Direct detection of Black Holes via electromagnetic radiation

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ABSTRACT

Many black hole (BH) candidates exist, ranging from supermassive ($\sim 10^6$–$10^{10} M_\odot$) to stellar masses ($\sim 1$–$100 M_\odot$), all of them identified by indirect processes. Although there are no known candidate BHs with sub-stellar masses, these might have been produced in the primordial Universe. BHs emit radiation composed of photons, gravitons and, later in their lives, massive particles.

We explored the detection of such BHs with present day masses from $10^{-22} M_\odot$ to $10^{-11} M_\odot$. We determined the maximum distances ($d$) at which the current best detectors should be placed in order to identify such isolated BHs. Broadly, we conclude that in the visible and ultraviolet BHs can be directly detected at $d \lesssim 10^7$ m while in the X-ray band the distances might reach $\sim 10^8$ m (of the order of the Earth-Moon distance) and in the $\gamma$-ray band BHs might even be detected from as far as $\sim 0.1$ pc.

Since these results give us realistic hopes of directly detecting BHs, we suggest the scrutiny of current and future space mission data to reach this goal.

Key words: black hole physics.

1 INTRODUCTION

Black Holes (BHs) are objects predicted by the laws of Physics: they naturally arise by solving the field equations of General Relativity. In terms of mass, a BH can be classified as supermassive ($\sim 10^6$–$10^{10} M_\odot$), intermediate ($\sim 10^3$–$10^5 M_\odot$), stellar ($\sim 1$–$100 M_\odot$) or sub-stellar ($< 1 M_\odot$). It is now well-established that supermassive BHs (SMBHs) reside in the centres of galaxies (e.g. Natarajan & Treister 2009) including our own galaxy with a $4.4 \times 10^6 M_\odot$ SMBH (e.g. Genzel, Eisenhauer, & Gillessen 2010). Intermediate mass BHs might form either in the core of star clusters (e.g. Portegies Zwart et al. 2004) or galaxies (e.g. Greene & Ho 2004). These BHs can be detected indirectly by studying the gas and star dynamics on their surroundigs. In fact, a few have now been found (e.g. Greene 2012).

A stellar mass BH is the likely remnant of an exploded star with an initial mass greater than $\sim 40$–$60 M_\odot$. It is best detected if it is part of a binary system with a giant star as companion from studying its dynamics. Another path to detection arises when the giant star gas, if fueling a BH, forms an accretion disk, the inner parts of which shine brightly in X-rays and $\gamma$-rays. With an estimated mass of $14$–$16 M_\odot$, the X-ray source Cyg X1 is the strongest candidate for a stellar mass BH in a binary system (Orosz et al. 2011).

It seems that the only way to form BHs with masses smaller than about 3 $M_\odot$ in the present Universe is in accelerators such as the Large Hadron Collider (e.g. Dimopoulos & Landsberg 2001; Cavaglià, Das, & Maartens 2003) or, eventually, when cosmic-rays collide with the upper layers of the atmosphere (e.g. Anchordoqui et al. 2002). However, in both cases, the detection of BHs (with a few Planck masses $M_P \sim 10^{-8}$ kg) might only take place within the framework of extra dimensions. Rather more promising is the possibility of these smaller BHs ($< 3 M_\odot$) having been formed during the early stages of the Universe (in which case they are called Primordial Black Holes (PBHs)) due, for example, to the gravitational collapse of density fluctuations (Hawking 1974).

Hawking (1974) has shown that, when quantum effects are taken into account, BHs radiate. This process hardly affects stellar mass BHs, but it could be very significant in the case of smaller mass PBHs. In fact, PBHs with initial masses $\sim 10^{15}$g ($\sim 10^{-18} M_\odot$) might be exploding right now (e.g. Page & Hawking 1976; Carr 1976; MacGibbon & Carr 1991; Barrau 2000) while less massive ones should already have completely evaporated. PBHs with initial masses $\gtrsim 10^{15}$g ($\gtrsim 10^{-18} M_\odot$) might still be lurking around us, evaporating and/or accreting matter (Sobrinho 2011).

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In this paper we explore the pathway for direct BH detection which, if someday successful, could revolutionize the way we identify BHs in the Universe. We finalize by suggesting the use of space mission data in order to achieve this.

