Transient Astrophysical Pulses and Quantum Gravity

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Abstract

Searches for transient astrophysical pulses could open an exciting new window into the fundamental physics of quantum gravity. In particular, an evaporating primordial black hole in the presence of an extra dimension can produce a detectable transient pulse. Observations of such a phenomenon can in principle explore the electroweak energy scale, indicating that astrophysical probes of quantum gravity can successfully complement the exciting new physics expected to be discovered in the near future at the Large Hadron Collider.
1 Introduction

For millennia, astronomy has concentrated on the unchanging nature of the cosmos. Even throughout the 20th century, astrophysical theory and observation focused on the physics of persistent objects — stars, galaxies, etc. Observations were often directed at a single target, and for as long as possible to obtain high precision measurements. However, high energy events may occur in seemingly random parts of the sky, over a short time scale, and could be missed if traditional astronomical methods are employed. It is our contention that such transients are just the type of phenomena that could be related to quantum gravitational effects, and that searches for these could provide a new arena in which to probe this elusive area of inquiry.

A theory of quantum gravitation would deepen our understanding of spacetime, matter, and the origin of the universe [1, 2]. However, it is crucial that any such theory be subject to experimental and observational verification. Observable effects of quantum gravity are expected to manifest themselves most directly at exceptionally high energies or in the presence of a spacetime singularity. Thus, experimental tests of quantum gravity present a severe challenge. Particle accelerators have long served as an indispensable tool for exploring new regimes of fundamental physics, but it may be some time before they yield a discernible signature of quantum gravitation. Given the extreme difficulties posed by the search for quantum gravitational effects, another source of data would be of great value, and could provide a means of comparison with accelerator-based experiments.

2 Transient Pulses from Exploding Primordial Black Holes

Here we consider just one example of a transient event, associated with the explosion of primordial black holes (PBHs), which depends upon two distinct quantum gravitational phenomena: Hawking radiation and the existence of an extra spatial dimension.

The defining relation governing the Hawking evaporation of a black hole [3] is

\[ T = \frac{\hbar c^3}{8\pi Gk M}, \]

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

\[ P \propto \frac{\alpha(T)}{M^2}, \]

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. PBHs of sufficiently low mass would be reaching this late stage now [4, 5]. Searches for these explosive outbursts have traditionally focused on \( \gamma \)-ray detection [6]. However, Rees noted that exploding primordial black holes could provide an observable coherent radio pulse that would be easier to detect [7].
Rees and Blandford [7, 8] 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 $\gamma_f$) 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

$$kT \approx \frac{\gamma_f}{10^5} \text{0.1 TeV.}$$

Thus the energy associated with $\gamma_f \sim 10^5$ corresponds roughly to the electroweak scale.

3 Exploding Primordial Black Holes & the TeV Scale

There exists a remarkable relationship between the range of pulse-producing Lorentz factors for the emitted particles, and the TeV scale [9]. Since $\gamma_f \propto T$ at the time of the explosive burst, equation (1) yields

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

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

$$(R_s/\bar{h}c)^{-1} \sim 1 - 100 \text{ TeV.}$$

This relationship suggests that the production of an electromagnetic pulse by PBHs might be used to probe TeV-scale physics.

On general grounds one could expect quantum gravity to probe other scales that are vastly different from the experimentally forbidding Planck energy region. The effective action for gravity coupled to Standard Model matter carries additional information apart from a sensitivity to the Planck scale. It also encodes information about the scale associated with the vacuum energy density, which also sets the relevant cosmological scale, as described by the cosmological constant, as well as the energy scale relevant for the generation of particle masses. In the case of the Standard Model of particle physics this corresponds to the electroweak scale. Also, by unitarity, new phenomena are expected at a characteristic scale of the order of a TeV. Thus PBH explosions, and therefore the accompanying quantum gravitational phenomena, can be sensitive to other energy scales, such as the electroweak scale or the TeV scale, which are many orders of magnitude different from the Planck scale.

4 Transient Pulses from Primordial Black Holes in the Presence of an Extra Dimension

To make use of these interesting generic observations, a specific phenomenologically relevant explosive process is required. One such process, discussed by Kol [10], which connects
quantum gravitational phenomena and the TeV scale, makes use of the possible existence of an extra dimension and relies on the physics of the black string/black hole phase transition.

