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Fast radio bursts and white hole signals

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Quantum gravity effects could make a black hole explode in a time shorter than the Hawking radiation time, via local tunneling through a white hole solution. Here we estimate the size of a primordial black hole exploding today via this process, using a simple generic model. Fast radio bursts, strong signals with millisecond duration, which are probably of extragalactic origin and have an unknown source, have wavelengths not far from the expected size of the exploding hole. We also discuss the high-energy component of the signal. These results suggest a new window for quantum gravity phenomenology.

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The fate of the matter we see falling into black holes is unknown. A possibility is that quantum gravity generates pressure (or weakens gravity) halting the collapse at a "Planck star" stage, possibly triggering a bounce leading to an explosion [1–18], possibly at a size larger than Planckian [19–21]. The idea is based on generic nonperturbative quantum gravity arguments and is not tied to a specific model.

Lifetimes of stellar or galactic holes are too long to give us a chance to detect such an explosion. But primordial black holes that formed in the early Universe, if they exist [22–25], could be exploding today. For a black hole of initial mass m, the hypothesis that the phenomenon prevents the firewall issue [26] implies a lifetime shorter than the Hawking evaporation time [27] ($\sim m^3$ in Planck units $c = \hbar = G = 1$). In Ref. [21] the signal emitted was estimated under this hypothesis to be in the GeV range and its phenomenology has been studied in Ref. [28]. For related suggestions see Refs. [29–35].

Later work has pointed out that quantum gravity effects might become relevant earlier, allowing for shorter black hole lifetimes [36]. Classical general relativity outside the region of the hole, indeed, is compatible with a black-to-white quantum transition. The black and white hole solutions of the Einstein equations can be glued and their singularities replaced by a *finite* (in space and in time) nonclassical tunneling region. An estimate of the time to exit in the semiclassical regime yields a lifetime

$$\tau = 4km^2 \tag{1}$$

in Planck units, where k was estimated to $k = .05$ in Ref. [36]. If so, Hawking radiation can be disregarded in a first approximation and considered a correction due to dissipative effects. Primordial black holes of initial mass

$$m = \sqrt{\frac{t_H}{4k}} \sim 1.2 \times 10^{23}\ \mathrm{kg} \tag{2}$$

where t_H is the Hubble time, can therefore be expected to explode today. The possibility of observing signals from white holes was first pointed out by Narlikar, Appa Rao and Dadhich in Ref. [37].

The nonperturbative nature of the effect considered here makes it different from corrections to the Hawking radiation such as those studied in Ref. [38]. Rather, the effect is similar to bouncing cosmology where contracting and expanding phases are connected by a short quantum region. But a short "bounce" may correspond to a long external time because of the general-relativistic time dilation: the proper time of an observer inside the Planck star can be small ($\sim m$, the time for light to cross the object), while the proper time of an observer *outside* the hole can be extremely long ($\sim m^2$, namely cosmological).

In this scenario most of the energy of the black hole is still present at explosion time, because Hawking radiation does not have the time to consume it. The exploding black hole should therefore have total energy of order

$$E = mc^2 \sim 1.7 \times 10^{47}\ \mathrm{erg} \tag{3}$$

concentrated in a size given by its Schwarzschild radius

$$R = \frac{2Gm}{c^2} \sim .02\ \mathrm{cm}. \tag{4}$$

We expect two characteristic components of the signal from such an explosion: (i) a low-energy signal at wavelengths of the order of the size of the exploding object; (ii) a high-energy signal depending on the liberated hole content. Below, we first discuss the low energy signal, then the possibility of identifying it with observed signals, and finally the high-energy signal.

Low-energy signal.—A strong explosion in a small region emits a signal with a component at a wavelength of the order of the size of the region or somehow larger, and converts some fraction of its energy into photons. Therefore it is reasonable to expect from this scenario an electromagnetic signal emitted in the infrared:

$$\lambda_{\text{predicted}} \gtrsim .02 \text{ cm}. \tag{5}$$

The received signal is going to be corrected by the standard cosmological redshift. However, signals coming form farther away were originated earlier, namely by younger, and therefore less massive, holes, giving a peculiar decrease of the emitted wavelength with distance. The received wavelength, taking into account both the expansion of the Universe and the change of time available for the black hole to bounce, can be obtained by folding Eq. (1) into the standard cosmological relation between redshift and proper time. A straightforward calculation gives

$$\lambda_{\text{obs}} \sim \frac{2Gm}{c^2}(1+z) \times \sqrt{\frac{H_0^{-1}}{6k\Omega_\Lambda^{1/2}} \sinh^{-1}\left[\left(\frac{\Omega_\Lambda}{\Omega_M}\right)^{1/2}(z+1)^{-3/2}\right]}, \tag{6}$$

where we have reinserted the Newton constant G and the speed of light c while H_0, Ω_Λ and Ω_M are the Hubble constant, the cosmological constant, and the matter density. This is a very slowly varying function of the redshift. The effect of the hole's age almost compensates for the redshift. The signal, indeed, varies by less than an order of magnitude for redshifts up to the decoupling time ($z = 1100$). (See Fig. 1.)