2 BLACK HOLE THERMODYNAMICS

2.1 Primary emission

A BH is completely characterized by only three parameters: mass $m$, electric charge $e$ and angular momentum per unit mass $a$. These parameters must follow the relation $a^2 + e^2 \leq m^2$ (e.g. Davies 1978) with $m$, $e$, and $a$ written in geometric units ($c = G = 1$; $G$ is the gravitational constant; $c$ the speed of light). There is a remarkable analogy between the laws of BH mechanics and the laws of Thermodynamics (e.g. Wald 1998). Thus, it is possible to assign between the laws of BH mechanics and the laws of Thermodynamics: mass $m$, angular momentum per unit mass $\epsilon = e/m$ and energy $\hbar \nu$. Writing $\Psi = \Psi (\epsilon, a)$.

\[ T = \frac{\hbar c^3}{2 \pi \kappa G M} \approx 6.2 \times 10^{-8} \frac{M_{\odot}}{M} \text{[K]} \]  

We may relate this temperature with the wavelength $\lambda_{\mathrm{max}}$ at which the emission gets its intensity peak since we have, according to Wien’s Displacement Law (e.g. Eisberg & Resnick 1985):

\[ T \lambda_{\mathrm{max}} = 2.898 \times 10^{-3} \text{[Km]} \]

A Schwarzschild BH emits particles with energy in the range $(E, E + dE)$ at a rate (e.g. Halzen et al. 1991)

\[ \frac{d^2N}{dE dt} = \frac{\Gamma} {2 \pi \hbar} \left[ \exp \left( \frac{8 \pi G M E}{\hbar c^3} \right) - (-1)^{2s} \right]^{-1} \]

per degree of particle freedom. Here $s$ is the spin particle, $M$ the mass of the BH and $\Gamma$, the dimensionless absorption coefficient which is, in general, a function of $s$, $M$ and $E$. In the low-energy limit ($GME/\hbar c^3 \ll 1$) we have (MacGibbon & Webber 1990)

\[ \Gamma_s (M, E)_{E \rightarrow 0} \approx \frac{4 \pi G M^4 E^4}{3 \hbar c^2} \]  

\[ \Gamma_s (M, E)_{E \rightarrow -\infty} \approx \frac{27 G^2 M^2 E^2}{h^2 c^6} \]

In the case of the photon ($s = 1$) equation (4) becomes

\[ \frac{d^2N}{dE dt} = \frac{\Gamma} {2 \pi \hbar} \left( \exp \left( \frac{8 \pi G M E}{\hbar c^3} \right) - 1 \right)^{-1} \]

which gives us the number of photons emitted per unit energy, per unit time. Considering that $E = \hbar \nu$ this becomes

\[ \frac{d^2N}{d\nu dt} = \Gamma_s \left( \exp \left( \frac{8 \pi G M E}{\hbar c^3} \right) - 1 \right)^{-1} \]

which gives us the number of photons emitted per unit frequency, per unit time.

2.2 $\gamma$-ray emission

As a BH radiates due to the Hawking process it loses mass or, in other words, it evaporates. The rate at which a BH evaporates can be written as (e.g. Maki, Mitsui, & Orito 1996)

\[ \frac{dM}{dt} = -5.34 \times 10^{16} f(M) \text{[kgs$^{-1}$]} \]

where $f$ is a non-dimensional function of the BH mass $M$ accounting for the contributions of the different species of particles being emitted by the BH (e.g. MacGibbon 1991, Gibilisco 1997). When $M \geq 10^{14}$ kg we have $f(M) \approx 1$ (e.g. Maki et al. 1996) and for $M \ll 10^8$ kg we have $f(M) \approx 15.4$ (e.g. Semikoz 1994). Taking into account that $f(M)$ varies very slowly with $M$ (e.g. He & Fang 2002) we can integrate equation (10) in order to obtain

\[ t_{\text{evap}} \approx \frac{M_i^3 - M_f^3}{1.6 \times 10^{17} f(M_f)} \text{[s]} \]

which is the time required for a BH to change its mass from the initial value $M_i$ to the final value $M_f$ ($M_f < M_i$).

As the evaporation goes on, the BH will start emitting massive particles, besides photons and gravitons (Page & Hawking 1976). In particular, an evaporating BH starts emitting hadrons, beginning with the lightest ones which are the $\pi^0$ mesons ($m_{\pi^0} \approx 2.4 \times 10^{-28}$ kg) when its mass is $\sim 10^{12}$ kg which corresponds to a Schwarzschild radius
of the order of the strong nuclear force range (~10^{-15} m). Because of that, the BH will emit jets of quarks and gluons instead of composed particles (Page & Hawking 1976). Emitted quarks and gluons develop into hadron jets with a predominance of π mesons (e.g. Semikoz 1994).

