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Authors

Shi, X
Fuller, GM
Halzen, F

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Observing the Birth of Supermassive Black Holes with the Planned ICECUBE Neutrino Detector

Xiangdong Shi and George M. Fuller

Department of Physics, University of California, San Diego, La Jolla, California 92093-0319

Francis Halzen

Department of Physics, University of Wisconsin, Madison, Wisconsin 53705

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It has been suggested that the supermassive black holes, at the centers of galaxies and quasars, may initially form in single collapses of relativistic star clusters or supermassive stars built up during the evolution of dense star clusters. We show that it may be possible for ICECUBE (a planned 1 km^3 neutrino detector in Antarctica) to detect the neutrino bursts associated with those collapses at redshift $z \lesssim 0.2$ with a rate of ~ 0.1 – 1 burst per year. Such detections could give new insights into the formation of structure in the Universe, especially when correlated with gravitational wave signatures or even gamma-ray bursts. [S0031-9007(98)07918-6]

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In this Letter we describe a possible means for detecting the neutrino bursts accompanying the formation of supermassive black holes at cosmological distances. (Hereafter the term “supermassive” implies a mass $\gtrsim 3 \times 10^4 M_\odot$.) Mounting evidence suggests that supermassive black holes are fairly common in the Universe. Observations with the Hubble Space Telescope point to supermassive black holes in nearly every galaxy examined so far [1]. Likewise, supermassive black holes have long been thought to be the central engines of quasars and active galactic nuclei (AGN) [2]. The masses inferred for these black holes typically range from $\sim 10^6 M_\odot$ (as in our galaxy) to $\sim 10^9 M_\odot$ (as in some quasars). It is conceivable that every galaxy, large or small, harbors a supermassive black hole at its center. In other words, supermassive black holes may have an abundance of one per $10^{10} M_\odot$ (baryon mass) object, the typical baryon content of dwarf galaxies such as M32. Such a conjecture is entirely consistent with observations if, like those nearby ones, most galactic nuclei are inactive [3].

How these supermassive black holes were formed is still a mystery. However, a natural formation route is through accretion onto a seed black hole. The seed black hole presumably must be formed earlier from the collapse of a single object or a cluster of objects. It is likely that these seed black holes were themselves supermassive, having masses perhaps only an order of magnitude or two below that of the current end-state black holes. This is because it would be very difficult for a much smaller seed black hole, such as that resulting from an ordinary solar-mass-scale stellar collapse, to accrete material efficiently enough so as to reach a supermassive mass scale in a Hubble time at an early epoch [4,5].

It has been suggested that the supermassive seed black holes may form from collapses of dense star clusters or supermassive stars that were built up as an intermediate phase during the final evolutionary stage of collapsing star clusters [6]. Dense star clusters have been observed to

reside at the center of galaxies [7], and in general have been invoked to explain AGN activities [8,9]. The formation of an intermediate-stage supermassive star has been argued to be on several of the possible evolution routes of collapsing star clusters [6].

A supermassive star with mass $M \gtrsim 3 \times 10^4 M_\odot$ is an index $n = 3$ polytropic configuration with a high entropy per baryon $S \approx 300(M/10^5 M_\odot)^{1/2}$ (in units of Boltzmann’s constant) [10]. A supermassive star eventually collapses into a black hole as a result of the Feynman-Chandrasekhar [11] instability. Numerical calculations have also shown that a dense star cluster of compact objects would eventually collapse as a result of the Feynman-Chandrasekhar instability just as would a single supermassive object [12].

If a supermassive black hole formed as a result of a single collapse, whether from a single supermassive star or a supermassive relativistic cluster of compact objects, we would expect the collapse to be accompanied by a burst of thermally produced neutrinos. The neutrino emission would carry away a significant fraction of the gravitational binding energy of the collapse, which is of order the rest mass energy of the homologous core, $\sim 10^{59} M_5^{\text{HC}} \text{ erg}$ (where homologous core mass, denoted by $(10^5 M_\odot) M_5^{\text{HC}}$, is the mass that plunges through the event horizon as a unit). The homologous core mass M_5^{HC} is only a fraction of the initial stellar mass $M_5^{\text{init}} \equiv M^{\text{init}}/10^5 M_\odot$, with the fraction determined by the entropy loss during the collapse [13]. This fraction is roughly $\sim 10\%$ for a nonrotational and nonmagnetized spherical supermassive star of $M_5^{\text{init}} \sim 10$.

