MINI-BLACK-HOLES ARE FORMING NOW

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I. The New Concept

Gravitational collapse to physical singularities is an unambiguous consequence of the classical theory of general relativity [1]. In the past two decades, the black holes resulting from this process have been subjected to intense scrutiny by theoretical relativistic astrophysicists and observational astronomers. Almost without exception [2], the context of these studies has been either (a) objects of stellar mass, (b) super-massive "collapsars" in galactic nuclei, or (c) big-bang cosmology.

Only recently has Hawking [3] introduced the concept of a mini-black-hole: a black hole whose mass is substantially smaller than that of our Sun. Moreover, Hawking [4] has also demonstrated the surprising fact, that all Schwarzschild black holes must lose mass by "quantum evaporation". This latter effect is critically important for mini-black-holes in the mass range 10^{-5} gram to 10^{15} grams. Though Hawking's quantum evaporation effect was challenged when it first appeared, the reality of the mechanism is now generally accepted by all workers in the field [5-7].

Strong arguments have been advanced [2, 3, 8-9] to restrict the epoch of formation of mini-black-holes to the very early stages of big-bang cosmology. The implication is that it is virtually impossible to form a mini-black-hole today.

In this essay we will contend that mini-black-holes are forming today in the centers of some stellar-mass objects. Three possible formation mechanisms are presented in the next section, followed by a brief discussion of the consequences of the newly-formed mini-black-holes. We end with a few of the observational implications of our hypothesis.

II. Modes Of Formation

Consider an isolated, spherical, neutron star near the Landau-Oppenheimer-Volkoff mass limit. Suppose that the star slowly accretes matter. As the stellar mass increases, a "pressure-and-density spike" will begin to develop at the star's center [10-11]. The "spike" radius decreases, and the central density increases without bound, as the LOV mass limit is approached. Were the neutron star to exceed the LOV limit, then the entire star would undergo dynamical gravitational collapse to form a stellar-mass black hole [10]. However, just prior to this stage three new physical effects become possible (we do not yet know which one dominates), which can drastically alter the further evolution of the star.

All three mechanisms depend critically upon the existence of the growing "central density spike", and all three lead to the same outcome: the formation of a mini-black-hole at the star's center.

The simplest mechanism is the following: Let r denote the standard Schwarzschild radial coordinate, while $\rho(r)$ is the density of mass-energy at r. The mass interior to r is just

$$m(r) = 4\pi \int_0^r r^2 \rho(r) dr \qquad (2.1)$$

Therefore, at each r we may compute a "formal Schwarzschild radius"

$$R_S(r) = 2Gm(r)/c^2 \qquad (2.2)$$

A static star which has not become a black hole must satisfy $R_S(r) < r$ everywhere inside the star. In the past, it has been implicitly assumed that $R_S(r)$ would first exceed r at the star's surface, so that the entire star becomes a black hole. However, there exist "density profiles", $\rho(r)$, for which the stellar core first enters its own horizon while the remainder (outer parts) of the star is outside this horizon; the "density spike" mentioned above is just such a profile! Therefore, the tiny core of our neutron star will collapse to a mini-black-hole, leaving the rest of the star "outside the horizon".

The second mechanism is more subtle. In the same scenario as above, focus attention upon the elementary particles present in the "density spike". Suppose that the neutron Fermi energy just exceeds the rest-mass energy of a pi meson ($\approx$ 140 MeV), so that pions are abundant in the stellar core. Sufficiently "cold" pions will undergo Bose condensation in energy space. But Ruffini and Bonazzola [11] have shown that approximately 10^{40} degenerate pions constitutes a self-gravitating "critical mass". Therefore, we again expect a core of mass $\lesssim 10^{15}$ grams to collapse to a mini-black-hole. (Note that if the pions do not inaugurate the core collapse, then it is still possible as successively-higher-mass species of bosons arise with increasing central density in the neutron star.)

The most speculative mechanism of all is the third: Following Harrison et al [10], we note that an "energy barrier" to gravitational collapse exists in the stellar core. When account is not taken of the "density spike" at the center of the neutron star, the probability for some mass there to quantum-mechanically tunnel through the barrier to a black-hole state is negligible. However, the growing "density spike" rapidly raises that probability to a significant value, and we can expect such tunnelling to occur--leading to the formation of a central mini-black-hole of very small mass!

III. Quantum Consequences

Hereafter we assume that a mini-black-hole (mass $\lesssim 10^{15}$ grams) has formed at the center of the neutron star, and we investigate the interaction of the mini-black-hole with its environment.