All three known kinds of π mesons appear in a jet with the same probability. Every π^+ or π^- meson decays into electrons, positrons and neutrinos. As for the π^0 mesons, each one of them decays into two γ-ray photons (e.g. Semikoz 1994). We call these secondary γ-rays in contrast to the γ-rays emitted directly by the BH which we call primary γ-rays.

In order to properly determine the global γ-ray spectrum emitted by the BH, equation (4) must be convolved with the fragmentation function for pions which gives the number of pions produced in the energy interval (\(E, E + dE\)) due to a quark-gluon jet of energy \(Q\) (MacGibbon & Webber 1990). An empirical expression for this function is given by (e.g. Halzen et al. 1991)

\[
d\frac{d\pi}{dE} = \frac{15}{16} \pi \frac{z}{1 - z}^2 \quad (12)
\]

where \(z = E/Q\). Detailed simulations have shown that the γ-ray spectrum from evaporating BHs is quite broad, peaking at ~100 MeV and cutting off at \(E \approx m_\pi\) (MacGibbon & Webber 1990; Halzen et al. 1991).

If the lifetime of the BH is large compared with the observation time then the instantaneous flux of γ-ray photons (primary and secondary) emitted by a BH above some energy threshold \(E_D\) can be written as (Halzen et al. 1991)

\[
d\frac{dN_\gamma}{dE}(> E_D) \approx 8.0 \times 10^{23} \frac{Q}{1 \text{ GeV}} \left[ \frac{1}{4} \left( \frac{Q}{E_D} \right)^{1/2} \left( 1 + \frac{E_D^2}{Q^2} \right)^{1/2} - \frac{3}{2} \frac{E_D}{Q} \right] s^{-1} \quad (13)
\]

where \(Q\) is the peak energy of the quark flux expressed in GeV.

3 DETECTION OF BH RADIATION

3.1 Maximum distance for detection (general)

The BH brightness, i.e., the energy emitted per unit time, per unit area, per unit frequency \(\nu\), can be written, multiplying equation (9) by the photon energy \(\nu h\) and dividing it by the BH surface area \(4\pi r_s^2\) (where \(r_s = 2GM/c^2\)) as

\[
B_\nu(T) = \frac{\Gamma \nu h}{4\pi r_s^2 c} \left[ \exp\left( \frac{8\pi^2 r_s \nu}{c} \right) - 1 \right]^{-1}. \quad (14)
\]

Let \(S_\nu\) be the flux density (energy arriving per unit time, per unit frequency \(\nu\)) reaching a detector placed at some distance \(d\) from the centre of the BH. The values of \(B_\nu\), \(S_\nu\) and \(d\) are then related by (e.g. Lang 1999)

\[
S_\nu = \Omega_s B_\nu(T) = \frac{\pi r_s^2}{d^2} B_\nu(T) \quad (15)
\]

where \(r_s\) is the Schwarzschild radius and \(\Omega_s\) is the solid angle subtended by the BH in the sky. Considering \(S_\nu\) equal to some detector sensitivity, then the distance \(d\) is the maximum distance at which we can detect a Schwarzschild BH of radius \(r_s\) at a particular frequency \(\nu\). We get from equation (15)

\[
d_{\text{max}} = \left( \frac{\pi r_s^2}{S_\nu} B_\nu(T) \right)^{1/2} \quad (16)
\]

In practice, a detector operates at some frequency band \([\nu_1, \nu_2]\) which means that it is more accurate to consider

\[
d_{\text{max}} = \left( \frac{\pi r_s^2}{S_\nu} \frac{1}{\Delta \nu} \int_{\nu_1}^{\nu_2} B_\nu(T) d\nu \right)^{1/2} \quad (17)
\]

where \(\Delta \nu = \nu_2 - \nu_1\). When the emission stays within the same order of magnitude along the entire bandwidth it is sufficient to consider the value of \(B_\nu(T)\) evaluated at the central frequency (equation (16)). When the emission peak is far from this central frequency it is more accurate to use equation (17) instead.

