On the Nature of the Compact Objects in the AGNs

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If the cores of Galaxies and AGNs comprise Supermassive Stars (SMSs) (Hoyle and Fowler 1963), nuclear energy generation may not be ignited for masses \( M > 6 \times 10^4 M_\odot \), and highly supermassive stars are likely to generate their luminosity, \( L_{KH} \), slow gravitational contraction. We show that for such massive Newtonian SMSs, both the value of \( L_{KH} \) and the the accretion luminosity, \( L_{acc} \), could be much less than the appropriate Eddington value. Such highly SMSs will have a surface density as low as \( 10^{-14} \text{ g/cm}^3 \) and they will not behave like a compact object with a “hard surface”. For all such reasons, it is indeed possible to have \( L_{SMS} \ll L_{ed} \). And this effect may be incorrectly interpreted as the evidence for the existence of central Super Massive Black Holes with Event Horizons.

In fact, in a very detailed work, and from various angles, we have recently shown that, the General Theory of Relativity does not permit the occurrence of “trapped surfaces” and Black Holes (Mitra 1998a, gr-qc/9810038).

I. INTRODUCTION

One of the cornerstones of modern physics and astronomy is the idea of the Black Holes (BH) in which everything can enter but from which nothing can come out, at least at the classical level. Black holes are supposed to exist as the compact object in many X-ray binaries, in the center of core collapsed star clusters and in the core of the socalled Active Galactic Nuclei (AGN) as well as in the core of many normal galaxies, like the Milky way. They may exist in isolation too, but it is difficult to detect such isolated BHs. In this work, we will focus attention on the supposed Galactic core BHs. Despite such popular notions, it is simultaneously acknowledged that most of the evidences for the existence of BHs are highly circumstantial, and, what one observes is actually Massive Compact Dark Objects (MCDO). For instance, it is widely believed that the center of our galaxy harbors a BH of mass \( M \sim 10^6 M_\odot \) having a radius \( R_{BH} \sim 3 \times 10^{11} \text{ cm} \). But actually the spatial resolution with which we can scan this region is \( \sim 0.1 \text{ pc} \sim 3 \times 10^{17} \text{ cm} \sim 10^6 R_{BH} \), and thus, as such, we can rule out the possibility that the core may actually comprise densely packed X-ray binaries, Wolf-Rayet stars or other massive stellar cores. In the course of time such objects might also form a single self-gravitating entity called Super Massive Star (SMS, Hoyle and Fowler 1963). The same is true for the AGNs too although the intraday variabilities observed in many AGNs would yield a tighter limit on the core size \( R < 10^{15} \text{ cm} \) (however, note that the estimates of core masses are in general uncertain at least by a factor of \( \sim 10^2 \)).

Even if such cores are accepted to be massive BHs, they are likely to have been formed by a preceding phase as SMSs (Begelman and Rees 1978). Thus at a given epoch, many such cores must be SMSs. It is believed that the unassailable evidence in favor of BHs and their Event Horizons arise from the fact that accretion luminosity \( (L_{acc}) \) from many AGNs or galactic cores is insignificantly compared to the corresponding Eddington values \( (L_{acc} \ll L_{ed}) \). This could be so because for weak or excessively high accretion rates, the flow could be advection dominated with small radiative efficiency. As a result, for spherical accretion, not mediated by a disk, most of the accreted energy and mass will be lost inside the event horizon. However, without (first) entering into a debate on the possible existence BHs, we will show below that for SMSs too it is possible to have \( L_{acc} \ll L_{ed} \). Thus Super Massive Stars too may emulate the Mass-Energy gobbling properties of a BH.

II. SUPERMASSIVE STARS

A SMS is supported almost entirely by its radiation pressure

\[
p_r = \frac{1}{3} a T^4
\]

where \( a \) is the radiation constant. On the other hand, by assuming the plasma to be made of hydrogen only, the matter pressure is given by

\[
p_m = nkT
\]
where \( k \) is the Boltzmann constant and \( n \) is the proton number density. The structure of a Newtonian SMS is closely given by a polytrope of index 3, and the ratio of matter pressure to gas pressure works out to be (Weinberg 1972):

\[
\beta = \frac{p_m}{p_g} \approx 8.3 \left( \frac{M}{M_\odot} \right)^{-1/2} = 8.3 \times 10^{-4} M_8^{-1/2}
\]

(3)

where \( M = M_8 10^8 M_\odot \). This shows that a SMS should have a minimum mass \( \sim 7200 M_\odot \) (Weinberg 1972) in order to have a value of \( \beta < 0.1 \). A Newtonian SMS may be defined as one for which the rest mass energy density of the plasma dominates over the radiation energy density even though \( p_m \ll p_r \), i.e., \( m_p n c^2 \gg 3 p_r \). It then follows that, the \textit{“compactness”} of a Newtonian SMS is very small (Weinberg 1972):

\[
\frac{2GM}{Rc^2} \ll 0.78
\]

