LETTER

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Letter to the Editor

Pulsar radiation and quantum gravity

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Abstract. Quantum gravity may lead to an energy dependence in the speed of light. The high energy radiation from gamma-ray pulsars can be used to place limits on such effects. We find that emission from the Crab pulsar at energies above 2 GeV trails that at 70–100 MeV by no more than 0.35 ms (95% confidence) and place a lower bound on the energy scale of quantum gravitational effects on the speed of light of 1.8×10^{15} GeV. This bound might be improved by two orders of magnitude by observation of pulsations from the Crab at higher energies, 50–100 GeV, in the near future.

Key words: gravitation – stars: pulsars: general – stars: pulsars: individual: Crab – gamma rays: observations

1. Introduction

Quantum gravity may cause modification of the dispersion relation for photons at high energies. It has recently been suggested that certain quantum gravity models may lead to a first order correction to the dispersion relation which can be parameterized as $\Delta t = L\Delta E/cE_{QG}$, where Δt is the magnitude of the travel time difference between two photons whose energies differ by ΔE and that have traveled a distance L, and E_{QG} is the energy scale of the dispersion effects (Amelino-Camelia et al. 1998). To probe dispersion effects at high energy scales, accurate relative timing of nearly simultaneously produced photons of different energies which have traveled long distances is required. Use of sub-millisecond time structure of the keV photon flux of gamma-ray bursts at cosmological distances (Amelino-Camelia et al. 1998; Schaefer 1998) and use of several minute time structure in TeV flares from AGN (Biller et al. 1998) have been suggested. Here, we show that sub-millisecond timing of GeV emission from gamma-ray pulsars may also place useful constraints on the dispersion relation for photons at high energies.

Below, we use existing gamma-ray data to determine the accuracy with which high energy pulsar emission can be timed and to place bounds on the energy scale for quantum gravity corrections to the speed of light. We then discuss how this limit might be improved by pulsar observations at higher energies in the near future.

2. Gamma-ray pulsations from the Crab

We chose to analyze the energy dependence of pulse arrival times from the Crab pulsar as it has the largest ratio of distance to pulse period of the bright gamma-ray pulsars, thus maximizing the constraints which can be placed. Also, the pulses from the Crab are well aligned in time from radio waves, through optical and x-ray emission, to gamma-rays. Thus, it is likely that the photons of different energies are produced nearly simultaneously.

We used data from the *Energetic Gamma-Ray Experiment Telescope* (EGRET) (Thompson et al. 1993) of the *Compton Gamma-Ray Observatory* (CGRO). We extracted gamma-ray photon event lists from the CGRO public archive for observations pointed within $40°$ of the Crab and then, using the program pulsar (version 3.2, available from the CGRO Science Support Center) selected events lying within the energy dependent 68% point spread function of EGRET and calculated the phase of each photon relative to the radio ephemeris of the Crab (Arzoumanian et al. 1992). The pulse period of the Crab changed from 33.39 ms to 33.49 ms over the course of these observations. The radio timing must be corrected for the variable dispersion along the line of sight to the Crab. The accuracy of this correction is estimated to be 0.2 ms (Nice 1998), consistent with previous estimates of the accuracy of the dispersion correction for the Crab (Gullahorn et al. 1977).

Pulse phase histograms for several energy bands are shown in Fig. 1. The main pulse peak, near phase 0.0, is the most appropriate feature for timing. The main peak is similar across the energy range from 70 MeV to 2 GeV (Fierro 1995). The peak width is about 0.05 in phase, and appears somewhat narrower at high energies. There is no obvious shift of the peak centroid with energy.

To study the energy dependence of the speed of light, we measured the main peak pulse arrival time in each energy band. We did this in two ways. First, we calculated the average arrival time for photons in the main peak. We found the average time for each energy band using photons with phases between -0.0464 and 0.0336, an interval centered on the mean arrival time for all photons used in this analysis. Second, we parameterized the pulse arrival times by fitting a Lorentzian to the pulse profile, within the same phase range specified above, for each