3.2 Maximum distance for detection (γ-rays)

The present day γ-ray detectors count individual photons over the background instead of measuring energy fluxes. The detectable number of γ-ray photons per unit time, emitted by a BH at some distance \(d\) and zenith angle \(\theta\) is given by (e.g. Alexandreas et al. 1993; Petkov et al. 2011)

\[
n_{\gamma}(d, \theta, t) = \frac{1}{4\pi d^2} \int_{E_1}^{E_2} \frac{d^2N_{\gamma}}{dEdt} \delta(E, \theta) dE \quad (18)
\]

where \(\frac{d^2N_{\gamma}}{dEdt}\) is the number of photons emitted on \([E, E + dE]\) per unit time, \(\delta(E, \theta)\) the effective area of the detector as a function of the γ-ray photons energy and the zenith angle \(\theta\), and \([E_1, E_2]\) represents the detector energy bandwidth.

For simplicity, we assume that the source is always near the zenith (\(\theta \approx 0^\circ\)) and that the effective area at normal incidence remains constant for the entire bandwidth. We can then write equation (18) in the form

\[
\frac{n_{\gamma}}{A} \approx \frac{1}{4\pi d^2} \left( \frac{dN_{\gamma}}{dt}(> E_1) - \frac{dN_{\gamma}}{dt}(> E_2) \right). \quad (19)
\]

The left hand side of equation (19) gives us the number of γ-ray photons reaching the detector per unit time per unit area. This value decreases as one moves away from the BH. Eventually there is a particular distance for which the left hand side of equation (19) equals the detector sensitivity (which, in the case of γ-ray detectors, is usually expressed in \(\text{ph cm}^{-2}\text{s}^{-1}\)). This distance corresponds to the maximum distance at which we can detect the BH with some particular detector. Thus, replacing the entire left hand side of equation (19) by that detector sensitivity \(S\) we get for the maximum distance of detection

\[
d_{\text{max}} = \left[ \frac{1}{4\pi S} \left( \frac{dN_{\gamma}}{dt}(> E_1) - \frac{dN_{\gamma}}{dt}(> E_2) \right) \right]^{(1/2)}. \quad (20)
\]

3.3 Current detector sensitivities from radio to γ-ray

If the sensitivity comes in magnitudes (as it is usual at UV, optical, and IR wavelengths; through the use of a filter – e.g. Johnson B (Johnson 1966)) we must convert it to a flux
density. In order to express an apparent magnitude $m_a$ as a flux density $S_f$ we use the expression (e.g. Zombeck 1990)

$$m_a - m_0 = -2.5 \log \frac{S_f}{S_0}$$  \hspace{1cm} (21)

where $m_0$ is a reference magnitude (usually $m_0 = 0$ is defined for the star Vega at all colours/filters) and $S_0$ is the corresponding flux density. If $m_a$ corresponds to the limiting magnitude of the telescope for a filter $X$ with central wavelength $\lambda_X$ and bandwidth $2\Delta \lambda_X$ (defined at half the peak through-flux), then $S_f$ will be the corresponding sensitivity $S_f$, at $\nu_X = c/\lambda_X$ (with propagating error $\Delta \nu_X = c \Delta \lambda_X / \lambda_X^2$).

In what follows we particularize our study by separating the electromagnetic spectrum into six bands, using the currently known limitations in sensitivity for each one (Table 4).

There are, at present, several radio telescopes and interferometer arrays operating from the millimeter and sub-mm to metric waves. Sensitivities vary according to the detector versus and the most sensitive reaches (i.e., SST) and considered a maximum sensitivity of $S_\nu = 5 \times 10^{-16}$ Jy (232 nm) and $S_\nu = 1.6 \times 10^{-9}$ Jy (154 nm).

The Herschel Space Observatory covers the far-infrared band (now that it is working in its warm phase). We picked 3 wavelengths in the near-infrared band (Johnson 1966): $0.44 \, \mu m$, $0.55 \, \mu m$, and $0.70 \, \mu m$, respectively. Refering to Vega, $m_0 = 0$ corresponds, in the case of the filter V, to $S_0 = 3670 \, Jy$ (Zombeck 1990). Then, from equation (21), with $m_a = 30 \, mag$, we get $S_\nu = 3.7 \times 10^{-9} \, Jy$. For filters B and R we get similar results. We, then, picked filter V which is central to the optical band.