(4)

In other words the surface red-shift of a Newtonian SMS is very small

\[
z = \left( 1 - \frac{2GM}{Rc^2} \right)^{1/2} - 1 \ll 0.39
\]

(5)

In this limit of small \( z \), we can approximate \( z \approx GM/Rc^2 \). Most of the stable (Newtonian) SMSs are likely to have \( 10^{-4} < z < 10^{-2} \) (Shapiro & Teukolsky 1983). However, it is also possible to have real compact \textit{Relativistic SMSs} with high values of \( z \approx 1 \) for which \textit{radiation dominates even in the energy budget}. Such Relativistic SMSs may be described by a relativistic polytrope of degree 3 (Tooper 1964). But, in this work we shall discuss the case of Newtonian SMSs only.

If a SMS is in \textit{hydrostatic equilibrium}, its luminosity is close to the corresponding Eddington value:

\[
L = (1 - \beta) \frac{4\pi cGM}{\kappa} \approx 1.26 \times 10^{46} M_8 \text{ erg/s}
\]

(6)

where \( \kappa \) is the Thompson opacity. And as is well known, this fact was one of the basic reasons behind hypothesizing that the quasars could be powered by SMSs (Hoyle and Fowler 1963). Note, the hydrostatic equilibrium must be effected by the release of energy by nuclear fusion at the center. But the efficiency for energy generation by hydrogen fusion is only \( \sim 0.7\% \), and given Eddington limited accretion rate, the fusion process can not deliver the necessary luminosity for massive SMSs. In fact, it is difficult to conceive of nuclear-fuel supported SMS for \( M > 6 \times 10^4 M_\odot \) (Shapiro & Teukolsky 1983). Thus, \textit{more massive SMSs are not in hydrostatic equilibrium and must be undergoing slow gravitational contraction}.

### III. HIGHLY SUPERMASSIVE STARS (HSMS)

Now we shall estimate the luminosity of Newtonian HSMS releasing energy by the Kelvin-Helmholtz process and for which nuclear energy generation is insignificant: First note that, the effective adiabatic index of a pure H-SMS is given by (Weinberg 1972)

\[
\gamma \approx \frac{4}{3} + \frac{\beta}{81}
\]

(7)

Then the Virial Theorem looks like

\[
E_{in} + 3(\gamma - 1)E_g = 0; \quad \text{or}, \quad E_{in} + (1 + \beta/27)E_g = 0
\]

(8)

where \( E_{in} \) is the total internal energy and \( E_g \) is the self-gravitational energy. On the other hand, the Newtonian total energy of the star (polytrope of index 3) is

\[
E_N = E_{in} + E_g = -\frac{\beta}{27} |E_g| = -\frac{\beta GM^2}{18R}
\]

(9)

The K-H contraction luminosity is then given by

\[
L_{KH} = \frac{dE_N}{dt} \approx \frac{\beta GM^2}{18R^2} v
\]

(10)
where \( v \ll c \) is the rate of slow contraction. In the limit of small \( z \), by using Eqs. (3) and (5), the above expression can be rewritten in a physically significant manner:

\[
L_{KH} = \frac{\beta z^2 c^4 v}{18G} \approx 8.3 \times 10^{-4} \frac{z^2 c^4}{v^2} M_8^{-1/2} \sim 6.25 \times 10^{38} z_3^2 v M_8^{-1/2} \text{ erg/s} \tag{11}
\]

where \( z = z_3 10^{-3} \). By comparing this pure gravitational contraction luminosity with the corresponding Eddington value, we find that

\[
\frac{L_{KH}}{L_{ed}} \sim 5 \times 10^{-8} z_3^2 v M_8^{-3/2} \tag{12}
\]

Here, we emphasize that, the fact that the system is out of hydrodynamical equilibrium need not mean the system is undergoing free fall, and the value of \( v \) could be much smaller than the corresponding free fall speed \( v_{ff} \approx \sqrt{2zc} \).

The KH contraction may continue for thousand of years and the value of \( v \) could be as low as few \( \text{km/s} \) for the initial phase. Then we have

\[
\frac{L_{KH}}{L_{ed}} \sim 5 \times 10^{-3} z_3^2 v_1 M_8^{-3/2} \tag{13}
\]

where \( v = v_1 1 \text{Km/s} \). Thus the intrinsic KH luminosity of a HSMS could be insignificant compared to the expected Eddington luminosity.

