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Transient pulses from exploding primordial black holes as a signature of an extra dimension

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Abstract. An evaporating black hole in the presence of an extra spatial dimension would undergo an explosive phase of evaporation. We show that such an event, involving a primordial black hole, can produce a detectable, distinguishable electromagnetic pulse, signaling the existence of an extra dimension of size $L \sim 10^{-18}$–10^{-20} m. We derive a generic relationship between the Lorentz factor of a pulse-producing 'fireball' and the TeV energy scale. For an ordinary toroidally compactified extra dimension, transient radio-pulse searches probe the electroweak energy scale (~0.1 TeV), enabling comparison with the Large Hadron Collider.

Keywords: black holes, extra dimensions, quantum gravity phenomenology

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Contents

1. Introduction

A new generation of radio telescopes will search for transient pulses from the universe [1]–[5]. Such searches, using pre-existing data, have recently found surprising pulses of galactic and extragalactic origin [6]–[8]. While the results will be of obvious astrophysical importance, they could also answer basic questions in physics which are difficult to address. In particular, as we will discuss here, searches for transient pulses from exploding primordial black holes (PBHs) can yield evidence of the existence of an extra spatial dimension, and explore electroweak-scale physics[1]. The potential impact could be timely and cut across many areas of investigation. For example, the Large Hadron Collider (LHC) is poised to investigate electroweak-scale physics, and may also yield evidence of the existence of extra spatial dimensions. Also, intensive work on the unification of quantum mechanics and gravitation has yielded insightful theoretical advances, often requiring extra spatial dimensions [9], yet there is little experimental observation which gives feedback on this proposed phenomenon. Furthermore, mapping of the anisotropies in the cosmic microwave background radiation has enabled ‘precision cosmology’, yet searches for PBHs, which would explore smaller scale primordial irregularities (a source of PBHs), would be valuable [10]. Searches for transient pulses from exploding primordial black holes can provide information impacting all of these areas of investigation, which at first glance appear unrelated, but are intimately connected.

The defining relation governing the Hawking evaporation of a black hole [11] is

$$T = \frac{\hbar c^3}{8\pi G k}\frac{1}{M}, \tag{1}$$

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[1] The existence of primordial black holes is an open question. However, there exist models of the early universe which produce large numbers of primordial black holes and are consistent with all current observational data (see, for example [40]).

for mass M and temperature T. The power emitted by the black hole is

$$P \propto \frac{\alpha(T)}{M^2}, \tag{2}$$

where $\alpha(T)$ is the number of particle modes available. Equations (1) and (2), along with an increase in the number of particle modes available at high temperature, leads to the possibility of an explosive outburst as the black hole evaporates its remaining mass in an emission of radiation and particles[2]. PBHs of sufficiently low mass would be reaching this late stage now [10]. Searches for these explosive outbursts have traditionally focused on γ-ray detection [12]. However, Rees noted that exploding primordial black holes could provide an observable coherent radio pulse that would be easier to detect [13].

Rees [13] and Blandford [14] describe the production of a coherent electromagnetic pulse by an explosive event in which the entire mass of the black hole is emitted. If significant numbers of electron–positron pairs are produced in the event, the relativistically expanding shell of these particles (a 'fireball' of Lorentz factor $\gamma_{\rm f}$) acts as a perfect conductor, reflecting and boosting the virtual photons of the interstellar magnetic field. An electromagnetic pulse results only for $\gamma_{\rm f} \sim 10^5$–10^7, for typical interstellar magnetic flux densities and free electron densities. The energy of the electron–positron pairs is

$$kT \approx \frac{\gamma_{\rm f}}{10^5} 0.1\ \mathrm{TeV}. \tag{3}$$

Thus the energy associated with $\gamma_{\rm f} \sim 10^5$ corresponds roughly to the electroweak scale.

