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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 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 a toroidally compactified extra dimension, transient radio-pulse searches probe the electroweak energy scale (∼0.1 TeV), enabling comparison with the Large Hadron Collider. The enormous challenges of detecting quantum gravitational effects, and exploring electroweak-scale physics, make this a particularly attractive possibility.

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1 Introduction

A new generation of radio telescopes will search for transient pulses from the universe [1, 2, 3, 4, 5, 6]. Such searches, using pre-existing data, have recently found surprising pulses of galactic and extragalactic origin [7, 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. 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 [9]. Comparison of LHC and transient search results would be very useful. Also, intensive work on the unification of quantum mechanics and gravitation has yielded insightful theoretical advances [10], often requiring extra spatial dimensions, yet there is little experimental observation which gives feedback on this proposed phenomenon. Furthermore, mapping of the anisotropies in the microwave background radiation from the big bang have enabled "precision cosmology," yet searches for PBHs, which would explore smaller scale primordial irregularities (the source of PBHs), would be valuable [11]. 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 [12] is

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

for mass M and temperature T, where the power emitted by the black hole is

$$P = \frac{\hbar c^6}{15360 \pi G^2} \frac{1}{M^2}. \tag{2}$$

This, 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 charged particles[1]. PBHs of sufficiently low mass would be reaching this late stage now [11]. Searches for these explostive outbursts have traditionally focused on gamma-ray detection [14]. However, Rees noted that exploding primordial black holes could provide an observable coherent radio pulse that would be easier to detect [15].

Rees and Blandford [15, 16] 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

[1] The behavior of the evaporation process, as the Planck mass is reached, is not certain [13]. However, the description of the final explosive phase, used here, is sufficient for our analysis.

Lorentz factor γ_f) acts as a perfect conductor, reflecting and boosting the virtual photons of the interstellar magnetic field. An electromagnetic pulse results only for $\gamma_f \sim 10^5$ to 10^7, for typical interstellar magnetic flux densities and free electron densities. The energy of the electron-positron pairs is

$$\frac{\gamma_f}{10^5} \approx \frac{kT}{0.1 \text{ TeV}}, \tag{3}$$

which is on the order of the electroweak scale.

2 Exploding primordial black holes and the TeV scale

There is a remarkable, heretofore unrecognized, relationship between the range of Lorentz factors for the emitted particles and the TeV scale. Since $\gamma_f \propto T$ at the time of the explosive burst, equation (1) yields

$$\frac{\gamma_f}{10^5} \approx \frac{10^{-19} \text{ m}}{R_s}, \tag{4}$$

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

$$(R_s/\hbar c)^{-1} \sim 1 - 100 \text{ TeV}. \tag{5}$$

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.

3 Explosive primordial black hole evaporation in 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 [17, 18]. Extra dimensions are also required in string/M-theory for the consistency of the theory [10]. 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 [19, 20, 21, 22].

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 5-dimensional black hole smaller than the extra dimension. A topological phase transition from the black string to the black hole is of first order [23], and results in a significant release of energy equivalent to a substantial increase in the luminosity of Hawking radiation [24].

Following the analysis of Kol [25], to parametrize the phase of the black hole we define a dimensionless order parameter $\mu = GM/Lc^2$. For large values of μ the black string phase is dominant, while for small values of μ the 5-D 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 [26, 27] ($\mu \approx 0.07$) is reached, at which time the first-order phase transition occurs [25, 23].[2] The Schwarzschild radius is related to L as $R_s = 2GM/c^2 = 2\mu L$. Thus, the energy emitted at the topological phase transition is

$$E = \eta Mc^2 = \eta \frac{R_s c^4}{2G} = \eta \mu L \frac{c^4}{G}, \tag{6}$$

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

4 Transient pulse production due to the presence of an extra dimension

The analysis of Rees and Blandford [15, 16] can be adapted to the topological phase transition scenario. For a coherent electromagnetic pulse to result, the time scale of the energy release must be $L/c \ll \lambda$, where λ is the characteristic wavelength of the pulse. This requirement is well satisfied. Since $\gamma_f \propto T$ 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 γ_f is inversely related to the energy of the fireball. Assuming 50% of the ejected energy is in the form of electron-positron pairs, we have

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

as in Rees and Blandford [15, 16] but now with the efficiency η present, where $\eta_{01} = \eta/0.01$ and $\gamma_{f5} = \gamma_f/10^5$. 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, $\gamma_f \sim 10^5$ to 10^7. Setting $E = \eta Mc^2$, we find

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

[2]While the final state that results is not entirely understood, such details will not significantly alter the analysis presented here.

