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PHYSICS

Speculative Sunday: Can a Black Hole Explode?

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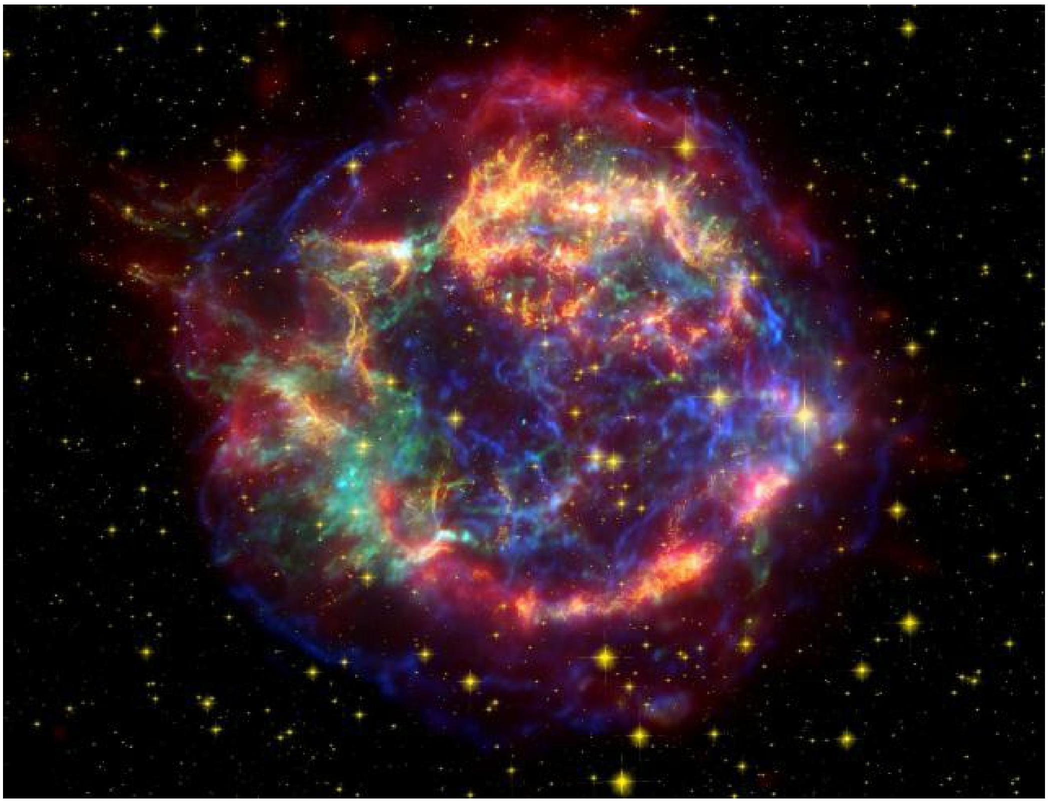

FIGURE 1. THE SUPERNOVA REMNANT CASSIOPEIA A, ALL THAT REMAINS OF A STAR THAT RAN OUT OF FUEL. IT CONTAINS EITHER A NEUTRON STAR OR A BLACK HOLE… COULD THAT BLACK HOLE SOMEDAY EXPLODE? (IMAGE CREATED USING DATA FROM THE HUBBLE, SPITZER, AND CHANDRA SPACE TELESCOPES.)

Nothing can escape the gravitational pull of a black hole, not even light. That's why they're, well, black. (Of course, as I've described before, black holes can glow very brightly, thanks to all the in-falling matter. Sometimes they even produce gamma rays. I'm also ignoring the negligible amount of Hawking radiation that black holes theoretically produce.) Once you pass the event horizon of a black hole, you cannot ever escape. Escape is simply forbidden by the laws of physics.

That is, of course…if there actually *is* an event horizon, not just something that looks like one. Carlo Rovelli , one of the founders of loop quantum gravity, recently proposed something crazy: Not only do black holes not *really* have event horizons, they eventually *explode.*

The conclusion is crazy, but the reasoning is surprisingly elegant. Let me walk you through it.

FIGURE 2. CARLO ROVELLI, ONE OF THE FOUNDERS OF LOOP QUANTUM GRAVITY. (SOURCE WIKIPEDIA.)