2. Exploding primordial black holes and the TeV scale

There is a remarkable, heretofore unrecognized, relationship between the range of pulse-producing Lorentz factors for the emitted particles, and the TeV scale. Since $\gamma_{\rm f} \propto T$ at the time of the explosive burst, equation (1) yields

$$\frac{\gamma_{\rm f}}{10^5} \approx \frac{10^{-19}\ \mathrm{m}}{R_{\rm s}}, \tag{4}$$

where $R_{\rm s}$ is the Schwarzschild radius. Thus, the allowed range of Lorentz factors implies length scales $R_{\rm s} \sim 10^{-19}$–10^{-21} m. Taking these as Compton wavelengths we find the associated energy scales to be

$$(R_{\rm s}/\hbar c)^{-1} \sim 1\text{–}100\ \mathrm{TeV}. \tag{5}$$

This relationship suggests that the production of an electromagnetic pulse by PBHs might be used to probe TeV-scale physics. To make use of this interesting, but fairly generic observation, a specific phenomenologically relevant explosive process is required. One such process, which connects quantum gravitational phenomena and the TeV scale, makes use of the possible existence of an extra dimension.

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[2] The behavior of the evaporation process, as the Planck mass is reached, is not certain [41]. However, the description of the final explosive phase, used here, is sufficient for our analysis.

3. Explosive primordial black hole evaporation due to the presence of an extra dimension

Spatial dimensions in addition to the observed $3 + 1$-dimensional spacetime have a long tradition in gravitational models that goes back to the work of Kaluza and Klein [15, 16]. Extra dimensions are also required in string/M-theory for the consistency of the theory [9]. It was traditionally assumed, in these approaches, that the extra dimensions are Planck length in size. However, various phenomenologically motivated models were recently developed with extra dimensions much larger than the Planck length, which could have observable implications for electroweak-scale physics [17]–[21].

Black holes in four dimensions are uniquely defined by charge, mass, and angular momentum. However, with the addition of an extra spatial dimension, black holes could exist in different phases and undergo phase transitions. For one toroidally compactified extra dimension, two possible phases are a black string wrapping the compactified extra dimension, and a five-dimensional black hole smaller than the extra dimension. A topological phase transition from the black string to the black hole is of first order [22], and results in a significant release of energy equivalent to a substantial increase in the luminosity of Hawking radiation [23].

Following the analysis of Kol [24], to parameterize the phase of the black hole we define a dimensionless order parameter $\mu = GM/Lc^2$, where L is the size of the extra dimension with coordinate z identified with $z + L$. For large values of μ the black string phase is dominant, while for small values of μ the 5D black hole phase is favored. PBHs evaporating in the current epoch would lose mass through evaporation causing μ to decrease until a metrical instability, the Gregory–Laflamme point [25, 26] ($\mu \approx 0.07$), is reached, at which time the first-order phase transition occurs [22, 24][3]. The Schwarzschild radius is related to L as $R_\mathrm{s} = 2GM/c^2 = 2\mu L$. Thus, the energy emitted at the topological phase transition is

$$E = \eta M c^2 = \eta \frac{R_\mathrm{s} c^4}{2G} = \eta \mu L \frac{c^4}{G}, \tag{6}$$

equivalent to a Planck power (reduced by $\eta\mu$) emitted during a timescale L/c. The factor η is an efficiency parameter, estimated by Kol to be a few per cent in analogy with black hole collision simulations [27].

4. Transient pulse production

The analysis of Rees [13] and Blandford [14] can be adapted to the topological phase transition scenario. For a coherent electromagnetic pulse to result, the timescale of the energy release must be $L/c \ll \lambda/c$, where λ is the characteristic wavelength of the pulse. This requirement is well satisfied. Since $\gamma_\mathrm{f} \propto T$ and a fraction η of the object's mass–energy is released, the inverse relationship between temperature and mass for the Hawking process, equation (1), implies that γ_f is inversely related to the energy of the fireball.

Determining the emitted particle spectrum would require a full theory of quantum gravity. Lacking such a theory, we make the simple assumption that 50% of the ejected

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[3] While the final state resulting from the topological phase transition is not entirely understood, such details will not significantly alter the analysis presented here.

energy is in the form of electron–positron pairs (the same assumption as was used in [13, 14])[4]. Thus, we have

$$E \approx \eta_{01}\gamma_{f5}^{-1}10^{23}\ \mathrm{J}, \tag{7}$$

where $\eta_{01} = \eta/0.01$ and $\gamma_{f5} = \gamma_{\mathrm{f}}/10^5$. The bounds on the Lorentz factor for pulse production in the topological phase transition scenario are of the same order as for the scenario considered by Rees and Blandford, $\gamma_{\mathrm{f}} \sim 10^5$–$10^7$. Setting $E = \eta Mc^2$, we find

$$L \approx \mu_{07}^{-1}\gamma_{f5}^{-1}10^{-18}\ \mathrm{m}, \tag{8}$$

where $\mu_{07} = \mu/0.07$.