The instruments onboard the Galaxy Evolution Explorer (GALEX), were able to detect radiation at 232 nm (near-UV) and 154 nm (far-UV) down to a limiting magnitude of, respectively, $m_a = 24.4$ and $m_a = 24.8$. The white dwarf LDS749B is used as the primary GALEX standard with the reference magnitudes $m_0 = 20.1$ (232 nm) and $m_0 = 18.8$ (154 nm) (Morrissey et al. 2007). The radiation flux of L749B is $2.68 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ when $\lambda = 232 \, nm$ and $2.66 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ when $\lambda = 154 \, nm$ (Bok et al. 2008) which corresponds to, respectively, $S_\nu = 2.3 \times 10^{-4}$ Jy and $S_\nu = 9 \times 10^{-7}$ Jy (multiplying the given values by the corresponding bandwidths — see Table 4 and converting the obtained results to Wm$^{-2}$s). Making use of equation (21) we get the sensitivities $S_\nu = 1.8 \times 10^{-8}$ Jy (232 nm) and $S_\nu = 1.6 \times 10^{-9}$ Jy (154 nm).

The most sensitive X-ray telescope operating in orbit is the X-ray Multi-mirror Mission (XMM-Newton). It has, for example, a sensitivity of $S_\nu = 5 \times 10^{-16}$ Jy at 0.2–0.5 keV (soft X-rays) (Hasinger et al. 2001), $S_\nu = 8.5 \times 10^{-15}$ Jy at 0.5–2.0 keV (soft and mid X-rays), and $S_\nu = 2 \times 10^{-10}$ Jy at 5–10 keV (mid X-rays). Sensitivities in Jy were obtained dividing the given value in ergs cm$^{-2}$ s$^{-1}$ (after conversion to Wm$^{-2}$s$^{-1}$) by the corresponding bandwidth. For example, at 0.5–2.0 keV we have (see Hasinger et al. 2001) $S_\nu = 3.1 \times 10^{-16}$ ergs cm$^{-2}$ s$^{-1} = 3 \times 10^{-12}$ Wm$^{-2}$ Hz$^{-1}$. Dividing this value by the bandwidth $\Delta \nu \approx 3.6 \times 10^{17}$ Hz (which corresponds, in terms of energy, to 1.5 keV) we get $S_\nu = 8.5 \times 10^{-17}$ Wm$^{-2}$ Hz$^{-1}$ (near-UV) and 154 nm down to a limiting magnitude of $0.165 \, \mu m$ (mid X-rays) which are central to the considered bands — see Table 4.

In the soft γ-ray domain the detectors on board the INTEGRAL Gamma-Ray Astrophysics Laboratory (INTEGRAL) allow for observations between 175 keV (hard X-rays) and 10 MeV (soft γ-rays) with a typical sensitivity of $\approx 5 \times 10^{-7}$ ph cm$^{-2}$ s$^{-1}$ keV$^{-1}$ (Ubertini et al. 2003). In the medium γ-ray domain the Fermi Gamma-ray Space Telescope allows for observations between 20 MeV and 300 GeV with a sensitivity of $\approx 3 \times 10^{-9}$ ph cm$^{-2}$ s$^{-1}$ (Atwood et al. 2009). Operating at hard γ-rays, the High Energy Stereoscopic System (HESS) has a sensitivity that varies from $\approx 5 \times 10^{-11}$ ph cm$^{-2}$ s$^{-1}$ at 0.1 TeV down to $\approx 5 \times 10^{-14}$ ph cm$^{-2}$ s$^{-1}$ at 10 TeV (Raue & Mazin 2010). Since we are interested in PBHs with more than $10^5 M\odot$ (see discussion in Section 4), i.e., PBHs with the emission peak $Q < 0.2$ TeV (cf. equation 3), we consider for the HESS sensitivity the value $5 \times 10^{-11}$ ph cm$^{-2}$ s$^{-1}$. We, then, picked the wavelengths $2.5 \times 10^{-13}$ m (soft γ-rays), $8.3 \times 10^{-18}$ m (mid γ-rays), and $2.5 \times 10^{-19}$ m (strong γ-rays) which are central to the considered bands — see Table 4.

4 RESULTS (MAXIMUM DISTANCE FOR DETECTION)

In Figures 4 and 2 we present the maximum distance $d(r_s)$ at which some detector working with sensitivity $S_\nu$ (within our current technologies, cf. Table 4) at a particular wavelength $\lambda$ should be placed in order to detect the emission of a given BH (from equations 10, 17, and 21).