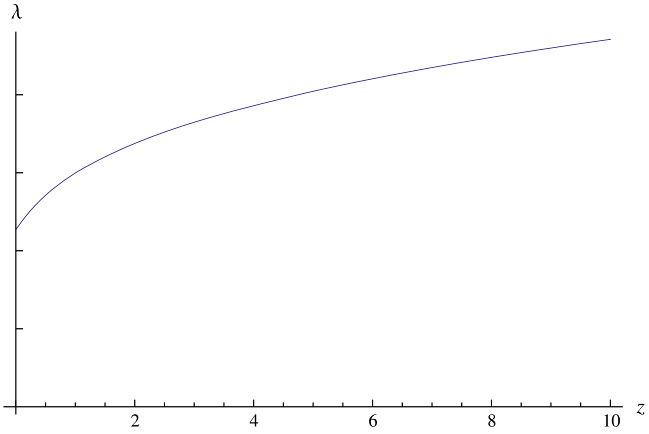

FIG. 1 (color online). White hole signal wavelength (unspecified units) as a function of z. Notice the characteristic flattening at large distance: the youth of the hole compensates for the redshift.

If the redshift of the source can be estimated by using dispersion measures or by identifying a host galaxy, given sufficient statistics this flattening represents a decisive signature of the phenomenon we are describing.

Do we have experiments searching for these signals? There are detectors operating at such wavelengths, beginning with the recently launched Herschel instrument. The 200 micron range can be observed both by PACS (two bolometer arrays and two Ge:Ga photoconductor arrays) and SPIRE (a camera associated with a low- to medium-resolution spectrometer). The predicted signal falls in between the PACS and SPIRE sensitivity zones. There is also a very high-resolution heterodyne spectrometer, HIFI, onboard Herschel, but this is not an imaging instrument; it observes a single pixel on the sky at a time. However, the bolometer technology makes detecting short white-hole bursts difficult. Cosmic rays cross the detectors very often and induce glitches that are removed from the data. Were physical IR bursts due to bouncing black holes registered by the instrument, they would most probably have been flagged and deleted, mimicking mere cosmic-ray noise. There might be room for improvement. It is not impossible that the time structure of the bounce could lead to a characteristic time scale of the event larger than the response time of the bolometer. In that case, a specific analysis should allow for a dedicated search of such events. We leave this study for a future work as it requires astrophysical considerations beyond this first investigation. An isotropic angular distribution of the bursts, signifying their cosmological origin, could also be considered as an evidence for the model. In case many events were measured, it would be important to ensure that there is no correlation with the mean cosmic-ray flux (varying with the solar activity) at the satellite location.

Let us turn to something that *has* been observed.

Fast radio bursts.—Fast radio bursts are intense isolated astrophysical radio signals with millisecond duration. A small number of these were initially detected only at the Parkes radio telescope [39–41]. Observations from the Arecibo Observatory have confirmed the detection [42]. The frequency of these signals is around 1.3 GHz, namely a wavelength

$$\lambda_{\text{observed}} \sim 20 \text{ cm}. \tag{7}$$

These signals are believed to be of extragalactic origin, because the observed delay of the signal arrival time with frequency agrees well with the dispersion due to an ionized medium as expected from a distant source. The total energy emitted in the radio is estimated to be of the order 10^{38} erg. The progenitors and physical nature of the fast radio bursts are currently unknown [42].

There are 3 orders of magnitude between the predicted signal (5) and the observed signal (7). But the black-to-white hole transition model is still very rough. It disregards rotation, dissipative phenomena, anisotropies, and other phenomena, and these could account for the discrepancy.

In particular, astrophysical black holes rotate: one may expect the centrifugal force to lower the attraction and bring the lifetime of the hole down. This should allow for larger black holes to explode today, and signals of larger wavelengths. Also, we have not taken the astrophysics of the explosion into account. The total energy (3) available in the black hole is largely sufficient—9 orders of magnitude larger—than the total energy emitted in the radio estimated by the astronomers.