(**DISCLAIMER**: I want to emphasize that, although the science in this post is peer-reviewed, it's *extremely speculative.* The quantum gravity predictions I describe in this post are not guaranteed or even likely to be true.)

STELLAR COLLAPSE

The typical story of black hole formation (at least for stellar-mass black holes) goes something like this: A massive star runs out of nuclear fuel, and the fusion reaction keeping the star alive peters out. Without the energy from the fusion, the star can no longer resist its own gravitational pull and collapses in on itself. The resulting compression of its gases triggers a catastrophic explosion, ejecting a fair amount of the gas to leave behind the stellar core, which becomes increasingly dense. If the star is massive enough, the collapsing core squeezes into such a dense ball that it forms an event horizon and becomes a black hole. (If the star isn't quite massive enough, the core remnant is pushed outward by the Pauli exclusion principle and becomes a neutron star.) This is called a core-collapse supernova. Here's a video of a simulation of a supernova that results in a neutron star:

(I am, of course, glossing over a huge number of details. Core-collapse supernovae are not fully understood and there is a rich body of work devoted to understanding them…which many of my friends and collaborators are contributing to. See the bottom of the article for a small, hopefully accessible sampling of current research in core-collapse supernovae.)

THE SINGULARITY

Once the event horizon forms around the collapsing matter, no information can emerge from the black hole, so we don't know what's going on inside. General relativity predicts that the matter will keep collapsing until it forms an infinitely dense singularity. But the modern view among physicists is that this isn't what actually happens. Rather, the singularity is a sign that the theory of general relativity is incomplete. What happens inside the black hole can only be described by quantum gravity. We don't have a theory of quantum gravity, but we are actively searching for one and making (slow) progress.

THE QUANTUM BOUNCE

Rovelli and his collaborators speculate that these quantum gravity effects not only prevent the singularity from forming, but may in fact cause the black hole to explode.

One generic property of quantum mechanics is that it is probabilistic. Any self-respecting theory of quantum gravity will be probabilistic, too. Therefore, just as a proton has some probability of quantum tunnelling out of an atomic nucleus, a collapsing stellar core has some (admittedly tiny) probability of *quantum transitioning* into an explosion. But this will only happen when quantum gravity dominates–i.e., when the matter is so compact that it's almost a singularity.

Loop quantum gravity makes an analogous prediction about the early universe. Instead of a Big Bang singularity at the beginning of time, we had a "Big Bounce," where a collapsing universe transitions into an expanding one just in the regime where quantum gravity dominates. So why can't a black hole experience a similar *quantum bounce?*

Indeed, Rovelli and collaborators performed an ad-hoc calculation in the context of quantum gravity to find the amount of time it should take for a collapsing star to quantum tunnel into an explosion. They found that it happens quickly enough to avoid forming a singularity.

WHAT ABOUT THE EVENT HORIZON?

Some of you may be asking, "What about the event horizon?" If nothing can escape the event horizon, then doesn't that mean the stellar material that makes up the black hole also can't escape?

You're absolutely right! If an event horizon forms, nothing can escape it. However, in Rovelli et al.'s proposal, an event horizon never forms. Instead, an *apparent* horizon forms. Like an event horizon, this is a region that light cannot escape from. But unlike an event horizon, it is only temporary. The details are technical, but Rovelli and collaborators have cooked up a model spacetime in which the horizon is\n not a true event horizon—only an apparent horizon.

SO WHERE ARE ALL THE EXPLODING BLACK HOLES?

If black holes do experience a *quantum bounce* and form neither singularities nor event horizons, and if the bounce happens at the end of collapse, where are all the explosions? Surely we would have seen them!

Well, not so fast. Time warps in the presence of a strong gravitational field. In fact, near the collapsing star, time will distort so much that a tiny amount of time near the star will appear to be b\nillions of years to a distant observer. Therefore, all the black holes we observe out in the universe—and we observe many—are in the process of collapsing and bouncing into an explosion behind their apparent horizons.