The characteristic frequency of the pulse is

$$\nu_c = \gamma_{f5}^{8/3}E_{23}^{-1/3}b^{2/3}5.1\ \mathrm{GHz}, \tag{9}$$

where b is the interstellar magnetic flux in units of 0.5 nT, and E_{23} is the emitted energy in units of 10^{23} J. Pulses for low γ_{f} are best observed in the radio spectrum. The maximum radius attained by the shell is $\approx R_{\odot}\eta_{01}^{1/3}\gamma_{f5}^{-1}b^{-2/3}$. The interstellar magnetic field is expected to be essentially uniform on this length scale. Thus a pulse should be nearly 100% linearly polarized, which will help to distinguish pulses from PBHs from those produced by other sources.

Following Blandford [14], the pulse energy spectrum is

$$I_{\nu\Omega} = 1.4\times10^{12}\eta_{01}^{4/3}\gamma_{f5}^{-4}b^{-2/3}\left|F\left(\frac{\nu}{\nu_c}\right)\right|^2\ \mathrm{J\ Hz^{-1}\ sr^{-1}}, \tag{10}$$

where the limiting forms of $|F(x)|^2$ are

$$|F(x)|^2 \approx \begin{cases} 0.615x^{-4/7} & \text{if}\ \ x \ll 1 \\ x^{-4} & \text{if}\ \ x \gg 1. \end{cases} \tag{11}$$

Equations (10) and (11) imply that for a chosen observing frequency ν, in GHz, the observed pulse energy sharply peaks at a specific Lorentz factor,

$$\gamma_{f5} \approx 0.5\eta_{01}^{1/9}b^{-2/9}\nu_{\mathrm{GHz}}^{1/3}. \tag{12}$$

By varying the observing frequency, one can search for potential phase transition pulses associated with different γ_{f}, and thus different sizes of the extra dimension. The corresponding extra dimension that is tested for using a particular search frequency has the size

$$L \approx \mu_{07}^{-1}\eta_{01}^{-1/9}b^{2/9}\nu_{\mathrm{GHz}}^{-1/3}\ 2\times10^{-18}\ \mathrm{m}. \tag{13}$$

The strength of the typical interstellar magnetic field varies around the nominal value that we use by about an order of magnitude [28]. For the weak dependence of L on b shown in equation (13) the resulting error in a determination of L is less than a factor of 2. However, given the idealized nature of the Blandford model it is likely that the

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[4] The emitted particle spectrum (and decay chain) for the event considered by Rees and Blandford, taking into account possible details of the QCD phase transition, has been investigated [42, 43]. However, the topological phase transition scenario considered here is of a fundamentally different nature making this analysis inapplicable.

observations that we suggest can only determine the size of an extra dimension to an order of magnitude.

Frequencies between $\sim$1 GHz and 10^{15} Hz ($\gamma_{\rm f} \sim 10^5$–10^7) sample possible extra dimensions in the range $L \sim 10^{-18}$–10^{-20} m. These length scales correspond to energies of $(L/\hbar c)^{-1} \sim 0.1$–10 TeV. The electroweak scale is $\sim$0.1 TeV, and thus, radio observations at $\nu \sim 1$ GHz may be most significant.

The observed polarization, dispersion measure, and energy of a radio pulse would provide a means for distinguishing a PBH explosion from other possible sources. As noted above, an electromagnetic pulse produced by an exploding PBH would be nearly completely linearly polarized, helping to distinguish it from other possible sources. In addition, the dispersion measure of a radio pulse can be used to estimate the distance to the source of the pulse. This distance, in combination with the observed pulse energy, can yield an emitted pulse energy per Hz, at observing frequency ν, that can be compared to the expected model results shown in figure 1.

The efficiency η differs by two orders of magnitude for the PBH explosion scenario considered by Rees and the topological phase transition scenario. Therefore, the emitted pulse energy derived from observations, for the Lorentz factor probed, would distinguish between these two scenarios. Thus, as figure 1 shows, given a chosen observing frequency, one can distinguish between the cases of $\eta = 1$ (all the mass is emitted in a final explosive burst) and $\eta = 0.01$ (for the topological phase transition).