For the longest wavelengths we found out that the de-
tector should be quite near the BH in order to detect the corresponding emission which means that it would be under the influence of a very strong gravitational field. In fact, for the first five cases on Table 1 the detection would not be possible. For example, when $\lambda = 70 \mu m$ the detector should be placed at a distance of $\sim 200 m$ in order to detect the IR emission of a $\sim 10^{20} kg$ BH, which is now a safe distance (the detector would experience a strong gravitational field). In fact, for $\lambda = 3.58 \mu m$ the detector should be quite near the BH in order to detect the IR emission of a $\sim 10^{14} kg$ BH. In summary, we get the following result: $[10^{-22}, 10^{-11}] M_\odot$ BHs (present day masses) can be detected at $d_{\text{max}} = [0.1 \text{ pc}, 10^5 \text{ m}]$.

### 5 DISCUSSION

BHs are objects predicted by the Laws of Physics. In terms of mass they could have from a few Planck masses ($M_P \sim 10^{-8} kg$) up to $\sim 10^{10} M_\odot$. SMBHs have already been identified in the centre of many galaxies, including our own. In terms of stellar mass, strong candidates have been identified in binary systems. All, however were detected via indirect means (e.g. dynamical interactions with their surroundings).

Sub-stellar mass BHs might have been produced during the early stages of the Universe. In particular, those with an initial mass of $\sim 10^{12} kg$ or greater should still be lurking around us at the present time (smaller ones should have already completely evaporated). There are hopes of directly detecting these PBHs via the electromagnetic radiation that they emit.

It was this path that we explored in this paper. In summary, such a BH must: a) have a mass on $[10^{-22}, 10^{-11}] M_\odot$; i.e., it must be primordial and not have already exploded (e.g. Carr et al. 2010); b) radiate according to equation (4); c) be a Schwarzschild BH (not being one will reduce its chances of detection).

We have assumed present detector technologies, as regards sensitivity (conservative, since these will become better in the future). It was our aim to show that, using detec-

### Table 1. The best sensitivities available for a range of wavelengths inside the six major bands of the electromagnetic spectrum (column (1)): (2): central wavelength (the Johnson filter is indicated for the optical); (3): central frequency ($\nu_X = c/\lambda_X$); (4): sensitivity, obtained from the references of column (7), as explained in the text; (5): bandwidth; (6): the most sensitive telescope, for each observing wavelength; (7): references from where the values were taken: [1] Röttgering et al. (2006); [2] Perley et al. (2011); [3] Griffin et al. (2010); [4] Poglitsch et al. (2010); [5] Fazio et al. (2004); [6] Ubeda et al. (2012); [7] Morrissey et al. (2007); [8] Hasinger et al. (2001); [9] Ubertini et al. (2003); [10] Atwood et al. (2009); [11] Raue & Mazin (2010).

