New constraints on quantum foam models from X-ray and gamma-ray observations of distant quasars

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Astronomical observations of distant quasars may be important to test models for quantum gravity, which posit Planck-scale spatial uncertainties (‘spacetime foam’) that would produce phase fluctuations in the wavefront of radiation emitted by a source, which may accumulate over large path lengths. We show explicitly how wavefront distortions cause the image intensity to decay to the point where distant objects become undetectable if the accumulated path-length fluctuations become comparable to the wavelength of the radiation. We also reassess previous efforts in this area. We use X-ray and gamma-ray observations to rule out several models of spacetime foam, including the interesting random-walk and holographic models.

Keywords: Experimental tests of gravitational theories, Quantum gravity, Spacetime topology causal structure spinor structure

1. Introduction

Even at the minute scales of distance and duration examined with increasingly discriminating instruments, spacetime still appears to be smooth and structureless. However, a variety of models of quantum gravity posit that spacetime is, on Planck scales, subject to quantum fluctuations. As such, the effect of quantum gravity on light propagation (if detected) can possibly reveal a coupling to vacuum states postulated by Inflation and String Theories. In particular, models consistent with the “Holographic Principle” predict that space-time foam may be detectable via intensity-degraded or blurred images of distant objects. While these models are not a direct test of the Holographic Principle itself, the success or failure of such models
may provide important clues to connect black hole physics with quantum gravity and information theory.

The fundamental idea is that, if probed at a small enough scale, spacetime will appear complicated – something akin in complexity to a turbulent froth that Wheeler (1963) has dubbed “quantum foam,” also known as “spacetime foam.” In models of quantum gravity, the foaminess of spacetime is a consequence of the Energy Uncertainty Principle connecting the Planck mass and Planck time. Thus, the detection of spacetime foam is important for constraining models of quantum gravity. If a foamy structure is found, it would require that space-time itself has a probabilistic, rather than deterministic nature. As a result, the phases of photons emitted by a distant source would acquire a random component which increases with distance.

A number of prior studies have explored the possible image degradation of distant astronomical objects due to the effects of spacetime foam. In particular, most of these focus on possible image blurring of distant astronomical objects. We demonstrate that this previous approach was incomplete, and take a different approach, examining the possibility that spacetime foam might actually prevent the appearance of images altogether at sufficiently short wavelengths. Short-wavelength observations are particularly useful in constraining quantum gravity models since, in most models of quantum gravity, the path-length fluctuations and the corresponding phase fluctuations imparted to the wavefront of the radiation emitted by a distant source are given

\[ \delta \varphi \approx 2\pi \ell^{1-\alpha} \rho_p^\alpha / \lambda \]  

where \( \lambda \) is the wavelength one is observing, the parameter \( \alpha \lesssim 1 \) specifies different space-time foam models, and \( \ell \) is the line-of-sight co-moving distance to the source.

2. Effects of Spacetime Foam on Astronomical Images

As discussed in the Introduction, there are good reasons to believe that spacetime foam would produce small phase shifts in the wavefronts of light arriving at telescopes. Eqn. (1) points out that the path-length fluctuations envisioned by models of quantum gravity distort the wavefront emitted by cosmologically distant sources, imparting phase fluctuations. The individual fluctuations are infinitesimally small, but depending on the model for quantum gravity being discussed, they may accumulate over long path lengths, perhaps to a point where their effects can be detected. This is the essence of our work. To help understand what images of distant, unresolved sources (e.g., quasars or gamma-ray bursts) might look like after propagating to Earth through a space-time foam-induced ‘phase screen’, we consider the Fourier transform of \( e^{i\Delta \varphi(x,y)} \) over the coordinates \( \{x, y\} \) of the entrance aperture. This approach is particularly helpful because the image formed will be simply the absolute square of this function. Moreover, if the phase fluctuations in \( \Delta \varphi \) are assumed to be analytic, part of the problem can also be done analytically.
making simulations particularly easy to carry out.

In particular, we find that as long as \( \delta \phi_{\text{rms}} \lesssim 0.6 \text{ radians} \) (or \( \delta \ell_{\text{rms}} \lesssim 0.1 \lambda \)) the Strehl ratio, which measures the ratio of the point spread function (‘PSF’) compared to an ideal PSF for the same optics, is to a good approximation,

\[
S \simeq e^{-\delta \phi_{\text{rms}}^2}. \tag{2}
\]

Furthermore, if these phase shifts are distributed randomly over the aperture (unlike the case of phase shifts associated with well-known aberrations, such as coma, astigmatism, etc.) then the shape of the PSF, after the inclusion of the phase shifts due to the spacetime foam, is basically unchanged, except for a progressive decrease in \( S \) with increasing \( \delta \phi_{\text{rms}} \).