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

The characteristic frequency of the pulse is

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

where b is the interstellar magnetic flux in units of 0.5 nT. 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 field is expected to be essentially uniform on this length scale. Thus a pulse should be nearly 100 percent linearly polarized, which will help to distinguish pulses from PBHs from those produced by other objects.

Following Blandford [16], the pulse energy spectrum is

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

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

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

This spectrum is shown in Fig. 1.

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,

$$\gamma_{f5} \approx 0.70 \; \nu_{\text{GHz}}^{1/3}. \tag{12}$$

As Fig. 2 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). Thus, 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 such a search frequency has the size

$$L \approx \mu_{07}^{-1} \; \nu_{\text{GHz}}^{-1/3} \; 1.4 \times 10^{-18} \text{ m}. \tag{13}$$

Frequencies between $\sim$ 1 GHz and 10^{15} Hz ($\gamma_f \sim 10^5$ to 10^7) sample possible extra dimensions between $L \sim 10^{-18} - 10^{-20}$ 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. Thus, radio observations at $\nu \sim 1$ GHz may be most significant.

5 Transient pulse searches

To date, searches for transient radio pulses from PBHs have utilized data collected for other purposes, or for limited times, all with negative results, cf. [28, 29]. However, a new generation of instruments designed to operate at low radio frequencies, may be able to conduct extended searches for radio transients

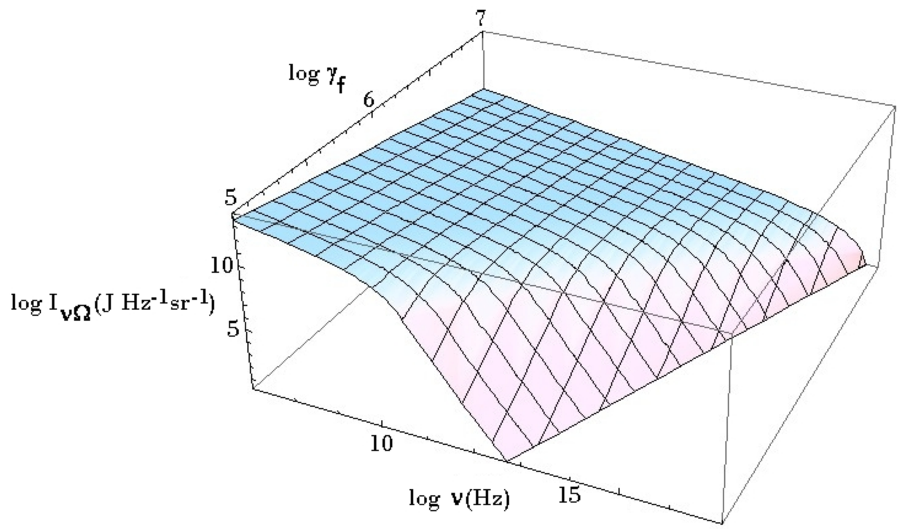

Figure 1: The electromagnetic-pulse energy spectrum for an explosive burst produced by a topological phase transition from a black string to a black hole. The plot shows the energy per unit frequency interval, per unit steradian, plotted versus frequency and the "fireball" Lorentz factor γ_f (equivalent to the Lorentz factor of the electron-positron pairs emitted in the burst). For larger γ_f there is less pulse energy emitted at a specific low frequency, but there is a larger characteristic frequency, beyond which the spectrum decreases quickly. For a topological phase transition the fraction of the object's energy that is emitted (the efficiency of the explosive burst) is taken to be $\eta = 0.01$.

