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Can black hole superradiance be induced by galactic plasmas?

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ABSTRACT

Highly spinning Kerr black holes with masses $M = 1$–$100\ M_\odot$ are subject to an efficient superradiant instability in the presence of bosons with masses $\mu \sim 10^{-10}$–10^{-12} eV. We observe that this matches the effective plasma-induced photon mass in diffuse galactic or intracluster environments ($\omega_{\rm pl} \sim 10^{-10}$–$10^{-12}$ eV). This suggests that bare Kerr black holes within galactic or intracluster environments, possibly even including the ones produced in recently observed gravitational wave events, are unstable to formation of a photon cloud that may contain a significant fraction of the mass of the original black hole. At maximal efficiency, the instability timescale for a massive vector is milliseconds, potentially leading to a transient rate of energy extraction from a black hole in principle as large as $\sim 10^{55}$ erg s^{-1}. We discuss possible astrophysical effects this could give rise to, including a speculative connection to Fast Radio Bursts.

1. Introduction

The recent observations of gravitational waves by LIGO, interpreted as binary black hole (BH) mergers [1–5], provide evidence for the abundant existence of stellar mass BHs with $M \lesssim 70\ M_\odot$, likely described by the Kerr metric [6]. It is well known that these rotating BHs can release their rotational energy via the remarkable phenomenon of *superradiance* [7]. This mechanism amplifies modes of a bosonic particle which are sufficiently low frequency and co-rotate with the BH. Confining such modes within the vicinity of the Kerr BH, for instance due to the particle's mass μ, triggers an instability [8]. The superradiant modes undergo repeated amplification, and the BH's rotational energy sources the growth of a boson cloud around the BH.

The endpoint of the process is unknown, despite recent progress with fully non-linear numerical simulations [9]. For a real boson field (unlike a complex one [10–12]), there is no known stationary state of a BH with a boson cloud, and so the latter must decay. Depending on the effect of non-linearities, two possible scenarios are (i) a smooth saturation of the growth, followed by a steady cloud decay via the emission of gravitational radiation [13]; or (ii) the occurrence of an explosive phenomenon akin to a *bosenova* that generates higher frequency bosonic modes that are expelled from the cloud towards infinity [14,15].

For test fields in the linear regime, the instability has been studied most extensively for the case of a massive scalar [16–23], but recently it has also been possible to obtain the growth rates for the case of a massive vector, using either approximate schemes [24–26] or time evolutions [27,28].

Superradiant instabilities triggered by a massive bosonic field are most efficient when the gravitational radius of the BH is of the order of the Compton wavelength of the particle. In natural units, this means the *mass coupling* is order unity:

$$M\mu \sim 1 \quad \Leftrightarrow \quad \left(\frac{M}{M_\odot}\right)\left(\frac{\mu}{10^{-10}\ \text{eV}}\right) \sim 1\ , \tag{1}$$

where M is the BH mass. Thus, for astrophysical stellar mass BHs ranging from 1–100 $M_\odot$, an efficient instability is achieved for ultralight bosons with masses $\mu \sim 10^{-10}$–10^{-12} eV. The case of supermassive BHs requires even lighter particles. Since no fundamental particles in this mass range are known, many astrophysical studies of the superradiant instability invoke physics beyond the standard model, *e.g.* the axiverse scenario [13].

An alternative possibility, which does not rely on new physics, is that superradiance is caused by an *effectively* massive particle. In this context, it has long been observed that superradiance could be due to photons propagating in a plasma [8], wherein they are effectively described by a Proca equation $\nabla_\alpha F^{\alpha\beta} = \omega_{\rm pl}^2 A^\beta$. This idea

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has been used in [29] for constraining the contribution to dark matter of spinning primordial BHs.

This paper is founded on a simple numerical observation which, nonetheless, has not to our knowledge been made before: the numerical matching of equation (1) is satisfied for stellar mass BHs and the photon plasma mass applicable within the diffuse environment of galaxies or galaxy clusters. More precisely, the effective photon mass in a plasma is given by

$$\omega_{pl} = \left(4\pi\alpha \frac{n_e}{m_e}\right)^{1/2} = 1.2\cdot 10^{-12}\sqrt{\frac{n_e}{10^{-3}\ \mathrm{cm}^{-3}}}\ \mathrm{eV}\,,$$

where $\alpha = \frac{e^2}{4\pi c\epsilon_0\hbar}$ is the fine structure constant. The diffuse galactic free electron density is described by (for example) the NE2001 model [30]. It varies from around $n_e \sim 10\ \mathrm{cm}^{-3}$ in the inner ~ 50 pc of the galaxy, through around $4\times 10^{-2}\ \mathrm{cm}^{-3}$ near our solar system, falling away rapidly as one moves vertically away from the disk (*e.g.* see [30–32]). In the intracluster medium within galaxy clusters, $n_e \sim 3\times 10^{-2}\ \mathrm{cm}^{-2}$ near the centre of cool core clusters, with $n_e \sim 3\times 10^{-3}\ \mathrm{cm}^{-3}$ at the centre of a bright non-cool-core cluster such as Coma, and with $n_e \sim 10^{-3}\ \mathrm{cm}^{-3}$ as a 'typical' value within a galaxy cluster. In deep intergalactic space, n_e reaches $\sim 10^{-7}\ \mathrm{cm}^{-3}$.

It follows that within a typical 'empty' interstellar environment within a galaxy or galaxy cluster, the photon has an effective mass given by ω_{pl} which is in the range 10^{-12}–10^{-10} eV. Electromagnetic modes with $\omega < \omega_{pl}$ are therefore unable to propagate, suggesting that, when confined by the plasma near to the BH, they will undergo superradiant amplification. Thus, this observation seems to imply that *bare*, highly spinning stellar mass Kerr BHs in galactic or intracluster environments would be unstable to superradiant amplification of low-energy electromagnetic modes that are confined by the ambient galactic plasma.