We carried out numerical simulations utilizing various random fields \( \Delta \phi(x, y) \), including Gaussian, linear, and exponential. We considered a large range of rms values and different correlation lengths within the aperture. Fig. 1 illustrates these simulations, and shows a sequence of the simulated PSFs, in the form of radial profiles, for a range of increasing amplitudes of random phase fluctuations. As can be seen, there are three major effects: (i) the peak of the PSF is decreased; (ii) beyond a certain radial distance, the PSF reaches a noise plateau that can be interpreted as an indication of the partial de-correlation of the wave caused by increasing phase fluctuations; and (iii) in between, the shape (including the slope, intensity ratios of Airy rings, etc.) of the PSF is unchanged by the increasing phase fluctuations. The self-similar invariance of the PSF shape (aside from the appearance of the noise plateau) contradicts the expectation from previous work \([1,7–12,14–16]\) that phase fluctuations could broaden images of a distant quasars. In contrast, we now find that while the images are essentially unaffected, for sufficiently large amplitude phase fluctuations (e.g., \( \delta \ell / \lambda \gtrsim \pi \)) the entire central peak disappears and the image is undetectable.

As Figure 1 shows, the overall PSF shape for a cosmologically distant source, and the slope of its decline, will be nearly unchanged until the phase differences imposed by spacetime foam approach \( \sim \pi \) radians, at which point the profile just merges into the background noise floor. At this point, the quasar intensity would basically be degraded to the point where it would no longer be detected. This forces us to re-conceptualize how one might constrain models for quantum gravity, and particularly the \( \alpha \)-models. By inverting our analytical model of the PSF, we find that

\[
\alpha > \frac{\ln(\pi \ell / \lambda)}{\ln(\ell / \ell_P)}, \tag{3}
\]

where we have required a phase dispersion \( \delta \phi_{\text{rms}} = 2 \) radians, corresponding to the location where the Strehl ratio falls to \( \sim 2\% \) of its full value. We show in Fig. 2 a plot of the limit that can be set on the parameter \( \alpha \) as a function of measurement wavelength, for four different values of comoving distance. The result is an essentially universal constraint that can be set simply by the detection of
Fig. 1. At left, an illustrative example of our numerical simulations of a point spread function that has been affected by a Gaussian random field of phase shifts over the aperture. The top left panel shows the circular aperture with Gaussian phase shifts of rms amplitude $0.03\lambda$. The bottom left panel shows the inner $128 \times 128$ pixels of the absolute square of the Fourier transform of the aperture function, using a 1/4-power law color palette. The right-hand panel shows a sequence of radial profiles of the numerically computed PSFs for rms phase shifts ranging from 0.01 $\lambda$ to 0.5 $\lambda$, as indicated by the color coding. Note how the shape of the PSF for small angles is nearly unchanged until it plateaus into the background.

distant quasars as a function of the observing wavelength. This more rigorous understanding has significant effects on the constraints one can set on $\alpha$ using observations in any given waveband. While it loosens the constraints set by optical observations to $\alpha > 0.53$, contrary to previous works (including our own), i.e., ruling out the random walk model, but not coming close to the parameter space required for the holographic model. Another way to think of this constraint is that for any given wavelength, $\alpha$-models predict that there is a maximum distance, beyond which it would be impossible to detect a source.

The simulations we have done have profound implications for constraining the spacetime foam parameter $\alpha$. Equation (1) shows that for a given source distance, $\ell$, the rms phase shifts over the wavefront are proportional to $\lambda^{-1}$. This opens up the possibility of using X-ray and gamma-ray observations to set the tightest constraints yet. The constraints produced in a given band are symbolized in Fig. 2 by vertical lines that denote optical (5000 Å wavelength or 2.48 eV photon energy), X-ray (5 keV), GeV and TeV photons. These represent the energies where observations of distant quasars by the Chandra X-ray Observatory, Fermi Gamma-ray Space Telescope, and the VERITAS telescope array, all of which show well-resolved images, may be used to constrain $\alpha$. The constraints thus produced (Fig. 2) are
lower limits to $\alpha$ produced by the mere observation of an image (whether diffraction limited or not!) of a cosmologically distant quasar.

Fig. 2. Constraints on the parameter $\alpha$, for four different comoving distances to the object, respectively 300 Mpc ($z \approx 0.07$; red curve), 1 Gpc ($z \approx 0.25$; green), 3 Gpc ($z \approx 1$; blue) and 10 Gpc ($z \approx 12$; purple). The two horizontal refer to the holographic and random-walk models, respectively, as labeled. The vertical dashed lines represent the optical (5000 $\AA$), X-ray (5 keV), GeV and TeV wavebands. As astronomical images betray no evidence of cosmic phase fluctuations that might be due to spacetime foam, the region of parameter space excluded by observations in each band lies below the curves. For any given wavelength, $\lambda$, images will not propagate for values of $\alpha$ below the various lines corresponding to different comoving distances.