| Band | $\lambda_X$ | $\nu_X$ (Hz) | $S_\nu$ | Bandwidth | Telescope | Ref. |
|------|-------------|--------------|--------|-----------|-----------|------|
| Radio | 20 m | $1.5 \times 10^7$ | $1.1 \times 10^{-2} Jy$ | 4 MHz | LOFAR | [1] |
|      | 1.5 m | $2.0 \times 10^8$ | $6.3 \times 10^{-5} Jy$ | 4 MHz | LOFAR | [1] |
|      | 3.5 cm | $9.0 \times 10^9$ | $1.0 \times 10^{-6} Jy$ | 3 MHz | e-VLA | [2] |
| Infrared | 500 $\mu m$ | $6.0 \times 10^{11}$ | $6.8 \times 10^{-3} Jy$ | 368 $\mu m$ | Herschel | [3] |
|      | 70 $\mu m$ | $4.3 \times 10^{12}$ | $4.4 \times 10^{-3} Jy$ | 25 $\mu m$ | Herschel | [4] |
|      | 3.58 $\mu m$ | $8.4 \times 10^{13}$ | $4 \times 10^{-7} Jy$ | 0.75 $\mu m$ | SST | [5] |
| Visible | 0.55 $\mu m$ (V) | $5.5 \times 10^{14}$ | $3.4 \times 10^{-9} Jy$ | 0.089 $\mu m$ | HST | [6] |
|      | 232 nm | $1.3 \times 10^{15}$ | $1.8 \times 10^{-8} Jy$ | 106 nm | GALEX | [7] |
|      | 154 nm | $1.9 \times 10^{15}$ | $1.6 \times 10^{-9} Jy$ | 44 nm | GALEX | [7] |
| X-rays | 3.5 nm | $8.6 \times 10^{16}$ | $5.5 \times 10^{-10} Jy$ | 0.3 keV | XMM | [8] |
|      | 1 nm | $3.0 \times 10^{17}$ | $8.5 \times 10^{-11} Jy$ | 1.5 keV | XMM | [8] |
|      | 0.165 nm | $1.8 \times 10^{18}$ | $2.0 \times 10^{-11} Jy$ | 5 keV | XMM | [8] |
| $\gamma$-rays | $2.5 \times 10^{-13}$ m | $1.2 \times 10^{21}$ | $5.0 \times 10^{-7} \text{ph cm}^{-2}\text{s}^{-1}\text{keV}^{-1}$ | 9.8 MeV | INTEGRAL | [9] |
|      | $8.3 \times 10^{-18}$ m | $3.6 \times 10^{25}$ | $3.0 \times 10^{-9} \text{ph cm}^{-2}\text{s}^{-1}$ | 300 GeV | Fermi | [10] |
|      | $2.5 \times 10^{-19}$ m | $1.2 \times 10^{27}$ | $5.0 \times 10^{-11} \text{ph cm}^{-2}\text{s}^{-1}$ | 9.9 TeV | HESS | [11] |
Table 2. The maximum distances for direct detection of BHs for the wavelengths considered on Table 1 (column (2)), only for the cases when the detector cannot be significantly influenced by the BH gravity. For each wavelength we show the BH that can be detected the farthest (corresponding to the peak of the respective curve on Figures 1 or 2): (2): Schwarzschild radius; (3) and (4): mass; (5): temperature; (6): maximum distance for detection; (7): figure where each curve appears. See further explanations on the main text.

| (1) $\lambda_X$ | (2) $r_s$ (m) | (3) $M$ (kg) | (4) $M$ ($M_{\odot}$) | (5) $T$ (K) | (6) $d_{\text{max}}$ (m) | (7) Figure |
|-----------------|---------------|-------------|-----------------|-------------|-----------------|-------------|
| 3.58 $\mu$m     | $1.1 \times 10^{-7}$ | $7.7 \times 10^{19}$ | $3.9 \times 10^{-11}$ | $1.6 \times 10^3$ | $1.7 \times 10^5$ | 1           |
| 0.55 $\mu$m     | $1.8 \times 10^{-8}$ | $1.2 \times 10^{19}$ | $5.9 \times 10^{-12}$ | $1.0 \times 10^4$ | $4.4 \times 10^6$ | 1           |
| 232 nm          | $7.4 \times 10^{-9}$ | $5.0 \times 10^{18}$ | $2.5 \times 10^{-12}$ | $2.5 \times 10^4$ | $3.1 \times 10^6$ | 1           |
| 154 nm          | $5.8 \times 10^{-9}$ | $3.9 \times 10^{18}$ | $1.9 \times 10^{-12}$ | $3.2 \times 10^4$ | $1.2 \times 10^7$ | 1           |
| 3.5 nm          | $1.1 \times 10^{-10}$ | $7.6 \times 10^{16}$ | $3.8 \times 10^{-14}$ | $1.6 \times 10^4$ | $1.4 \times 10^8$ | 2           |
| 1 nm            | $3.3 \times 10^{-11}$ | $2.2 \times 10^{16}$ | $1.1 \times 10^{-14}$ | $5.5 \times 10^4$ | $6.7 \times 10^8$ | 2           |
| 0.165 nm        | $5.3 \times 10^{-12}$ | $3.6 \times 10^{15}$ | $1.8 \times 10^{-15}$ | $3.4 \times 10^4$ | $1.1 \times 10^9$ | 2           |

Figure 1. [IR - Optical - UV] Maximum distance ($d_{\text{max}}$) for detecting the electromagnetic radiation directly emitted by a BH as a function of the Schwarzschild radius ($r_s$) for the wavelengths: (1) 3.58 $\mu$m; (2) 0.55 $\mu$m; (3) 232 nm; (4) 154 nm (cf. Table 1). At the top, the horizontal axis is also divided in terms of BH colours ($\lambda_{\text{max}}$; equation 3). For reference, the dashed line labeled (g) represents the distance for which the detector would be subject to a gravitational acceleration of 1 g. See the text for more details.