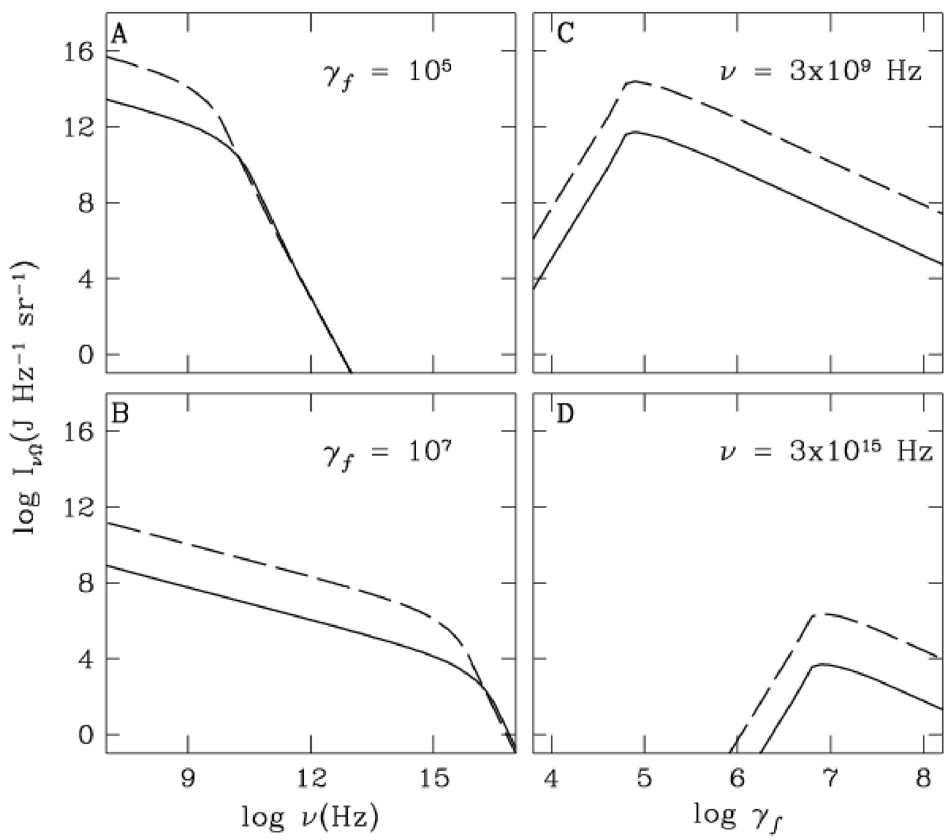

Figure 2: Electromagnetic-pulse energy spectrum for a topological phase transition, and a final explosive burst. The solid curves are slices along representative planes in Fig. 1 for a topological phase transition (efficiency $\eta = 0.01$). The dashed curves are for a final explosive phase (efficiency $\eta = 1$). (**A**) shows the pulse energy per unit frequency interval, versus frequency, for a fireball Lorentz factor $\gamma_f = 10^5$. (**B**) is for $\gamma_f = 10^7$. (**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 $\log \gamma_f$). 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 text). Pulses for the cases $\eta = 0.01$ and $\eta = 1$ can be distinguished. In (**C**), for example, the output energy is 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. Whereas, an $\eta = 1$ pulse of energy equal to the peak output for $\eta = 0.01$ would have a significantly different γ_f, and would be distinguishable through its spectrum sampled at multiple wavelengths.

over wide fields of view (~ 1 steradian): the Long Wavelength Array (LWA) [2], Murchison Widefield Array (MWA) [3], and the Low Frequency Array (LOFAR) [4].

A continuous wide-field low-frequency radio transient search already underway uses the Eight-meter-wavelength Transient Array (ETA) [5, 6] which operates at 38 MHz using 10 dual-polarization dipole antennas. ETA observations are most sensitive to $\gamma_f \approx 10^4$ to 10^5 ($L \approx 10^{-17}$ m to 10^{-18} m). A second array (ETA2) is under construction at a different site. Comparing the signals received at both 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.

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 [19], the current bound on the compactification scale is $(L/\pi\hbar c)^{-1} \gtrsim 6.8$ TeV [30]. The Large Hadron Collider (LHC) will probe these models up to an energy scale of ~ 16 TeV. If both gauge fields and fermions propagate in the extra dimension [20] the current bound is $(L/\pi\hbar c)^{-1} \gtrsim 300 - 500$ GeV with the LHC probing to ~ 1.5 TeV [30]. 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 case of the Randall-Sundrum I (RSI) scenario [22] 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 [31]. In this scenario a nominal value of this radius is 10 TeV^{-1} placing it within the appropriate range for transient pulse production.

For large extra dimension models [21] 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 (a source of PBHs), or accelerator-based searches in the case of TeV-scale compactification models.

7 Future avenues of investigation

An important avenue for future investigation is the effect more than one extra dimension would have on transient pulse production. The exact nature of this type of topological phase transition for more than one compact extra dimension is currently under investigation [32]. 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, eq. (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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