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Astrophysical Tests of Extra Dimensional Models

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Abstract. We investigate the possibility that astrophysical observations can be used to test models which predict the existence of extra spatial dimensions. The particular systems of an exploding primordial black hole in the presence of an extra dimension and a binary black hole/neutron star system in the Randall-Sundrum 2 model are considered.

1. INTRODUCTION

Early advances in understanding fundamental natural laws are inextricably linked to astrophysical observations. It is by no means a coincidence that three of the seminal figures in the early history of physics, Galileo Galilei, Johannes Kepler, and Sir Isaac Newton were all astrophysicists. It would seem that as physics matured as a science and terrestrial based experimentation became more prevalent astronomical observation was relegated to one voice in a chorus of sources for empirical data. However, upon more careful examination astronomical observations have continued to played a unique role in the investigation fundamental physics.

We need only consider the discovery of Hubble's law, or the detection of the cosmic microwave background to see the impact astrophysical observation had on physics in the twentieth century. Even more recently the finding of a non-zero neutrino mass from solar, cosmic ray, and supernova observations, and the discovery of dark matter and dark energy have again reminded us of the central role of astrophysics in fundamental physical inquiry.

Perhaps then the relationship between astronomy and fundamental physics extends to the realm of quantum gravity. Certainly black holes and the initial cosmological singularity (the big bang) serve as the two primary physical phenomena that require a theory of quantum gravity to fully describe. So we can ask whether there are extreme astrophysical phenomena which provide evidence of quantum gravity. We argue that such events are possible and we address two possible examples.

2. ASTROPHYSICAL SEARCHES FOR QUANTUM GRAVITY

While considering the best method to conduct an astrophysical search for quantum gravity we must bear in mind that a radically different approach may be required. We begin by noting that astronomical observations are 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. Such transients are just the type of phenomena that could be related to quantum gravitational effects, and searches for these could provide a new arena in which to probe this elusive area of inquiry.

Observations of transient phenomena have already played a role in astrophysical exploration. The discovery of pulsars and gamma-ray bursts (GRBs) are prime examples. Moreover, a recently observed radio pulse of extragalactic origin has been found [1]. It has further been argued that this pulse could have been produced by a superconducting cosmic string, another phenomena which can provide evidence of quantum gravity [2].

We should also look beyond electromagnetic signals. Many explosive events that can produce short time scale electromagnetic pulses also produce a gravitational wave signature (i.e. supernova, cosmic strings, compact object mergers, etc.). Thus searches for coincident gravitational waves and electromagnetic pulses could be very profitable.

3. EXPLODING PRIMORIDAL BLACK HOLES & EXTRA DIMENSIONS

Now we consider an 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 [3–5].

Rees noted that exploding primordial black holes could provide an observable coherent radio pulse that would be easier to detect than gamma-ray emissions [6].

Rees and Blandford [6; 7] 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 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

$$kT \approx \frac{\gamma_f}{10^5} 0.1 \text{ TeV}. \tag{1}$$

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

There exists a remarkable relationship between the range of pulse-producing Lorentz factors for the emitted particles, and the TeV scale [3]. Since $\gamma_f \propto T$ at the time of the explosive burst, equation (1) yields

$$\frac{\gamma_f}{10^5} \approx \frac{10^{-19} \text{ m}}{R_s}, \tag{2}$$

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

$$(R_s/\hbar c)^{-1} \sim 1 - 100 \text{ TeV}. \tag{3}$$

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

To make use of these interesting generic observations, a specific phenomenologically relevant explosive process is required. One such process, discussed by Kol [8], which connects quantum

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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.

A topological phase transition from the black string to the black hole occurs when an instability, the Gregory-LaFlamme point, is reached [9]. This transition is of first order, and results in a significant release of energy equivalent to a substantial increase in the luminosity of Hawking radiation [8].

The analysis of Rees and Blandford [6; 7] can be adapted to the topological phase transition scenario. Observing frequencies between ~ 1 GHz and 10^{15} Hz ($\gamma_f \sim 10^5$ to 10^7) samples the range of extra dimension size, $L \sim 10^{-18} - 10^{-20}$ m.