If the homologous core is massive enough (namely, $M_5^{\text{HC}} \gtrsim 0.1$), it will be transparent to neutrinos [13]. This is in stark contrast to the case of an ordinary core collapse supernova, where the neutrinos are trapped in the core. Since in our case the collapsing material will be essentially in free fall, we should have a set of well

defined neutrino luminosity/time templates with which to compare to observations. Such time templates of neutrino luminosity have a characteristic gradual rise followed by a sudden drop due to the core becoming a black hole. Figure 1 shows an example of such a time profile for the (unnormalized) neutrino luminosity, and the time profile of the corresponding (unnormalized) signal in ICECUBE. The duration of the neutrino burst is typically $\lesssim t_{\text{dyn}}$, where t_{dyn} is the dynamic collapse time scale. For a nonrotating, nonmagnetized progenitor, $t_{\text{dyn}} \sim M_5^{\text{HC}} \text{ s}$.

Shi and Fuller [13] showed that for the collapse of a nonrotating nonmagnetized spherical supermassive object the neutrino burst could carry away a fraction $\sim 0.04(M_5^{\text{HC}})^{-1.5}$ of the total gravitational binding energy (assuming $M_5^{\text{HC}} \geq 0.1$, so that this fraction is less than 1). The neutrino release is equally partitioned between neutrinos and antineutrinos, with $\nu_e \bar{\nu}_e$ accounting for 70% of the total neutrino flux. The average neutrino energy is similar for all species and is $\approx 4(M_5^{\text{HC}})^{-0.5} \text{ MeV}$.

If the progenitor is rapidly rotating or if magnetic stresses are appreciable, the collapse time scale could increase significantly. Neutrinos would then have a much better chance of escaping before the core moves through an event horizon. In such a case, the neutrino fluence could be an order of magnitude higher than in the nonrotating case (but still limited by the total gravitational binding energy), and the average neutrino energy could be a factor of 2 higher as well [13]. The partition of energy among the different neutrino species, however, would remain the same.

Although the neutrino emission accompanying the collapse of a supermassive object is gigantic, it is almost impossible to detect if it originates at a redshift $z \gtrsim 1$ [13]. But such a neutrino burst may become detectable if the collapse occurs at a redshift $z \lesssim 0.2$. These recent super-

massive collapse events may not be uncommon, since there are still large numbers of quasars (and AGNs) at redshift $\lesssim 0.2$.

To estimate how many supermassive progenitors might collapse at a redshift $z \lesssim 0.2$, we need to know how abundant they are and how their collapse rate evolves with redshift. A natural and reasonable starting point is to assume an abundance of one per galaxy (including dwarf galaxies, i.e., one per $\sim 10^{10} M_\odot$ of baryons), and assume a collapse rate that traces the formation rate of quasars, because quasars are powered by supermassive black holes. If we assume that the average quasar lifetime, which is short ($\sim 10^8 \text{ yr}$) compared to the Hubble time, does not evolve with redshift, the quasar formation rate would then trace quasar number density as a function of redshift. In Fig. 2 we replot the evolution of the quasar number density (proper) as measured by Shaver *et al.* [14], as well as that inferred from the quasar catalog compiled by Véron-Cetty and Véron [15]. The plot assumes a Hubble constant $H_0 = 50 \text{ (km/sec/Mpc)}$ and a deceleration parameter $q_0 = 0.5$, which will be the working assumption in the following calculations. (The details of cosmology do not affect our results significantly.) The sample of Shaver *et al.* is radio selected and is argued to have the least amount of selection bias [14]. We thus adopt the quasar number density evolution in the redshift range $z \gtrsim 0.5$ as implied by this sample. The catalog of Véron-Cetty and Véron, on the other hand, is a compilation of quasars brighter than absolute magnitude $M_B = -23$ from different samples with different selection criterion [15]. Its degree of completeness is uncertain. Therefore, even though the latter catalog has far more data at the low redshift end, its inferred quasar number density evolution below $z \lesssim 0.3$ cannot simply be taken as the extension of the Shaver *et al.*

FIG. 1. Solid line: the time profile of the (unnormalized) neutrino luminosity from the collapse of a nonrotating nonmagnetized spherical supermassive object [13]. Dashed line: the time profile of the neutrino signal in the ICECUBE detector. The time axis is in units of t_{dyn} , the dynamic collapse time scale.

FIG. 2. The relative proper number density of quasars as a function of redshift, normalized to peak at 1. Data points are the measurements of Shaver *et al.* [14]. The thin solid line is the fit of Shaver *et al.* [14] to the data. The dashed line is inferred from the quasar catalog of Véron-Cetty and Véron [15], without any correction for bias. The three thick lines represent our adopted values for the relative quasar number density in the redshift range $0.1 \leq z \leq 0.2$.

evolution function to $z \lesssim 0.3$. The catalogue does, however, seem to give a number density evolution in fair agreement with the Shaver *et al.* evolution function at $0.5 \lesssim z \lesssim 2$. If nothing else, the Véron-Cetty and Véron catalog may indicate that the quasar number density at $z \lesssim 0.3$ potentially is comparable to the quasar number density at $z \sim 0.5$. To account for the uncertainty in quasar number density evolution at low redshift, we will calculate the nearby supermassive black hole formation rate for three values of the relative quasar number density in the redshift range $0.1 \lesssim z \lesssim 0.2$ (the three thick solid lines in Fig. 2), corresponding to a quasar number density that is the same as (case 1), one-third of (case 2) and one-tenth of (case 3) the quasar number density at $z \sim 0.5$.