The general nature of the superradiant instability leads to a formation of a boson cloud around Kerr BHs. In the scalar (vector) case this has been shown to comprise up to $\mathcal{O}(20\%)$ [$\mathcal{O}(10\%)$] of the mass of the original BH [33] ([9]). A photon-induced instability may then lead to a rapid transfer, on millisecond timescales, of energy from the mass of the BH into a photon cloud bound by the gravitational potential of the BH with potentially observable consequences.

2. The superradiant instability

The linearity of the massive Klein–Gordon or Proca equations (mass μ), as test fields on the Kerr background, allows us to study a single mode, in the frequency domain, to understand the basic features of the superradiant instability's *linear phase*, triggered by these fields. Then, each Fourier mode of the scalar/Proca field is characterized by a set of quantum numbers, including the angular ones, ℓ, m, and a complex frequency, $\omega = \omega_R + i\omega_I$. Analytic computations of ω_R, ω_I can be done in the asymptotic regimes $M\mu \ll 1$ or $M\mu \gg 1$. For the real part, to lowest order in $M\mu$, one finds a hydrogen-like spectrum, since, asymptotically, the field experiences a $1/r$ potential on the Kerr geometry [22,25,34]. Here we are mostly interested in the imaginary part, whose inverse determines the instability timescale $\tau_{SR} = w_I^{-1}$. For $M\mu \ll 1$, the wave equation can be dealt with using a matching method and one finds that $M\omega_I$ is suppressed as $(M\mu)^a$, where $a = 9$ for scalars [16] and $a = 4\ell + 5 + 2S$ for vectors [25], with $S = 0, \pm 1$ being the mode's polarization. For $M\mu \gg 1$, which requires large quantum numbers $m, \ell \gg 1$, the wave equation is amenable to the WKB approximation and one finds that $M\omega_I$ is suppressed as $e^{-bM\mu}$, where $b = 1.84$ for scalars [17]. In the optimal regime for the instability $M\mu \sim 1$, the information must be obtained numerically. Then, for both the scalar case [21] and vector case [27], the largest growth rates are obtained for the $\ell = m = 1$ mode on an almost extremal Kerr BH $a \sim 0.99$ and for $M\mu \sim 0.4$ and they are: $\tau_{SR}^{scalar} \sim 10^7 M$, $\tau_{SR}^{Proca} \sim 10^3 M$. These results show that the timescale for the vector instability is far more rapid than that for the scalar instability. The strongest instability for the vector case can be expressed as

$$\tau_{SR}^{Proca} \sim 10^{-2}\gamma_{-11}^{-1}\left(\frac{M}{M_\odot}\right)\mathrm{s} \sim 5\times 10^{-4}\left(\frac{M}{M_\odot}\right)\mathrm{s}\,, \tag{2}$$

using $\gamma_{-11} \sim 20$ [25] (see also [35]). This number was estimated in the small rotation regime but the numerical results of [27] show that for highly spinning Kerr BHs the corresponding instability timescales differ only by a factor of 2 (see also [28]). Thus for $M \sim \mathcal{O}(1\text{–}100)\ M_\odot$, the corresponding timescales are $\tau_{SR}^{Proca} \sim 0.5$–50 ms.

Beyond the linear regime, the evolution for either the scalar or vector case is not precisely known. Partial results using different approximations suggest 1) the superradiant growth may extract a considerable fraction of the original BH's mass (up to ∼20% in the scalar case [33] and up to ∼10% in the vector case [9])). For a real field, the cloud will necessarily eventually decay by emission of gravitational and (for a photon cloud) electromagnetic waves; 2) before (or instead of a smooth) saturation, non-linear phenomena may trigger an explosion akin to a bosenova, terminating the superradiant growth. This phenomenon has been studied for a self-interacting scalar field via numerical simulations [15,36,37]. Depending on the initial data, different outcomes are possible, including the ejection of part of the bosonic cloud away from the BH, associated to the generation of higher frequency modes. Another part of the cloud falls towards the BH, terminating the energy extraction. The instability may, however, kick in again, creating recurrent cycles [14,15].

In the vector case, photon self-interactions can arise either from the induced four-photon interaction in the low energy limit of QED (the Euler–Heisenberg term [38]) or from the effect of the electric and magnetic fields of the photon cloud on the surrounding plasma. In the presence of photon self-interactions, which become important once the photon cloud grows beyond some threshold, a similar phenomenon should arise for the Proca case, causing dissipation of some part of the cloud, and re-absorption of the remaining part into the BH. Once this happens, the instability can become operative again.

As galactic plasma frequencies correspond to long-wave radio frequencies (10^{-10} eV $\equiv$ 24 kHz), such a "bosenova" would be observed as an electromagnetic burst in radio frequencies, which we dub a "*radionova*".

3. Astrophysical scenario: formation of a bare BH

Our above usage of the diffuse galactic plasma mass would only apply for photons around a BH if the latter is "bare". In the presence of a substantial accretion disk, or for the case of a stellar-BH binary in which the star provides a continual source of matter, the local free electron density is likely to be significantly higher than for the diffuse galactic plasma. For this reason, one would not expect a BH spun up by an accretion disk to be unstable whilst the accretion disk remains; the local plasma mass is large and for $M\omega_{\mathrm{pl}} \gg 1$ the superradiant instability timescale is exponentially suppressed with $e^{+M\omega_{\mathrm{pl}}}$. How can we ensure the presence of a bare BH?

A conservative way is to consider a BH produced following a binary BH merger. We know that such mergers occur in the universe and are capable of producing BHs with (dimensionless) spin