5. Transient pulse searches

Searches for transient radio pulses from PBH explosions, cf [29, 30], can probe for the existence of PBHs well below the limits established by observations of the diffuse γ-ray background [12, 31]. To date, these radio searches have utilized data collected for other purposes, or for limited times, all with negative results. A new generation of instruments, designed to operate at low radio frequencies, may be able to conduct extended searches for radio transients over wide fields of view ($\sim$1 sr): the long wavelength array (LWA) [1], Murchison wide-field array (MWA) [2], and the low frequency array (LOFAR) [3].

A continuous wide-field low frequency radio transient search already under way uses the eight-meter-wavelength transient array (ETA) [4, 5] which operates at 38 MHz using 10 dual-polarization dipole antennas. ETA observations are most sensitive to $\gamma_{\rm f} \approx 10^4$–$10^5$ ($L \approx 10^{-17}$–10^{-18} m). A second array (ETA2) is under construction at a different site. Comparing the signals received at the two sites will help mitigate radio interference—a technique that distinguishes all searches with distributed antenna arrays from single-antenna searches. This procedure enables the theoretical sensitivity to be attained. The sensitivity of a radio telescope to a pulse-producing source is dependent on the temporal broadening of an observed pulse due to interstellar scattering and due to dispersion across the finite-width frequency channels utilized in the observations. Taking account of these effects, the ETA is sensitive to transient pulses produced by black string/black hole phase transitions out to distances of about 300 pc.

It is natural to ask if gamma-ray satellites should have already detected an event of the sort we are considering. The Energetic Gamma-Ray Experiment Telescope (EGRET) set an upper limit on PBH explosions of <0.05 pc^{-3} y^{-1} [32]. This result assumes that PBH explosions are of the 'standard' variety: $\eta = 1$, and occurring with $\gamma_{\rm f} \sim 10^2$, producing a

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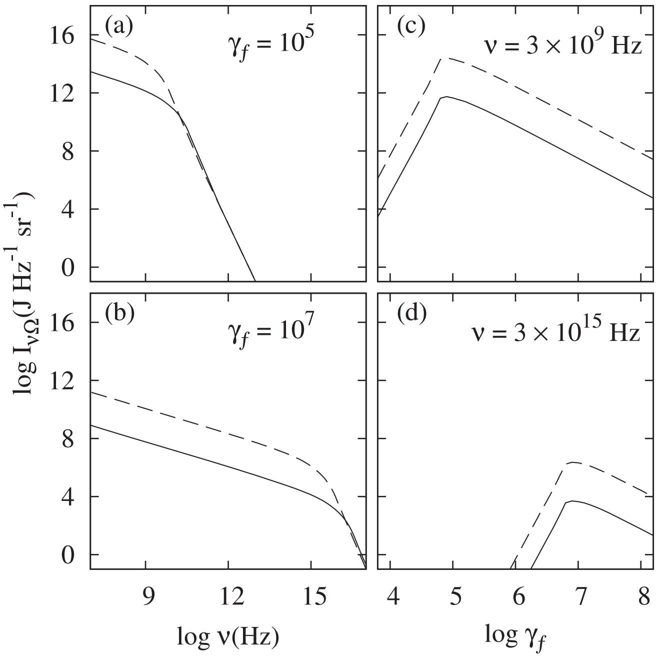

Figure 1. Electromagnetic pulse energy spectrum for a topological phase transition (solid curves, efficiency $\eta = 0.01$), and a final explosive burst as described by Rees and Blandford (dashed curves, efficiency $\eta = 1$). (a) shows the pulse energy per unit frequency interval, versus frequency, for a fireball Lorentz factor $\gamma_{\mathrm{f}} = 10^5$. (b) is for $\gamma_{\mathrm{f}} = 10^7$. (c) shows the pulse energy per unit frequency interval versus γ_{f}, at frequency 3×10^9 Hz. (d) is for frequency 3×10^{15} Hz. Note that the curves in (c) and (d) peak sharply at a specific γ_{f}, dependent on the observing frequency (full width at half-maximum $\approx 1/3$, in $\log \gamma_{\mathrm{f}}$). So, choosing an observing frequency enables searching for events of a particular γ_{f}. For a topological phase transition, a γ_{f} is associated with an extra dimension of a particular size (see the text). Pulses for the cases $\eta = 0.01$ and 1 can be distinguished. In (c), for example, the output energies are dramatically different for the two cases, at the γ_{f} of peak output. Thus, a distance to the object (e.g., from pulse dispersion measure for radio observations) would distinguish the two cases. A pulse for $\eta = 1$ can have the same energy as for $\eta = 0.01$ only for a significantly different γ_{f}, which could be determined by sampling the spectrum at multiple wavelengths.