### IV. ACCRETION LUMINOSITY

We have recently shown that the GTR expression for accretion luminosity from a “hard surface” (Mitra 1998b) is

\[
L_{acc} = \frac{z}{1+z} \dot{M} c^2 \approx z \dot{M} c^2 \ll L_{ed}; \quad \text{if, } z \ll 1 \tag{14}
\]

In the limit of small \( z \) the above general formula obviously yield the Newtonian formula : \( L_{acc} = \frac{GM\dot{M}}{\mathcal{R}} \). In this case, the accretion efficiency \( \dot{z} \) could be much smaller compared to the corresponding value of disk accretion onto a Schwarzschild BH, \( \sim 5.7\% \). Further, the actual accretion efficiency could be much smaller than what is indicated by Eq. because a HSMS does not really have a “hard surface”.

### V. HARD SURFACE ?

The mean baryonic density of a SMS is

\[
\bar{\rho} = \frac{M}{(4\pi/3) \mathcal{R}^3} = \frac{3z^3 G^6}{4 \pi G^3 \mathcal{R}^2} \sim 10^{-13} z_3^3 M_8^{-2} \text{ g/cm}^3 \tag{15}
\]

And for a polytrope of index 3, the density of the external layers is atleast one order smaller:

\[
\bar{\rho}_{ex} \sim 10^{-14} z_3^3 M_8^{-2} \text{ g/cm}^3 \tag{16}
\]

With the low luminosity inferred above, it may be found that, the temperatures of these layers could be \( < 1eV \), and the gas is actually partially ionized (heavy elements would be almost completely neutral) !

Then an incident electron of energy \( \sim 0.5z MeV \) or a proton of energy \( \sim z GeV \) would primarily undergo low energy ionization/nuclear losses. Even otherwise, at such low densities, the test particle may penetrate deep inside the HSMS and any photon that it might emit may be trapped in the general soup of photon and plasma. Thus it is possible that \( L_{acc} \ll L_{ed} \).

And this may be mistaken as an evidence in favor of the existence of an Event Horizon!!
VI. DISCUSSION

In this preliminary work we have outlined that Highly Supermassive stars with low values of compactness, $z$, are likely to undergo slow Kelvin-Helmoltz conflation. The resultant luminosity arising from either this conflation process or accretion of surrounding gas clouds, are likely to yield a luminosity which is insignificant compared to the corresponding Eddington value. And given such an observational result, in the absence of a serious consideration of the physics of the HSMSs, one might be tempted to describe the result as “Experimental Discovery of Black Holes”.

On the other hand, in the relativistic regime (not described here), the Supermassive stars may be very compact $z < 0.615$ and have central temperatures well above $T_c > 10^9$ K. The gravitational conflation luminosity of such stars may be released in the form of neutrinos. Such compact stars will possess a “hard surface” and their accretion luminosity could be comparable to the corresponding Eddington value.

In the context of suspected stellar mass BHs, it may be reminded that it might be possible to have novel kind of hadronic stars, called, Q-stars whose value could be as high as $> 100 M_{\odot}$ (Bachall et al. 1989, Miller et al. 1998). Further, Q-stars may be formed at sub-nuclear densities and depending on the uncertain model QCD parameters, have a wide range of $1 < z < 1$. In case, $z < 1$, one would have $L_{acc} \ll L_{Ed}$, and again this may be mistaken as an evidence for an “event horizon”.

Finally, in a very detailed work (Mitra 1998b, gr-qc/9810038), we have shown from all possible angles that BHs neither form in gravitational collapse of baryonic matter, nor can they be assumed to exist, in general. The only exact solution of Einstein eq. which (apparently) shows the production of BHs in spherical collapse is due to Oppenheimer and Snyder (1939, OS). As is well known, they (apparently) showed that the collapse of a homogeneous dust of mass $M$ gives rise to a BH of same mass in a proper time $\tau \propto M^{-1/2}$. However, what they overlooked in this historical paper is that the Schwarzschild time $t$ is related by a relation of the kind (see Eq. 36 of OS):

$$t \sim \ln \frac{y^{1/2} + 1}{y^{1/2} - 1}, \quad y \sim \frac{Rc^2}{2GM}$$

In order that $t$ is a real quantity in the above expression, one must have

$$y^{1/2} > 1; \quad or, \quad \frac{2GM}{Rc^2} < 1$$

Then in order to reach the central singularity, one must have

$$M \to 0; \quad as \ R \to 0; \quad so \ that \ \tau \propto M^{-1/2} \to \infty$$

This means that the BH is never produced and even if it would be produced its mass must be zero! We have then proved this result in a most general fashion for an inhomogeneous dust as well as for a perfect fluid having arbitrary EOS and radiative property (Mitra 1998a, gr-qc/9810038).

Thus we may say that whether the cores of galaxies are SMSs or not, they are certainly not BHs.

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