stable and thus end up as a stable quark star since it consists of quarks, gluons and leptons.

This scenario also explains the absence of a large number of black holes in the universe. In principle, like white dwarfs and neutron stars, there should be quite a large number of black holes in every galaxy. White dwarfs and neutron stars are the end products in the sequence of evolution of stars with mass less than the Chandrasekhar and the Oppenheimer-Volkoff limits respectively whereas black holes are the end products in the sequence of evolution of stars with mass more than the Oppenheimer-Volkoff limit. Therefore, there should not be an inequable distribution of black holes in the universe in general, and in any galaxy in particular. But contrary to this expectation, very few black holes have been observed. Though black holes cannot be observed directly, they would manifest their presence by the strong gravitational fields produced by them in their vicinity which would bend the ray of light appreciably, and perturb the motion of the celestial bodies passing by, or in its vicinity, but outside the event horizon.

Of course, an alternative possibility is the generally held view that a black hole finally collapses to a singularity. If this is true, then this presents an evidence of the violation of Pauli’s exclusion principle.

7. Conclusion

A gravitationally collapsing black hole acts as an ultrahigh energy particle accelerator that can accelerate particles comprising the matter in the black hole to inconceivably high energies. During the continual acceleration of particles, as a result of the continual gravitational collapse of the black hole, a stage will be reached when the energy of the particles $E \sim 10^2 \text{ GeV}$ corresponding to the temperature $T \sim 10^{15} \text{ K}$. At this stage the entire matter in the black hole will be converted into quark-gluon plasma permeated by leptons. With further collapse one of the two possibilities will occur, either Pauli’s exclusion principle would be violated and the black hole would eventually collapse to a singularity, or Pauli’s exclusion principle would hold good and would avert the collapse of the black hole to a singularity, and eventually the black hole would explode with a mini bang of a sort. Finally, the remnant core would stabilize as a quark star.

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