gamma-ray spectrum peaking at about 250 MeV, as discussed by Page and Hawking [31]. Given these assumptions, EGRET is sensitive to such events out to distances of about 100 pc [32]. If instead one considers outbursts due to topological phase transitions with an efficiency of $\eta = 0.01$, and at $\gamma_{\mathrm{f}} \sim 10^2$, the EGRET sensitivity would only be sufficient to observe events out to about 10 pc, assuming the same partitioning of output energy into gamma-rays and particles. Furthermore, if one is interested in searching for topological phase transition events at the TeV scale, where an extra dimension is more plausible, the outburst energy (proportional to the mass of the black hole) is an additional factor of 10^3 smaller, and so the distance is reduced to 0.3 pc. Moreover, the associated gamma-ray spectrum peaks at this much larger energy scale, and outside the energy range of EGRET.

Therefore, EGRET was not the most suitable instrument for finding the topological phase transition events we are considering.

The Fermi Gamma-Ray Space Telescope (formerly GLAST), will observe photons of energies up to about 300 GeV, encompassing energies that would be produced by a topological phase transition at 0.1 TeV. However, while Fermi is more than an order of magnitude more sensitive than was EGRET [33, 34], it will be sensitive to these events out to only $\sim$1 pc.

6. Implications

Although we have considered a process involving an extra dimension, we have kept our analysis general in the sense that we have not specified any particular extra dimension model. We now consider the above proposal in the context of several specific extra dimension scenarios.

In the case of TeV-scale compactification models in which all gauge fields propagate in a single, circular, extra dimension [17], the current bound on the compactification scale is $(L/\pi\hbar c)^{-1} \gtrsim 6.8$ TeV [35]. The Large Hadron Collider (LHC) will probe these models up to an energy scale of $\sim$16 TeV. If both gauge fields and fermions propagate in the extra dimension [18] the current bound is $(L/\pi\hbar c)^{-1} \gtrsim$ 300–500 GeV with the LHC probing to $\sim$1.5 TeV [35]. Detection of a transient pulse would imply, as noted above, an extra dimension with $L \sim 10^{-18}$–10^{-20} m, corresponding to an energy of $\sim$0.1–10 TeV. Thus constructive comparison of the pulse detection results and LHC results would be possible.

In the context of the braneworld scenario proposed by Randall and Sundrum [20, 21] it has been argued that evaporating black holes will reach a Gregory–Laflamme instability as the radius of the black hole approaches the AdS radius [36, 37]. More specifically, in the Randall–Sundrum I scenario a nominal value of this radius is 10 TeV^{-1} [38] placing it within the appropriate range for transient pulse production.

For large extra dimension models [19] the effective fundamental energy scale is much higher than the energy scale of the large extra dimension $(L/\hbar c)^{-1}$. For a single large extra dimension of size $L \sim 10^{-18}$–10^{-20} m the effective fundamental energy scale is $\sim 10^{10}$ TeV—much higher than the electroweak scale. Thus, searches for pulses from topological phase transitions would probe, for these models, energies inaccessible to accelerator-based approaches for the foreseeable future.

While a positive pulse detection would signal the existence of an extra dimension, a null detection would serve to constrain the possible size of an extra dimension in particular models. Such a constraint presupposes, of course, the existence of PBHs in abundant enough numbers to be detectable. These constraints could be strengthened through consideration of other experimental data, e.g., other types of searches for PBHs, or cosmological data which further constrain the spectral index for primordial density irregularities on the appropriate scales, or accelerator-based searches.

7. Outlook

An important avenue for future investigation is the effect more than one extra dimension would have on transient pulse production. The nature of this type of topological phase transition for more than one compact extra dimension is currently under investigation [39].

Also, the efficiency parameter η, whose value was estimated above, can be better determined numerically, which would help to make this analysis more precise. We have considered a particular explosive event in the evaporation process of a PBH involving an extra dimension. However, given the generic relationships noted above, equations (3) and (4), we believe that a connection between transient pulse production by PBHs and electroweak-scale physics is robust beyond the specific analysis present here, and is worthy of further investigation.

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