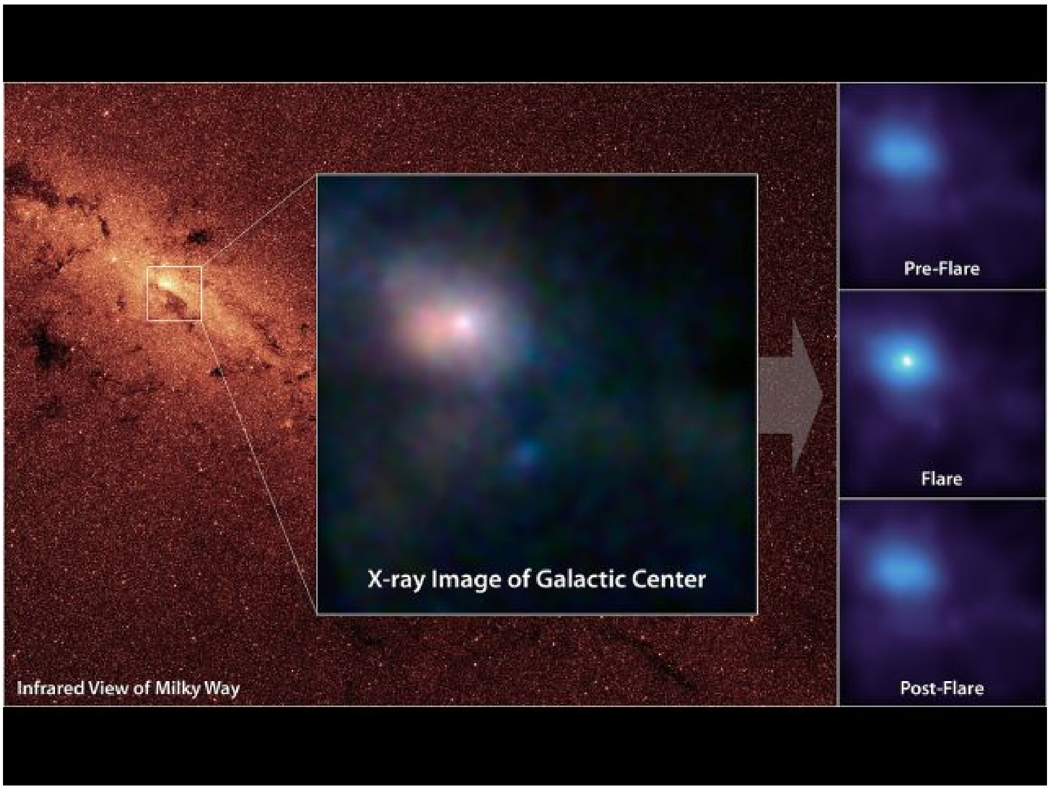

FIGURE 3. X-RAY IMAGERY OF THE SUPERMASSIVE BLACK HOLE AT THE CENTER OF THE MILKY WAY, SAGITTARIUS A*, CAPTURED BY NUSTAR.

PRIMORDIAL BLACK HOLES AND FAST RADIO BURSTS

If Rovelli and collaborators are right, the first black holes that formed in the universe, which formed many billions of years ago, should be exploding about now. And when they explode, they should release a huge amount of energy. Some of this energy will be emitted as light, which we can detect.

The earlier the exploding black hole formed in the history of the universe, the less massive it will be. And this corresponds to a shorter wavelength of the emitted light. But, because the speed of light is constant, looking further away from Earth means looking back in time. So the wavelength of light emitted by exploding black holes should change depending on how far away the black hole is. After correcting for cosmological redshift, this results in a very peculiar and distinct wavelength of light as a function of distance, shown in **figure 4.**