3. Summary and Conclusions

According to the simulations discussed here, it would seem that the very existence of distant astronomical images can be used to put significant constraints on models of spacetime foam. Perhaps the strongest constraints of all now come from the detection of large numbers of cosmologically distant sources – mostly blazars – in the $\gamma$-rays. These detections limit $\alpha$ to values higher than 0.67 and 0.72, at GeV and TeV energies, respectively. This strongly disfavors, if not completely rules out, the holographic model.
There are, however, a number of caveats to our idea for constraining $\alpha$-models of spacetime foam. In particular, as pointed out by Stefano Liberati at this meeting, GeV and even TeV gamma-rays have wavelengths that are vastly larger than the Planck scale. It is possible that photons propagate on an averaged space-time, so that their geodetics would be smooth, not noticeably affected by spacetime foam effects. Another possibility along these same lines is that time dilates as a function of distance scale, so that independent of the value of $\alpha$, geodetics would be unaffected by space-time foam effects and no phase dispersion would be expected, regardless of the wavelength of the photon. The latter proposal carries with it also an interesting prediction that the speed of light is energy independent. At this time it is difficult for us to see how to simulate such an effect.

In this work we have considered the instantaneous fluctuations in the distance between the location of the emission and a given point on the telescope aperture. Perhaps one should average over both the huge number of Planck timescales during the time it takes light to propagate through the telescope system, and over the equally large number of Planck squares across the detector aperture. It is then possible that the fluctuations we have been calculating vanish, but at the moment we have no formalism for carrying out such averages.

Finally, we should recall that the spacetime foam model parametrized by $\alpha = 2/3$, as formulated is called the ‘holographic model’ only because it is consistent with the holographic principle; the demise of the model may not necessarily imply the demise of the principle since it is conceivable that the correct spacetime foam model associated with the holographic principle can take on a different and more subtle form than that which can be given by $\delta\ell \approx t^{1/3}P^{2/3}$. It is important to be clear: what we are ruling out (subject to the caveats mentioned above) are the models with $\alpha < 0.72$ for the spacetime foam models that can be categorized according to $\delta\ell \approx t^{1-\alpha}P_{\alpha}$.

References

1. Y. Jack Ng, Selected topics in Planck-scale physics, Mod. Phys. Lett. A18, 1073 (2003).
2. Gerardus 'tHooft, Dimensional reduction in quantum gravity, Salamfestschrift, ed. A. Ali et al. (Singapore: World Scientific), 284 (1993).
3. Leonard Susskind, The world as a hologram, J. Math. Phys. 36, 6377 (1995).
4. Ofer Aharony et al., Large N field theories, string theory and gravity, Phys. Rep., 323, 183 (2000).
5. Stephen W. Hawking, Particle creation by black holes, Commun. Math. Phys., 43, 199 (1975).
6. John A. Wheeler, in Relativity, Groups and Topology, ed. B.S. DeWitt & C.M. DeWitt (New York: Gordon and Breach), 315 (1963).
7. Lieu, R., & Hillman, L. W., The phase coherence of light from extragalactic sources: direct evidence against first-order Planck scale fluctuations in time and
space, *Astrophys. J.*, 585, L77 (2003).

8. Y. Jack Ng, Wayne A. Christiansen, & Henrik van Dam, Probing Planck-scale physics with extragalactic sources? *Astrophys. J.*, 591, L87 (2003).

9. Ragazzoni, R., Turatto, M., & Gaessler, W., The lack of observational evidence for the quantum structure of space-time at Planck scales, *Astrophys. J.*, 587, L1 (2003).

10. Wayne A. Christiansen, Y. Jack Ng & Henrik van Dam, Probing spacetime foam with extragalactic sources, *Phys. Rev. Lett.* 96, 051301 (2006).

11. Wayne A. Christiansen et al., Limits on spacetime foam, *Phys. Rev. D.*, 83, 084003 (2011).

12. Eric S. Perlman et al. Using observations of distant quasars to probe quantum gravity, *Astron. Astrophys.*, 535, L9 (2011).

13. Eric S. Perlman et al., New constraints on quantum gravity from X-ray and gamma-ray observations, *Astrophys. J.* 805, 10 (2015).

14. Eric Steinbring, Are high-redshift auasars blurry?, *Astrophys. J.* 655, 714 (2007).

15. Eric Steinbring, Detectability of Planck-scale induced blurring with gamma-ray bursts, *Astrophys. J.*, 802, 38 (2015).

16. Fabrizio Tamburini, et al., No quantum gravity signature from the farthest quasars, *Astron. Astrophys.*, 533, 71 (2011).

17. Daniel Coumbe, On quantum gravity without vacuum dispersion, arXiv:1512.02591 (2015).

18. Y. Jack Ng, & Henrik van Dam, Limits to space-time measurement, *Mod. Phys. Lett.* A9, 335 (1994)

19. Y. Jack Ng, & Henrik van Dam, Remarks on gravitational sources, *Mod. Phys. Lett.* A10, 2801 (1995)