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 of length $L$, 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 occurs when an instability, the Gregory-LaFlamme point [11], is reached. This transition is of first order [12], and results in a significant release of energy equivalent to a substantial increase in the luminosity of Hawking radiation [13]. The sensitivity to widely separate energy scales can be nicely encapsulated in one overall efficiency parameter $\eta$ characterizing the PBH explosion.

The analysis of Rees and Blandford [7, 8] can be adapted to the topological phase transition scenario. 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 efficiency parameter and the expected linear polarization of the pulse will make this transient distinguishable from other possible sources [9].

The electroweak scale is $\sim 0.1$ TeV, and thus, radio observations at $\sim 1$ GHz may be most significant. Radio observations have historically been significant as probes of new physics, for example in the discovery and mapping of the Cosmic Microwave Background. Observations of transient radio phenomena have also played a role in astrophysical exploration, in the discovery of pulsars. A new generation of radio telescopes will search for transient radio pulses [14, 15, 16, 17, 18, 19]. Such searches, using pre-existing data, have recently found surprising pulses of galactic and extragalactic origin [20, 21, 22]. The Eight-meter-wavelength Transient Array (ETA) [18, 19], for example, can detect the type of pulse discussed here, out to a distance of order 100 pc.

In the case of TeV-scale compactification models in which both gauge fields and fermions propagate in the extra dimension [23] the current bound is $(L/\pi \hbar c)^{-1} \sim 300 - 500$ GeV with the Large Hadron Collider (LHC) probing to $\sim 1.5$ TeV [24]. 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 [25, 26] 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 [27, 28]. More specifically, in the Randall-Sundrum I scenario a nominal value of this radius is $10 \text{ TeV}^{-1}$ [29] placing it within the appropriate range for transient pulse production.

For large extra dimension models [30] 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.
A positive pulse detection would signal the existence of an extra dimension, and thus indicate the sensitivity of quantum gravity to scales far below the Planck scale. A null detection would serve to constrain the possible size of an extra dimension, and the relevant low energy scale in particular models.

5 Discussion & Outlook

We have considered only one among a number of possible distinct transient events which could reveal new physics. The analysis considered here can potentially be extended to stellar-mass black holes, regardless of their origin, when quantum gravitational effects are taken into account, as discussed in [31, 32]. Another candidate for producing an observable transient pulse, which is intimately dependent on quantum gravitational effects, is the spark from a cusp of a superconducting cosmic string [22]. Given the connection between highly energetic astrophysical events and the production of transient pulses, it is likely that searches for these signals will open a new observational avenue to the heart of quantum gravity.

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References

[1] Vishnu Jejjala, Michael Kavic, and Djordje Minic. Time and M-theory. *Int. J. Mod. Phys.*, A22:3317–3405, 2007.

[2] Vishnu Jejjala, Michael Kavic, and Djordje Minic. Fine Structure of Dark Energy and New Physics. *Adv. High Energy Phys.*, 2007:21586, 2007.

[3] S. W. Hawking. Particle creation by black holes. *Commun. Math. Phys.*, 43:199–220, 1975.

[4] Bernard J. Carr. Primordial black holes as a probe of cosmology and high energy physics. *Lect. Notes Phys.*, 631:301–321, 2003.

[5] M. Yu. Khlopov. Primordial Black Holes. arXiv:0801.0116 [astro-ph], 2008.

[6] F. Halzen, E. Zas, J. H. MacGibbon, and T. C. Weekes. Gamma rays and energetic particles from primordial black holes. *Nature*, 353:807–815, October 1991.
[7] M. J. Rees. A better way of searching for black-hole explosions? *Nature*, 266:333–334, 1977.

[8] R. D. Blandford. Spectrum of a radio pulse from an exploding black hole. *Mon. Not. R. Astron. Soc.*, 181:489–498, 1977.

[9] Michael Kavic, John H. Simonetti, Sean E. Cutchin, Steven W. Ellingson, and Cameron D. Patterson. Transient Pulses from Exploding Primordial Black Holes as a Signature of an Extra Dimension. arXiv:0801.4023 [astro-ph], 2008.

