Essay on Planck Star Phenomenology

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In the last decades, a large scale search for theories of quantum gravity was made. There are several of them on the market but no realistic experiments which are able to reach energies where one would expect quantum gravity effects to be measurable. Within the framework of general relativity there are open questions like the existence of a true singularity inside a black hole.

In order to avoid the singularity at the center of a black hole, several modifications to the Schwarzschild metric were proposed. Most of these models agree on the fact that at scales of order of the Planck length, quantum effects need to prevent that matter falls into the singularity. How the quantum effects are introduced varies from model to model and in this essay we focus on the Planck star model originally introduced by Francesca Vidotto and Carlo Rovelli [1].

The inspiration for the Planck star comes from loop quantum cosmology where the Friedmann equations are modified by adding a density dependent term that makes a collapsing compact universe bounce into an expanding universe. There are two main points one needs to account for. On the one hand, quantum effects can act as a repulsive force preventing collapses to singularities. On the other hand, the quantum effects can already be important on length scales larger than the Planck scale. The latter point emerges because the Planck density is reached long before the universe is of Planckian size.

In this essay an overview of the Planck star model of Francesca Vidotto and Carlo Rovelli is given. After a first orientation that inspired the model, a discussion of its details is made. Then the main achievements of the model are pointed out. Finally a possible connection between Planck star explosions and short gamma-ray bursts is given.

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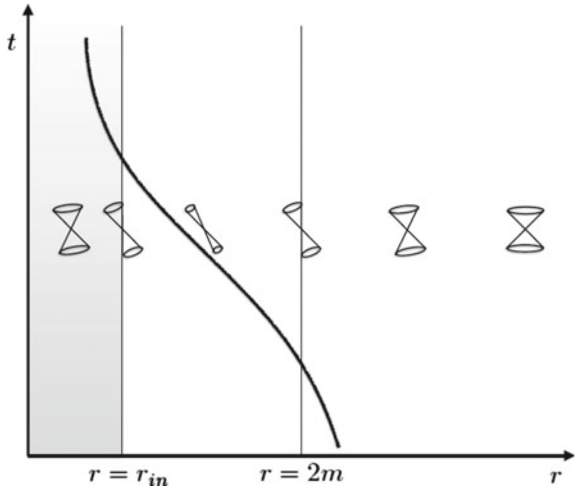

Fig. 1 Spacetime diagram of a non evaporating Planck star in Eddington-Finkelstein coordinates [1]

In the following we focus on the Planck star itself. If a neutron star collapses into an even denser object, the Law of Physics only allow for the formation of a black hole. By assuming that quantum effects are important at Planckian density, they should prevent the collapse into a singularity. Such models exist not only in loop quantum gravity but also in string theory and asymptoticaly safe gravity.

Figure 1 shows a spacetime diagram of a non-evaporating Planck star. One can see the tilting of the light cones in Eddington-Finkelstein coordinates. Quantum gravity is important in the shaded region. Also a second trapping horizon can be seen inside the Schwarzschild horizon.

In the case of the Planck star model, matter would be in a super dense core of the Planck star. Grude estimations of the size of this core give $\sim(m/m_p)^n \;\; l_P$, where m_p is the Planck-mass and l_P the Planck length. Consequently, for a stellar-mass black hole, the radius of the Planck star would be 10^{-10} cm if one uses $n = 1/3$. This means that the Planck star would be well inside its “event” horizon, such that it would look like a black hole for an exterior observer.

Because of the quantum nature of matter, the core of the Planck star does not longer satisfy Einstein equations. In order to describe this region of spacetime, a full non-perturbative quantum gravity is needed, such as loop quantum gravity.

However, this is only one aspect of the full Planck star model. Inspired by loop cosmology, it is suspected that the core of the Planck star will not stay in this high-density state. The repulsive force due to quantum effects will not only prevent the gravitational collapse, but will also force the Planck star to “bounce”.

A simple model that can describe the gravitational collapse into a highly dense object can be an infalling mass shell with negligible thickness. There are two distinct spacetime regions. The interior of the shell which should be flat and the exterior of the shell where effects of the mass m must change spacetime to a portion of the Schwarzschild metric.