For simplicity, we consider a spherical (Schwarzschild) mini-black-hole. Our uncertainties concerning quantum gravitation dictate that its initial mass be greater than 10^{-5} gram (the Planck mass). The horizon radius of the collapsed core is given by

$$R_S(\text{core}) \sim (1.5 \times 10^{-13}\text{cm})(M/10^{15}\text{gm}), \quad (3.1)$$

so that our exotic mini-black-hole is smaller than about a Fermi. Hence, our discussion must necessarily involve quantum-mechanical effects and second-quantized field theory for the matter fields present. Therefore, it is perfectly natural that Hawking's [4] "quantum evaporation" process will be important for the mini-black-hole.

In the broadest sense, two physical processes dominate the behavior of the mini-black-hole and its immediate environs: (1) the "Hawking evaporation" of the mini-black-hole and (2) accretion of mass-energy onto the mini-black-hole from the surrounding stellar core. Due to "quantum evaporation" [2, 4-9], a black hole radiates as a blackbody of effective temperature

$$T = \hbar c^3/8\pi k GM \approx 10^{11}K\ (10^{15}gm/M), \qquad (3.2)$$

so that the characteristic energy of the radiation is

$$kT \approx 10MeV\ (10^{15}gm/M)\ . \qquad (3.3)$$

Since the hole's luminosity is

$$L \approx 9\hbar c^6/10\pi(64)^2G^2M^2 \approx (10^{16}erg\ sec^{-1})(10^{15}gm/M)^2\ , \qquad (3.4)$$

the lifetime for total quantum evaporation of the hole becomes

$$\tau \approx (2.5 \times 10^{19}\ sec)(M/10^{15}gm)^3 \qquad (3.5)$$

Equation (3.5) indicates that τ approximates the current age of the Universe for $M \approx 2 \times 10^{14}gm$.

Accretion by the mini-black-hole can counter the mass loss associated with Equation (3.4). Unfortunately, research into the properties of black-hole accretion has been sparse [2, 8, 12-14] --- and, certainly, none of the results apply in our present context. An indication of what might occur is provided by the following simplistic scenario: Suppose that the luminosity of the mini-black-hole --- Equation (3.4) --- corresponds to the "Eddington luminosity" needed to regulate the accretion rate, so that the hole's mass M neither increases nor decreases in time. Then we can easily demonstrate that the hole's mass must assume the critical value

$$M_{critical} \approx (5.4 \times 10^{13}gm)[(\sigma/\sigma_o)/(m/m_n)]^{1/3}\ , \qquad (3.6)$$

where σ is the interaction cross-section of the hole's radiation with each particle in the accretion flow, σ_o is the classical Thomson scattering cross-section (photon-electron), m is a representative mass per accreting particle, and m_n is the mass of a nucleon. Equations (3.4) and (3.6) imply that the mini-black-hole is consuming the star's mass at the rate:

$$-\dot{M}_{star} \approx 3.8 \times 10^{-3}gm\ sec^{-1}\ . \qquad (3.7)$$

However, Equation (3.7) must be a lower limit to the consumption rate, since Equation (3.3) implies that nuclear cross-sections pertain ($\sigma \ll \sigma_o$); nonetheless, it appears difficult to increase the mass-loss-rate much above a few grams per second in this model.

Rather than dwelling upon our gross ignorance concerning mini-black-hole accretion at the center of a neutron star, let us outline the possible modes of evolution of our system. (i) When accretion exceeds the hole's radiation-mass-loss, and the hole's mass increases beyond $\approx 10^{15}$ gm, we have essentially a classical black hole slowly absorbing the star's mass at its center [2, 12-13]. Eventually, the entire star becomes a stellar-mass black hole. (ii) If the initial mini-black-hole has very little mass ($M \ll 10^{15}$gm), and the accretion rate cannot keep up with Equation (3.4), then the mini-black-hole will "burn up" and rapidly disappear --- leaving the star's core virtually as it was in the beginning, with the possibility that another mini-black-hole could form in the future. (iii) Finally, it is probable that Equation (3.6) is completely inapplicable, and that a very-low-mass mini-black-hole could be in quasi-equilibrium with the accretion rate. (Note: The stability of this situation is difficult to ascertain.) As an extreme example, consider a Plank hole with $M \approx 10^{-5}$ gm. Then Equation (3.4) yields a mass consumption rate of $\approx 56 M_\odot$ sec^{-1}! Since the dynamical response (i.e., free-fall) time for a neutron star is measured in milli-seconds, the entire star can be consumed by the central mini-black-hole in less than a second --- being converted into a short burst of very-high-energy radiation with a total energy content of approximately 10^{55} ergs!

IV. Astrophysical Implications

Our simple suggestion of "contemporary formation of mini-black-holes" is amazingly rich in its implications for astrophysics. We have room to mention only a few of the possibilities here. It will be abundantly clear that much more study and research is indicated in this field.

