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Planck star phenomenology

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ABSTRACT

It is possible that black holes hide a core of Planckian density, sustained by quantum-gravitational pressure. As a black hole evaporates, the core remembers the initial mass and the final explosion occurs at macroscopic scale. We investigate possible phenomenological consequences of this idea. Under several rough assumptions, we estimate that up to several short gamma-ray bursts per day, around 10 MeV, with isotropic distribution, can be expected coming from a region of a few hundred light years around us.

1. The model

Recently, a new possible consequence of quantum gravity has been suggested [1]. The idea is grounded in a robust result of loop cosmology [2]: when matter reaches Planck density, quantum gravity generates pressure sufficient to counterbalance weight. For a black hole, this implies that matter's collapse can be stopped before the central singularity is formed: the event horizon is replaced by a "trapping" horizon [3] which resembles the standard horizon locally, but from which matter can eventually bounce out. Because of the huge time dilation inside the gravitational potential well of the star, the bounce is seen in extreme slow motion from the outside, appearing as a nearly stationary black hole. The core, called "Planck star", retains memory of the initial collapsed mass m_i (because there is no reason for the metric of the core to be fully determined by the area of the external evaporating horizon) and the final exploding object depends on m_i and is much larger than Planckian [1]. The process is illustrated by the conformal diagram in Fig. 1.

In particular, primordial black holes exploding today may produce a distinctive signal. The observability of a quantum gravitational phenomenon is made possible by the amplification due to the large ratio of the black hole lifetime (Hubble time t_H) over the Planck time [4].

If this scenario is realized in nature, can the final explosion of a primordial Planck star be observed? This is the question we investigate here.

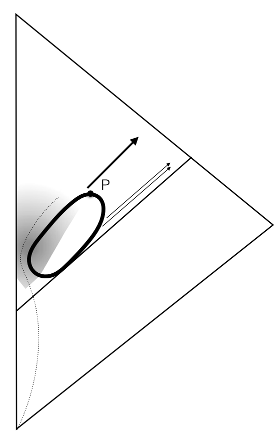

Fig. 1. Penrose diagram of a collapsing star. The dotted line is the external boundary of the star. The shaded area is the region where quantum gravity plays an important role. The dark line represents the two trapping horizons: the external evaporating one, and the internal expanding one. The lowest light-line is where the horizon of the black hole would be without evaporation. P is where the explosion happens. The thin arrows indicate the Hawking radiation. The thick arrow is the signal studied in this paper.

2. Dynamics

As a first step, we evaluate the energy of the particles emitted by the explosion of a primordial Planck star. Let $m_f = am_i$ be the final mass reached by the black hole before the dissipation of the horizon (at the point P in Fig. 1). In [1], an argument based on information conservation was given, pointing to the preferred value

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$$a \sim \frac{1}{\sqrt{2}}, \tag{2.1}$$

where m_i is the initial mass. This value contradicts the expectation from the semiclassical approximation; it follows from the hypothesis that the black hole information paradoxes might be resolved and firewalls avoided if the semiclassical approximation breaks down earlier than naively expected, as a consequence of the strong quantum gravitational effects in the core and the fact that they alter the effective causal structure of the evolving spacetime (the point P is in the causal future of the quantum gravitational region). In [5,6] the extreme opposite case derived from the same ideas is explored. As shown by Hawking, non-rotating uncharged black holes emit particles with energy in the interval $(E, E + \mathrm{d}E)$ at a rate [7]

$$\frac{\mathrm{d}^2N}{\mathrm{d}E\mathrm{d}t} = \frac{\Gamma_s}{h}\left[\exp\left(\frac{8\pi GmE}{\hbar c^3}\right) - (-1)^{2s}\right]^{-1} \tag{2.2}$$

per state of angular momentum and spin s. The absorption coefficient Γ_s, that is the probability that the particle would be absorbed if it were incident in this state on the black hole, is a function of E, m and s. By integrating this expression it is straightforward to show that the mass loss rate is given by

$$\frac{\mathrm{d}m}{\mathrm{d}t} = -\frac{f(m)}{m^2}, \tag{2.3}$$

where $f(m)$ accounts for the degrees of freedom of each emitted particle. As time goes on, the mass decreases, the temperature increases and new types of particles become "available" to the black hole. Above each threshold, $f(m)$ is given approximately by [8]

$$f(m) \approx (7.8\alpha_{s=1/2} + 3.1\alpha_{s=1}) \times 10^{24}\ \mathrm{g}^3\ \mathrm{s}^{-1}, \tag{2.4}$$

where $\alpha_{s=1/2}$ and $\alpha_{s=1}$ are the number of degrees of freedom (including spin, charge and color) of the emitted particles. If $f(m)$ is assumed to be constant, *e.g.* $f(m) = f(m_i)$, the initial and final masses of a black hole reaching its final stage today, that is in a Hubble time t_H, are easy to calculate. In the Planck star hypothesis, the final stage is reached when $m = m_f \gg m_{Pl}$. Integrating Eq. (2.3) leads to