Fig. 2 Penrose diagram of a bouncing star [4]

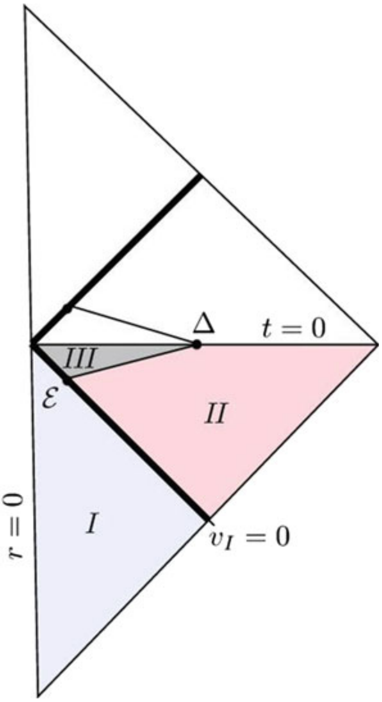

Figure 2 represents the spacetime of a bouncing star solution. The colored region '*I*' belongs to the interior of the infalling shell and region '*II*' represents the exterior. In this picture it is assumed that the bouncing process happens at the "$t = 0$"—hyperplane and the coordinate is chosen such that the center of mass is at the origin. The third region in this figure represents the spacetime region where quantum effects must appear. The radius of this region is approximately 7/6 r_S, where r_S is the radius of the event horizon of a Schwarzschild black hole. This region expands even outside of the possible horizon. The point denoted by Δ is the maximal spacelike extension of the classically violated region and ε denotes the time at which this violation happens for the first time.

One concludes that one should not trust classical GR solutions near the "event" horizon. The cumulative quantum effects can heavily effect the behavior of the metric, even if they are very small in this curved regions of spacetime [4].

We want to further expand this point for the Planck star model. The process previously described is like a quantum-mechanical tunneling process, from the collapsing black hole metric outside the quantum region, to an exploding white hole metric. The former "event" horizon would become a trapping horizon for the bouncing matter.

The most important point to note here is that the Planck star releases all of its matter in an explosion, so that there is no remnant of it after the evaporation. This has a huge impact on the thermodynamics of the Planck star and the associated Hawking radiation. However, this is beyond the scope of this essay [1–4].

Let us now have a look on what a Planck star looks like for different observers. An observer far away from the Planck star sees a long living black hole which suddenly explodes. He could detect the matter thrown out of the lookalike black hole. The Planck stars lifetime for this observer extremely differs from the proper time of the infalling matter due to the extreme gravitational time dilation for an exterior observer. Loop quantum gravity calculations for an effective metric for the quantum region yields a lifetime of the Planck star proportional to M^2, where M is the mass of the Planck star. The bouncing process is much faster than Hawking evaporation which is proportional to M^3. Consequently, if the hole process of gravitational collapse and bounce lasts milliseconds in proper time of matter, several billion years passes for an outside observer. This would mean that a Planck star act as a "time machine" to a far distanced future. If one uses the Hubble time, which has a value of 14.4 billion years, as the lifetime of a Planck star, one finds that it has a tiny mass. Primordial black holes are black holes, which were formed in the early universe by the high energy density of matter and not by the gravitation collapse of a star. Such tiny Planck stars could exist in the universe as primordial black holes. The existence of primordial black holes is controversial, although theories incorporated their existence because many creating processes for primordial black holes appear in different theories.

Short gamma-ray bursts are intense gamma radiation events observed in the cosmos. The origin of the extremely energetic explosions that create these bursts is not known so far. There are several theories of "standard" cosmology to explain the subclass of short gamma-ray bursts. The creators of the Planck star model think that nowadays light primordial black holes can explode and we would in principle be able to detect them. Moreover, they claim that the origin of the short gamma-ray bursts can be the explosion of a bouncing primordial black hole.

If exploding Planck stars are at the origin of short gamma-ray bursts, Vidotto, Rovelli and collaborators claim that there should be a unique red-shift signature in the signal. For a single event, one considers two signals which have different origins. First, the low energy signal is determined by the mass of the exploding Planck star. The second, the so-called high-energy signal component, is considered to be produced by high-energy photons which originally formed the Planck star in the early universe. These photons were created in a time where the universe was really hot compared to the present situation. Since Planck stars act as a time machines, one would expect these photons producing an energy spectrum similar to one, a black body at the temperature of the universe at the time of the Planck star formation. It is planned to perform precise calculations to determine the expected spectrum to compare with data of the detected short gamma-ray bursts [3].

This essay summarized the main ideas of the Planck star model and gave an overview of present research topics. In particular, the fact that quantum effects can have a major impact at scales many orders of magnitude larger than the Planck length, makes this model particularly interesting. Applying the quantum-mechanical tunneling process to the spacetime metric itself may change the understanding of its nature. The unknown origin of short gamma-ray bursts opens a large window for new ideas. Maybe Planck star explosions are responsible, but further research his needed in order to clarify this issue.

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