We denote the collapse rate of supermassive objects as $\dot{\phi}$, whose redshift evolution is inferred from Fig. 2. Assuming a matter-dominated flat universe, we find that the total baryon mass in a unit volume that was incorporated into supermassive black holes is now

$$\rho_{\text{sm}} = \int_0^{t_0} \frac{\dot{\phi} M}{(1+z)^3} dt \approx 0.025 \dot{\phi}_0 M t_0, \quad (1)$$

where t_0 is the age of the Universe today, M is the mass of the supermassive black hole today, and $\dot{\phi}_0$ is the normalization required to give the true formation rate in a unit volume. On the other hand, we have assumed $\rho_{\text{sm}} = (M/10^{10} M_\odot) \rho_b$ where $\rho_b \approx 1.88 \times 10^{-29} \Omega_b h^2 \text{ g cm}^{-3}$ (with Ω_b being the baryon density in units of the critical density and $h \equiv H_0/[100 \text{ (km/sec)/Mpc}]$) is the baryon density today. Therefore,

$$\dot{\phi}_0 \approx 7 \times 10^{-17} \left(\frac{\Omega_b h^2}{0.025} \right) \left(\frac{12.5 \text{ Gyr}}{t_0} \right) \text{Mpc}^{-3} \text{s}^{-1}. \quad (2)$$

The event rate, as observed now, of these supermassive collapses that occurred in the redshift range $z_1 \leq z \leq z_2$ is

$$R(z_1, z_2) = \int_{z_1}^{z_2} \dot{\phi} \frac{4\pi r^2}{(1+z)^4} \frac{dr}{dz} dz, \quad (3)$$

where r is the comoving spatial coordinate. Note that in this equation, in addition to the factor $(1+z)^{-3}$ stemming from volume expansion, there is an additional factor $(1+z)^{-1}$ due to the cosmic time dilation. In a matter-dominated universe with $q_0 = 0.5$, we have $r = 3ct_0(1 - 1/\sqrt{1+z})$, where c is the speed of light. The rate of those collapses at $0.1 \lesssim z \lesssim 0.2$ is then

$$\begin{aligned} R(0.1, 0.2) &= 2\pi(3ct_0)^3 \int_{0.1}^{0.2} \dot{\phi} \frac{(1 - 1/\sqrt{1+z})^2}{(1+z)^{5.5}} dz \\ &= R_0 \left(\frac{\Omega_b h^2}{0.025} \right) \left(\frac{12.5 \text{ Gyr}}{t_0} \right) \text{yr}^{-1}, \end{aligned} \quad (4)$$

where $R_0 \approx 1, 0.3$, and 0.1 , for cases 1, 2 and 3, respectively. (The rate for all supermassive collapses is roughly 0.1 per day with the same scaling factors.) These rates scale inversely with the amount of baryon mass that con-

tains one supermassive black hole, which we have assumed to be $10^{10} M_\odot$ on average. While we are certainly very interested in collapses at $z \lesssim 0.1$, we cut off the collapse rate at $z = 0.1$ to avoid extrapolating the quasar number density evolution function too far toward low z . Even so, the rate of the nearby collapse of supermassive black hole progenitors is potentially much higher than the type-II (and type-Ib) supernova rate in our galaxy.

With these estimated characteristics, the neutrino bursts from such relatively nearby supermassive object collapse events may be detectable with ICECUBE, a $\sim 1 \text{ km}^3$ neutrino detector with $\sim 10^4$ optical modules soon to be proposed. Just like the currently operating AMANDA (Antarctic Muon and Neutrino Detector Array) detector, it will have sensitivity to bursts of neutrinos with energies $\geq 10 \text{ MeV}$ [16]. The principle is similar to that involved in detecting supernova neutrinos, i.e., detecting the Čerenkov photon flashes resulting from relativistic positrons produced by the reaction $\bar{\nu}_e + p \rightarrow n + e^+$. The cross section for this process is $\approx 9 \times 10^{-44} (E_{\bar{\nu}_e}/1 \text{ MeV})^2 \text{ cm}^2$. The Čerenkov photons are collected by optical modules and their numbers are counted. Using the module efficiency and threshold estimates in Halzen, Jacobsen, and Zas [16], and the $\bar{\nu}_e$ spectrum calculated by Shi and Fuller [13], we find that the number of events expected in ICECUBE from a neutrino burst resulting from the collapse of a supermassive object would be