$$m_i = \left(\frac{3t_H f(m_i)}{1 - a^3}\right)^{\frac{1}{3}}. \tag{2.5}$$

In practice, to account for the smooth evolution of $f(m)$ when the different degrees of freedom open up, a numerical integration has to be carried out. This leads, for $a = 1/\sqrt{2}$, to

$$m_i \approx 6.1 \times 10^{14}\ \mathrm{g}, \tag{2.6}$$

and

$$m_f \approx 4.3 \times 10^{14}\ \mathrm{g}. \tag{2.7}$$

The value of m_i is very close to the usual value m_* corresponding to black holes requiring just the age of the Universe to fully evaporate. This was expected as the process is explosive. The details may change depending on the exact shape chosen for $f(m)$. In principle, the accurate value of m_i should be altered by the fact that the Hawking formula used to calculate it is purely semi-classical whereas the end of the process is strongly dominated by quantum gravity effects. In practice this has no effect as the evaporation time is very strongly dominated by the first stages. For example, increasing by a factor of 100 the mass loss rate in the last tenth of the mass interval spanned by the evaporating black hole would change its lifetime by less than 0.1%.

The value of the radius when m reaches m_f is $r_f \approx 6.4 \times 10^{-14}$ cm. The size of the black hole is the only scale in the problem and therefore fixes the energy of the emitted particles in this last stage. We assume that all fundamental particles are emitted with the same energy taken at

$$E_{burst} = hc/(2r_f) \approx 3.9\ \mathrm{GeV}. \tag{2.8}$$

Of course, a more reliable model would be desirable but this is the most natural hypothesis at this stage. In future works, different hypothesis will be considered. However, as the spectrum of gamma-rays is very widely spread even for monochromatic jets of quarks, it can be safely assumed that some broadening of the emitted spectrum would not qualitatively change the result.

3. Single event detection

We now study the signal that evaporating Planck star would produce. From the phenomenological viewpoint, it is natural to focus on emitted gamma-rays: charged particles undergo a diffusion process in the stochastic magnetic fields and cannot be used to identify a single event whereas neutrinos are hard to detect. The important fact is that most of the emitted gammas are not emitted at the energy E_{burst}. Only those directly emitted will have this energy. But assuming that the branching ratios are controlled, as in the Hawking process, by the internal degrees of freedom, this represents only a small fraction (1/34 of the emitted particles). Most gamma-rays will come from the decay of hadrons produced in the jets of quarks, notably from neutral pions. E_{burst} is already much smaller than the Planck scale but the mean emission of emitted photons is even smaller.

To simulate this process, we have used the "Lund Monte Carlo" PYTHIA code (with some scaling approximations due to the unusually low energy required for this analysis). It contains theory and models for a number of physics aspects, including hard and soft interactions, parton distributions, initial- and final-state parton showers, multiple interactions, fragmentation and decay. PYTHIA allowed us to generate the mean spectrum expected for secondary gamma-rays emitted by a Planck star reaching the end of its life. The main point to notice is that the mean energy is of the order of $0.03 \times E_{burst}$, that is in the tens of MeV range rather than in the GeV range. In addition, the multiplicity is quite high at around 10 photons per $q\bar{q}$ jet. Fig. 2 shows the mean spectrum of photons resulting from 10^5 jets of 3.9 GeV $u\bar{u}$ quarks.

It is straightforward to estimate the total number of particles emitted m_f/E_{burst} and then the number of photons $\langle N_{burst}\rangle$ emitted during the burst. As for a black hole radiating by the Hawking mechanism, we assume that the particles emitted during the bursts (that is those with $m < E_{burst}$) are emitted proportionally to their number of internal degrees of freedom: gravity is democratic. The spectrum resulting from the emitted u, d, c, s quarks (t and b are too heavy), gluons and photons is shown in Fig. 3. The little peak on the right corresponds to directly emitted photons that are clearly sub-dominant. By also taking into account the emission of neutrinos and leptons of all three families (leading to virtually no gamma-rays and therefore being here a pure missing energy), we obtain $\langle N_{burst}\rangle \approx 4.7 \times 10^{38}$.

The question of the maximum distance at which a single burst can be detected naturally arises. If one requires to measure N_{mes} photons in a detector of surface S, this is simply given by

$$R_{det} = \sqrt{\frac{S\langle N_{burst}\rangle}{4\pi N_{mes}}}. \tag{3.1}$$

If we set, *e.g.*, $N_{mes} \approx 10$ photons in a 1 m^2 detector, this leads to $R \approx 205$ light-years. Otherwise stated, the "single event"