4. TRANSIENT PULSE SEARCHES

Searches for transient radio pulses from PBH explosions, cf. [10; 11], can probe for the existence of PBHs well below the limits established by observations of the diffuse γ-ray background [12; 13]. 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 (~ 1 steradian): the Long Wavelength Array (LWA) [14], Murchison Widefield Array (MWA) [15], and the Low Frequency Array (LOFAR) [16].

A continuous wide-field low-frequency radio transient search already underway uses the Eight-meter-wavelength Transient Array (ETA) [17–19] 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. 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.

5. EVOLUTION OF A BLACK-HOLE NEUTRON-STAR BINARY SYSTEM

Much work has been done to understand the nature of black holes in the braneworld scenario [20]. In particular, application of AdS/CFT indicates that the full classical 5D solution is equivalent to a 4D quantum corrected black hole. Moreover, this analysis has yielded surprising results which include a dramatically increased evaporation rate for large black holes due to the existence of conformal degrees of freedom [21]. Some observational implications of these results were explored in [22].

The evaporation rate of a black hole in the AdS/CFT braneworld scenario is given by

$$\dot{m}_{BH} = -2.8 \times 10^{-7} \left(\frac{m_{BH}}{M_\odot}\right)^{-2} \left(\frac{L}{10\ \mu\mathrm{m}}\right)^{2} M_\odot\ \mathrm{y}^{-1}\,, \tag{4}$$

where m_{BH} is the mass of the black hole and L is the AdS radius [21; 22]. The current bound on the AdS radius is $\sim 10\mu$m [23] which we take as a nominal value in this discussion.

To explore the observational implications of the above scenario, it is interesting to consider a black-hole-neutron-star (BH-NS) binary system. If the NS is a pulsar, it is possible to make precision observations that could reveal the effects of the AdS/CFT braneworld scenario. Precision measurements of the changing orbital period of this system would be key, as was the case in the demonstration of gravitational radiation effects in the binary pulsar system PSR 1913+16 (a NS-NS binary, where one of components is an observed pulsar).

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Hadjidemetriou [24] discussed the detailed dynamical behavior of a binary system with isotropic mass loss from one or both components. In this situation the binary pair becomes less tightly bound while conserving angular momentum. Therefore the components must separate over time and the orbital period will increase. These results would apply directly to a BH-NS binary in the AdS/CFT braneworld scenario, if the mass-loss effect dominates the evolution of the orbital period in comparison with the effect of gravitational radiation.

Assuming mass loss dominates over energy loss by gravitational radiation, then to lowest order, the rates of change of the semi-major axis a and eccentricity e of the binary, averaged over an orbital period, are

$$\dot{a} = -\,a\frac{\dot{m}}{m}, \tag{5}$$

$$\dot{e} = 0. \tag{6}$$

where $\dot{m} = d/dt(m_{BH} + m_{NS}) = \dot{m}_{BH}$. Since the system obeys Kepler's third law at any moment, the corresponding rate of change of the orbital period is

$$\dot{P} = -2P\frac{\dot{m}}{m}. \tag{7}$$

The effect of mass loss would be to increase the semi-major axis and the orbital period. This is the opposite of the result produced by gravitational radiation. The observation of an increasing orbital period for a BH-NS binary system would yield dramatic evidence for an increased black-hole evaporation rate in an AdS/CFT braneworld scenario.

For a specific case with $P = 7.75$ hours and $e = 0.6$, motivated by PSR 1913+16, and $L = 10\mu$m the results due to mass-loss alone would be $\dot{a} = 16$ m y^{-1}, $\dot{P} = 0.40$ ms y^{-1}. In comparison, energy loss due to gravitational radiation, considered alone, would result in $\dot{a}_{GR} = -3.9$ m y^{-1}, and $\dot{P} = -0.12$ ms y^{-1}. To give an idea of how measurable the mass loss effect would be for $L = 10\mu$m, the observed rate of change of the orbital period for the binary pulsar PSR 1913+16 of $\dot{P} = (-2.4184 \pm 0.0009) \times 10^{-12}$ s/s [25] is equivalent to $\dot{P} = -0.076$ ms y^{-1} with an uncertainty about 2700 times smaller than the magnitude.

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