Given these uncertainties, the hypothesis that fast radio bursts could originate from exploding white holes is tempting and deserves to be explored.

High-energy signal.—When a black hole radiates by the Hawking mechanism, its Schwarzschild radius is the only scale in the problem and the emitted radiation has a typical wavelength of this size. In the model we are considering, the emitted particles do not come from the coupling of the event horizon with the vacuum quantum fluctuations, but rather from the time reversal of the phenomenon that formed (and filled) the black hole. Therefore the emitted signal is characterized by a second scale: the characteristic energy scale of the matter or radiation that entered the hole. Since the proper time of the bounce *inside* the hole is short, there is no reason to expect this to vary much during the process.

In most simple models, primordial black holes form with a mass of the order of the Hubble mass, $M_H \approx \frac{1}{8}t$ in Planck units. For the mass (2), this corresponds to a temperature of the Universe of the order of a TeV. It is natural to assume that a fraction of the energy of the photons emitted from the bouncing hole are of this order of magnitude.

The bouncing hole acts as a “redshift freezing machine” for fields inside; they are emitted back at the energy they had when absorbed. In the meanwhile, the scale factor of the surrounding Universe has grown tremendously.

Known gamma-ray bursts have lower energies than a TeV. Some searches have been carried out, but no burst in the TeV range has been observed to date. The small astrophysical background in this frequency is excellent for detection, but there is an instrumental issue: TeV detectors are ground-based Cherenkov telescopes with narrow fields of view. In addition, due to the absorption by the cosmic infrared background, TeV photons cannot come from far away: the horizon is limited. A new generation of detectors, the CTA experiment, is being designed with a huge array of telescopes that could monitor many portions of the sky at the same time, opening new possibilities for this search.

The redshift dependance of this signal is different from the IR/radio one. For a hole exploding at redshift z, corresponding to cosmic time t, the signal energy is given by the temperature of the Universe at formation time, which is proportional to the inverse square root of the formation time. This time is in turn proportional to the horizon mass which is (roughly) equal to the formation mass of the black hole. The emission wavelength is therefore proportional to the square root of the mass of the black hole. This gives, again with a straightforward calculation, the observed wavelength

$$\lambda_{\mathrm{obs}} \propto (1+z)\left(\sinh^{-1}\left[\left(\frac{\Omega_\Lambda}{\Omega_M}\right)^{\frac{1}{2}}(z+1)^{-\frac{3}{2}}\right]\right)^{\frac{1}{4}}. \qquad (8)$$

To measuring redshift we need to associate the event to a host structure, which is far from obvious, but in principle this z dependence provides again a specific signature.

If x is the fraction of the total energy as gamma rays, the number of photons radiated during the bounce will be $N_\gamma \sim xm/E_\gamma$. For a reasonable $x = 0.2$, this leads to 10^{46} γ rays in the TeV range. For an effective telescope area given by a disc of radius 100 meters (the size of the Cherenkov shower), requiring 10 measured photons for each burst, the bouncing object can be detected up to a distance of $D \approx 10^{24}$ m, or 100 million light years, or a redshift of $z = 0.01$. This is within the γ-ray horizon and the latter is therefore not the limiting factor. A promising strategy could be to point the telescope toward a galaxy with $z < 0.01$. If it is not a blazar, the TeV background is expected to be small or vanishing. If bouncing primordial black holes around 10^{23} kg are to represent a large fraction of dark matter, there could be as many as 10^{19} objects of this type within the galaxy. Each exploding (bouncing) one would be detected. Of course, the actual number of events per unit of time depends on the width of the primordial mass spectrum (if any), which is not known. But orders of magnitude show that detection is not hopeless.

We have discussed the signal of a primordial black hole exploding today via a black-to-white quantum transition [36] and the possibility of observing its low- and high-energy components. We have pointed out that the low-energy emission would have a characteristic distance-frequency relation flattening at large redshifts.

We have pointed out the possibility of identifying this signal with the fast radio bursts observed by the Arecibo and Parkes observatories.

A connection between black hole explosions and short radio signals was suggested some time ago by Rees [43]. The physics considered by Rees is different, i.e., radio or optical emission from the relativistic shock wave generated from the explosion of *small* black holes, interacting with an ambient magnetic field. In the scenario we have considered here, on the contrary, the phenomenon is of direct quantum-gravitational nature. A Planck-scale phenomenon may have effects at observable scales because of the large multiplicative factor [44]

$$t_H/t_P \sim 8 \times 10^{60} \qquad (9)$$

in the physics of the phenomenon. If the observed fast radio bursts are connected to this phenomenon, they represent the first known direct observation of a quantum gravity effect.

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