$$\begin{aligned} N_{\text{event}} &\sim 10^{-3} N_M \left(\frac{750 \text{ Mpc}}{d} \right)^2 \\ &\times \left(\frac{E_{\nu\bar{\nu}}}{4 \times 10^{57} (M_5^{\text{HC}})^{-0.5} \text{ erg}} \right) \alpha, \end{aligned} \quad (5)$$

where N_M is the number of optical modules in the detector, d is the proper distance to the source of the burst ($d \approx 750 \text{ Mpc}$ for $z = 0.15$), $E_{\nu\bar{\nu}}$ is the total energy release in neutrino emission, and $\alpha \sim \mathcal{O}(1)$ accounts for the energy spectrum of the $\bar{\nu}_e$ emission. The expected number of $\bar{\nu}_e$ events per optical module (N_{event}/N_M) from collapses of homologous cores with various masses at $z = 0.15$ is shown in Table I. In our calculation, we have imposed a 30% artificial limit on the fraction of the total gravitational binding energy that can be carried away by neutrino emission. We believe this fraction is attainable, considering that much higher efficiency is possible by magnetic mechanisms.

Optimal neutrino signal outputs are obtained from collapses with $M_5^{\text{HC}} \sim \mathcal{O}(0.1)$ and with rotation/magnetic fields. For these conditions the average neutrino energy $[\propto (M_5^{\text{HC}})^{-0.5}]$ is high, as is the fraction of gravitational binding energy carried away by neutrinos. Rotation and/or magnetic fields are always likely to be present during the collapses. It is also possible that the lower mass supermassive progenitors that yield $M_5^{\text{HC}} = \mathcal{O}(0.1)$ dominate the population of supermassive objects. The optimal conditions of neutrino detection, therefore, may in fact represent most of the supermassive collapses.

TABLE I. Expected neutrino events per optical module in ICECUBE from collapses at $z = 0.15$.

M^{HC} ($10^5 M_{\odot}$)	Rotation/Magnetic field	α	$E_{\nu\bar{\nu}}/0.5M^{\text{HC}}c^2$	N_{event}/N_M
0.3	No	0.8	7%	8×10^{-4}
0.3	Yes	9	30% ^a	1.2×10^{-2}
1	No	0.01	4%	1×10^{-5}
1	Yes	1.2	30% ^a	5×10^{-3}
3	Yes	0.017	22%	1.7×10^{-4}

^aSaturating our imposed limit.

Competing with the neutrino signal is the fluctuation of the background level of ICECUBE, which at the current AMANDA level should have a standard deviation of $20N_M^{0.5}$ counts in 1 sec. To obtain a signal-to-noise ratio (S/N) of unity for a collapse at $z = 0.15$ with $M_5^{\text{HC}} = 0.3$ would then require 2.8×10^6 optical modules. If we take advantage of the time template of the neutrino signal, we may not require a signal to noise as high as $S/N = 1$. A S/N of 0.1, for example, would only require 2.8×10^4 optical modules for a detection. The rate of such detections could be of the order of 0.1 to 1 per year, if most of the supermassive collapses at $z \lesssim 0.2$ have rotating/magnetized homologous cores with relatively lower masses in the supermassive mass spectrum, $M_5^{\text{HC}} = \mathcal{O}(0.1)$.

Since, to maintain the same S/N , the required N_M is proportional to d^4 , a chance detection of a supermassive collapse at $z \lesssim 0.1$ (and hence $d \lesssim 500$ Mpc) would make the detection scheme even more attractive. Note also that the number of modules (N_M) required scales linearly with the duration of the neutrino burst, which we have taken to be t_{dyn} in the above estimates. If this duration is only a fraction of t_{dyn} as shown in the example in Fig. 1, the number of optical modules can be further reduced. In addition, if the energy of neutrino emission during the collapses can exceed 30% of the total gravitational binding energy, N_M will scale down as the inverse square of this fraction. Therefore, the detection potential actually starts at the $N_M \sim 5 \times 10^3$ level, which is currently envisaged for the expansion of the operating AMANDA neutrino telescope to the ICECUBE configuration. An ICECUBE detector with the order of 10^5 optical modules has already been contemplated for other science missions, e.g., for searching for nucleon decay with a sensitivity that cannot be matched by conventional techniques.

The above calculations have been based on the detection technology available to AMANDA, without any change in design of the planned ICECUBE. This leaves room for future improvement. Moreover, if the formation of supermassive black holes via supermassive object collapse also gives rise to gamma-ray bursts [17], or gravitational radiation detectable in proposed low frequency gravitational

wave detectors such as LISA, we could enhance our ability to detect the associated neutrino bursts by knowing when to look. In addition, the combined neutrino/gamma-ray burst/gravitational wave signal would offer a golden chance to explore many questions in particle physics, astrophysics, and gravitational physics.

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