[10] Barak Kol. Explosive black hole fission and fusion in large extra dimensions. hep-ph/0207037, 2002.

[11] R. Gregory and R. Laflamme. Black strings and p-branes are unstable. *Phys. Rev. Lett.*, 70:2837–2840, 1993.

[12] Steven S. Gubser. On non-uniform black branes. *Class. Quant. Grav.*, 19:4825–4844, 2002.

[13] Barak Kol. The phase transition between caged black holes and black strings: A review. *Phys. Rept.*, 422:119–165, 2006.

[14] Geoffrey C. Bower. Astronomy: Mining for the ephemeral. *Science*, 318:759–760, 2007.

[15] G. B. Taylor. The Long Wavelength Array. *Long Wavelength Astrophysics, 26th meeting of the IAU, Joint Discussion 12, 21 August 2006, Prague, Czech Republic, JD12, #17, 12, August 2006.*

[16] Judd D. Bowman et al. Field deployment of prototype antenna tiles for the Mileura Widefield Array — low frequency demonstrator. *Astron. J.*, 133:1505–1518, 2007.

[17] H. R. Butcher. LOFAR: First of a new generation of radio telescopes. *Proc. SPIE*, 5489:537–544, 2004.

[18] S. W. Ellingson, J. H. Simonetti, and C. D. Patterson. Design and evaluation of an active antenna for a 29-47 MHz radio telescope array. *IEEE Trans. Antenn. Propag.*, 55:826–831, 2007.

[19] J. H. Simonetti, S. W. Ellingson, C. D. Patterson, W. Taylor, V. Venugopal, S. Cutchin, and Z. Boor. The Eight-meter-wavelength Transient Array (ETA). *Bull. Amer. Astron. Soc.*, 37:1438–1438, 2006.

[20] M. A. McLaughlin, A. G. Lyne, D. R. Lorimer, M. Kramer, R. N. Faulkner, A. J. Manchester, J. M. Cordes, F. Camilo, A. Possenti, I. H. Stairs, G. Hobbs, N. D’Amico, M. Burgay, and J. T. O’Brien. Transient radio bursts from rotating neutron stars. *Nature*, 439:817–820, 2006.

[21] D. R. Lorimer, M. Bailes, M. A. McLaughlin, D. J. Narkevic, and F. Crawford. A bright millisecond radio burst of extragalactic origin. *Science*, 318:777–780, 2007.
[22] Tanmay Vachaspati. Cosmic Sparks from Superconducting Strings. arXiv:0802.0711 [astro-ph], 2008.

[23] Thomas Appelquist, Hsin-Chia Cheng, and Bogdan A. Dobrescu. Bounds on universal extra dimensions. Phys. Rev., D64:035002, 2001.

[24] W. M. Yao et al. Review of particle physics. J. Phys., G33:1–1232, 2006.

[25] Lisa Randall and Raman Sundrum. A large mass hierarchy from a small extra dimension. Phys. Rev. Lett., 83:3370–3373, 1999.

[26] Lisa Randall and Raman Sundrum. An alternative to compactification. Phys. Rev. Lett., 83:4690–4693, 1999.

[27] A. Chamblin, S. W. Hawking, and H. S. Reall. Brane-world black holes. Phys. Rev., D61:065007, 2000.

[28] Roberto Emparan, Gary T. Horowitz, and Robert C. Myers. Exact description of black holes on branes. JHEP, 01:007, 2000.

[29] D. Karasik, C. Sahabandu, P. Suranyi, and L. C. R. Wijewardhana. Small (1-tev) black holes in randall-sundrum i scenario. Phys. Rev., D69:064022, 2004.

[30] Nima Arkani-Hamed, Savas Dimopoulos, and G. R. Dvali. The hierarchy problem and new dimensions at a millimeter. Phys. Lett., B429:263–272, 1998.

[31] Roberto Emparan, Juan Garcia-Bellido, and Nemanja Kaloper. Black hole astrophysics in AdS braneworlds. JHEP, 01:079, 2003.

[32] Roberto Emparan, Alessandro Fabbri, and Nemanja Kaloper. Quantum black holes as holograms in AdS braneworlds. JHEP, 08:043, 2002.