Figure 2. [X-rays - $\gamma$-rays] Maximum distance ($d_{\text{max}}$) for detecting the electromagnetic radiation directly emitted by a BH as a function of the Schwarzschild radius ($r_s$) for the wavelengths: (1) 3.5 nm; (2) 1 nm; (3) 0.165 nm; (4) $2.5 \times 10^{-13}$ m; (5) $8.3 \times 10^{-18}$ m; (6) $2.5 \times 10^{-19}$ m (cf. Table 1). In cases (4), (5) and (6) we do not see a peak since the main contribution for the total emitted flux is from secondary $\gamma$-rays. See the text and caption of Figure 1 for more details.

For signatures of individual BHs (not necessarily at the end stage of their evaporation process when they explode giving rise to a $\gamma$-ray burst). We point out three paradigmatic examples:

- A BH like the fourth in Table 2 ($\sim 10^{18}$ kg; $10^{-12}$ $M_{\odot}$) is detectable in the optical and UV up to $\sim 10^7$ m: in de-
tail, these detection possibilities are seen in curves (2,3,4) of Figure 1 ($r_s \sim 10^{-8}$ m). The evaporation time of such a BH is $\sim 10^{29}$ yr (cf. equation 11) which means that it would emit a steady and continuous flux for a long time at all wavelengths. Good sampling of the emission at IR, optical and UV wavelengths could be enough to unequivocally identify the source of emission as a BH, since the shape of the emission curve as given by equation 11 is quite unique.

- A BH with $\sim 10^{11}$ kg ($10^{-19} M_\odot$; $r_s \sim 10^{-16}$ m; $t_{\text{evap}} \sim 10^{15}$ s) can be detected in $\gamma$-rays at a maximum distance of $\sim 10^{11}$ m ($\approx 0.7$ au) or $\sim 10^{15}$ m ($\approx 70$ au) depending on the detector used (Figure 2, the points at the extreme left of the curves (4,5)). Such a detection will open the path to study the emission curve within the $\gamma$-ray domain.

- A BH with $\sim 10^8$ kg ($10^{-22} M_\odot$; $r_s \sim 10^{-19}$ m) can be detected in $\gamma$-rays at a maximum distance of 0.03 pc or 0.1 pc depending on the detector used (Figure 2, curves (5,6)). Such a BH would explode in a few decades (or less) which means that monitoring its flux levels could identify it as a PBH and even allow a prediction of the time of its explosion.

Laboratorial detection of electromagnetic radiation emitted by Planckian-size BHs might also be possible. In fact, if we live in a Universe with more than three spatial dimensions then it is expected that these Planckian-size BHs might be produced at the LHC. The detection of a BH at the LHC would provide a first experimental and secure test of the electromagnetic radiation emission mechanism.

Focusing now on practicalities, the farther we look into the Universe (the larger the volume sampled) the better our chances of finding a small-mass BH. It seems, then, that the best waveband to start searching for BHs is $\gamma$-rays $d_{\text{max}} \lesssim 0.1$ pc. However we do recomend that the detection should be attempted on the other electromagnetic spectrum bands as well. On the X-ray band, for example, we might be able to detect BHs at distances of the order of the Earth-Moon distance.

In Sobrinho (2011) it was shown that, within some scenarios, it is expected a number of $\sim 10^5$ PBHs within the Oort cloud. For these PBHs, mainly with $\sim 10^{18}$ g, the electromagnetic emission peaks at the hard X-ray band. It is plausible that, throughout the history of the Solar System, some PBHs might have been thrown into the inner Solar System following the same fate as the comets (i.e., we could have PBHs describing elliptical orbits with semi-major axis 100–200 au). That would improve the chances of direct detection of a PBH by a space probe. For example, NASA is planning to launch, possibly in 2014, the Innovative Interstellar Explorer (IIE) which is a mission that is expected to reach 200 au in about 30 years after launch (McNutt et al. 2006).

We will need to study the cosmological density of small-mass BHs in order to find the probability of detecting these directly, given the results of this paper (Sobrinho & Augusto, in prep.). Then, we will have a more complete idea on the potential of current and future space missions as regards direct detection of BHs.

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