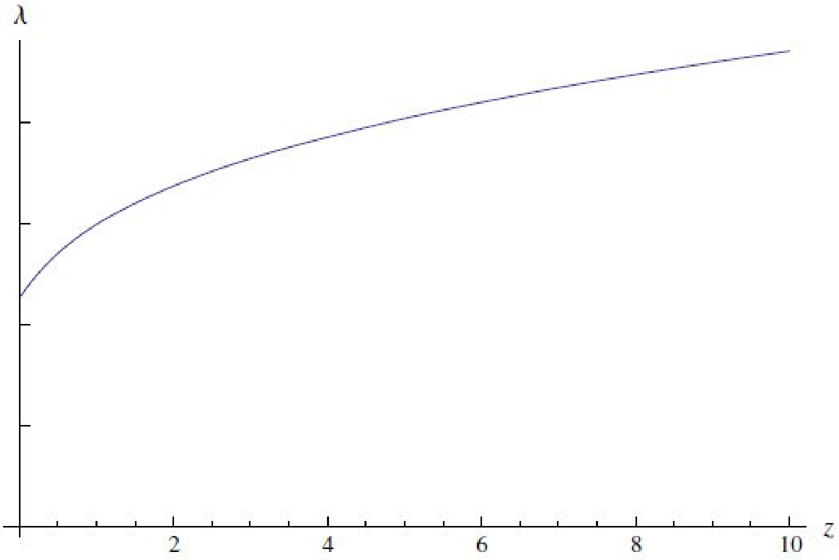

FIGURE 4. THE WAVELENGTH OF LIGHT PRODUCED BY EXPLODING BLACK HOLES (IN ARBITRARY UNITS) AS A FUNCTION OF DISTANCE FROM US (IN REDSHIFT). SOURCE: ROVELLI AND VIDOTTO

So all we have to do is look for some light coming from outside the galaxy and see if we can compare the wavelength of the light to its distance from us. If it matches the curve in **figure 4**, then Rovelli and collaborators are right. Otherwise, they're not.

Rovelli and collaborators suggest using fast radio bursts, which have approximately the right wavelength and may be of extragalactic origin, to test the model. So far, we don't know very much about fast radio bursts. If they turn out to come from exploding black holes, this would be very exciting, because it would be a real probe of quantum gravity.

BLACK HOLE INFORMATION LOSS

Rovelli and collaborators aren't the first to propose that black hole event horizons don't exist. Previously, Rovelli proposed that black holes evaporate into so-called "Planck stars" that remain after a black hole disappears. Stephen Hawking recently argued that black holes only appear to have event horizons be\ncause the spacetime around them is turbulent. There is a rich history of such proposals.

These proposals are all motivated by the so-called black hole information paradox. Basically, we believe that information in the universe is *conserved*. It cannot be created or destroyed. When information falls into a black hole, it is irretrievable. This wouldn't be so bad, except that the black hole eventually disappears because it gives up its energy to Hawking radiation, which doesn't transmit all the information in the black hole. Therefore, once the black hole evaporates, all the information that fell into it is lost forever…simply gone from the universe. But that seems to break the law of conservation of information.

Rovelli's proposal gets around the paradox by proposing that black holes explode and eject all information they contain. And this is certainly one motivation for him considering it.

SPHERICAL COWS

I want to emphasize that Rovelli's proposal is *ridiculously* speculative. He is relying on arguments from quantum gravity, which we don't even remotely understand. And even the arguments that don't use quantum gravity are rather contrived.

Rovelli writes down a quantitative model of the collapsing and bouncing star, but it's very simplistic…in fact, I'd call it the general relativity version of a "spherical cow." The spacetime has a region in which quantum gravity is non-negligible, which means a region in which physics we don't understand take place. And the collapsing star is modelled as a thin spherical shell of matter, which is way too simple. (Furthermore, spherical shells of matter are known to have pathologies) Worse yet, the expansion of the matter post-bounce is modelled as a white hole, which is known to be intrinsically unstable.

Yet, despite all that, Rovelli's proposal is a cool idea. And I like it.

FURTHER READING

- You can find Rovelli and collaborators' first paper on the bouncing black holes here. The paper where they predict that fast radio bursts come from exploding black holes is here.
- For a review of the physics of core-collapse supernovae, first published in*Nature*, check out this article.
- The physics of core-collapse supernovae are very complicated, and accurately modelling this phenomenon is an open problem in the numerical relativity community. Professor Christian Ott wrote an awesome article about some of the challenges the community faces (revealed by his and his collaborators' research), which you can find here.
- This is a nice article by PBS on Hawking's recent claim that black holes don't exist and how it relates to the black hole information paradox.
- This is a great article by Sabine Hossenfelder about what we hope to gain from a theory of quantum

gravity.