For example, such mini-black-holes may prevent the occurrence of stellar-mass black holes. Suppose a condensed object is more massive than the limit for stability against incipient collapse to a black-hole end-state. A mini-black-hole would form at its center, supply the energy needed to maintain the object in a slightly-expanded state (to preclude the collapse), and inevitably consume enough mass to gently carry the object below the requisite mass limit. Then the mini-black-hole would "snuff out" as the accretion rate onto it became inadequate to counter its quantum evaporation.

A similar---but more exotic---possibility occurs when a mini-black-hole appears in a neutron star near the LOV limit. When the hole's mass is small enough, it liberates so much energy that the entire neutron star is heated to the point where it becomes non-degenerate. Beta decay takes place, the star expands, and a hot white dwarf is the result!

Case (iii) of the preceding section suggests the intriguing possibility that the mini-black-hole could act as the trigger and energy source for a supernova explosion. The surface layers of the star would be expelled violently, that material would undergo extensive nuclear processing, and a plethora of ultra-high-energy particles (cosmic rays?) would certainly be liberated.

Finally, our mini-black-holes provide a natural--albeit, unusual---explanation for the observed gamma-ray bursts [15]. The scenario follows: A mini-black-hole forms in the center of a "neutron star". In the hole's radiation are numerous neutrinos and anti-neutrinos which penetrate much of the star to deposit their energy near the stellar surface [16], heating it to approximately 10^{10}K---thus is produced the gamma-ray "precursor". Meanwhile, the hole's intense radiation has heated its environs, so that a thermal "pulse" is propagating from the star's central regions, the accretion onto the hole is quenched, and the mini-black-hole "burns out". After a thermal time scale in the core, another mini-black-hole forms to repeat the process; several such repetitions yield the main gamma-ray burst. Finally, the star's interior is too hot for the further formation of mini-black-holes (except, perhaps, sporadically), and this activity ceases. It is useful to note that the spectrum of gamma-radiation so produced is consistent with the observations [17]...as are the time scales of the burst sub-structure! (In this context, we are impelled to remark upon the fascinating similarities in structure exhibited by a typical gamma-ray burst and by the electron-anti-neutrino, $\bar{\nu}_e$, burst detected by Lande et al [18]. The latter phenomenon is, of course, an obvious consequence of the model which we have just described.)

V. Summary

We have advanced the novel suggestion that mini-black-holes can form in the cores of highly-condensed stellar objects. A sketch of possible modes of formation was followed by a brief discussion of the interaction and evolution of such a mini-black-hole in its exotic environment. Finally, some of the astrophysical consequences of such mini-black-holes were presented; the most interesting possibility was that this hypothesis might well provide a simple explanation of the observed gamma-ray bursts. The hypothesis is rich in consequences, and deserves further study.

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SUMMARY/ABSTRACT

It has been thought that mini-black-holes could only be formed in the very early stages of a big-bang universe. We show how they can be forming today in the cores of condensed, stellar-mass objects. The unique interactions of such "contemporary mini-black-holes" with their environment, their courses of evolution, and their astrophysical implications are then described briefly. These latter effects are critically dependent upon the existence of Hawking's "quantum evaporation" process for black holes. A rich and challenging new field---mini-black-hole physics---is thereby introduced.

BIOGRAPHICAL SKETCHES

Kenneth Charles Jacobs was born in McAllen, Texas, on 17 September 1942. He attended the Massachusetts Institute of Technology on a National Merit Scholarship to earn his B.S. degree in Physics from September 1960 to June 1964. Graduate study at the California Institute of Technology produced his Ph.D. degree in Relativistic Cosmology in June 1969. Following two years of postdoctoral research at the University of Maryland, he assumed his present post---Assistant Professor of Astronomy---at the University of Virginia, Charlottesville, Virginia in late-1970.

Mr. Jacobs' research in relativity theory and astrophysics has also taken place in Munich, Germany; Cambridge, England; and Groningen, Holland. He has published fifteen scientific papers and three books. His background and interests are broad; his hobbies include tennis, the stock market, linguistics, and his wife, Bonnie, who joined him in mid-1968.

Patrick Osborne Seitzer was born 9 December 1952 at Saitama-ken, Honshu, Japan. His undergraduate education at Georgetown University in Washington, D.C.,from September 1970 to May 1974, yielded his B.S. degree in Physics. After three months of active duty in the Army at Fort Gordon, Georgia, he became a graduate student in the Astronomy Department at the University of Virginia in January 1975.

Mr. Seitzer plans to earn his Ph.D. degree in Astronomy by mid-1979, after which his fondest hope is to "become employed". His hobbies include sailing, hiking, model railroading, and amateur (ham) radio operations.