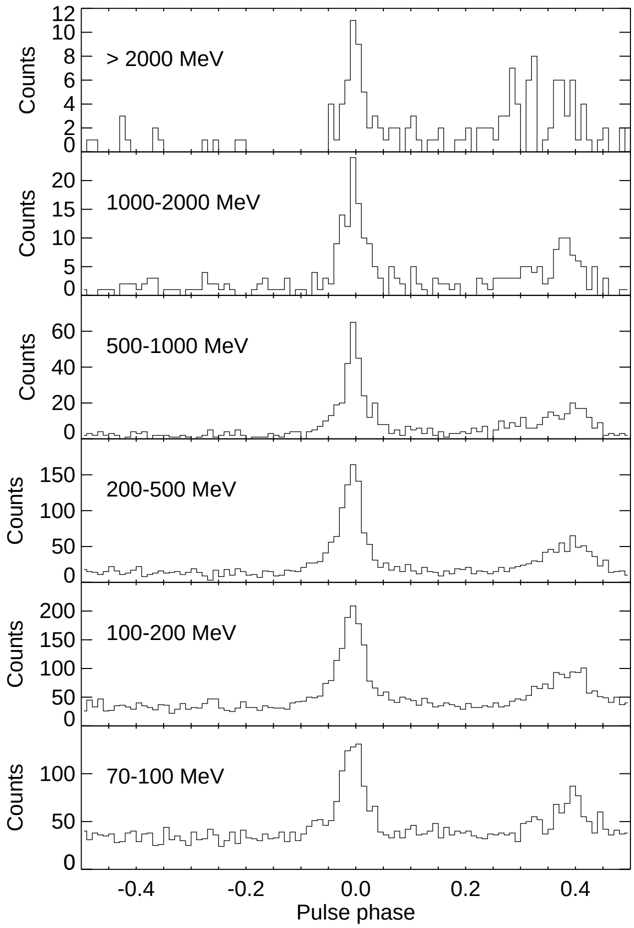

Fig. 1. Crab pulsar phase histograms for various γ-ray energy bands. Zero phase is set by the radio ephemeris.

energy band. Before fitting, a constant rate equal to the average rate between phases -0.4 and -0.2 was subtracted. The resultant was then fit with a Lorentzian using a gradient-expansion algorithm to compute a non-linear least squares fit. The fits were all acceptable with χ^2 in the range 2.9 to 7.6 for 5 degrees of freedom.

Fig. 2 shows the pulse arrival times calculated via both methods. The errors in Fig. 2 correspond to $\Delta\chi^2 = 1$ (68% confidence). The energy of each point is the median photon energy for each energy band. For the highest energy band, the median energy is substantially lower than the average, 2.9 GeV versus 5.0 GeV. The zero pulse phase is set by the radio ephemeris. The pulse arrival time for all photons used in this analysis is shown as a dashed line and differs by 0.21 ms from the radio zero phase. This is within the error in the radio dispersion correction (Nice 1998). We note that errors in the radio zero phase can broaden the gamma-ray peak, but will not induce an energy dependent shift in the gamma-ray pulse arrival time. The accuracy of the pulse arrival time determination for the Lorentzian fit is 0.07 ms ($\Delta\chi^2 = 3.84$ or 95% confidence for a single parameter of interest) in the 100–200 MeV band and 0.21 ms (95% confidence) in the highest energy band. The accuracy in the highest energy band is limited mainly by statistics.

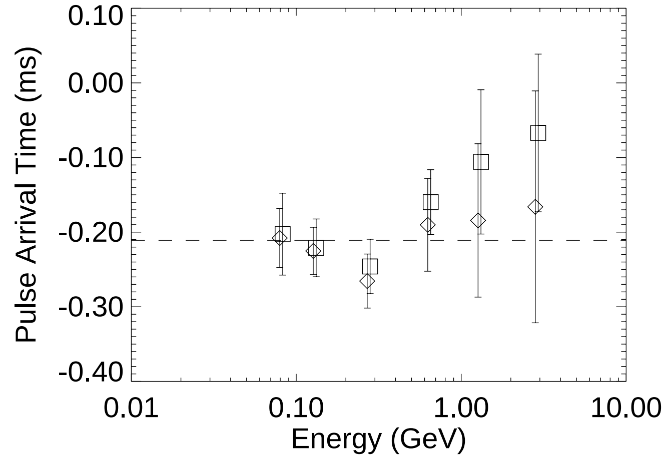

Fig. 2. Pulse arrival time versus energy for the Crab. The diamonds indicate the average arrival time for photons within the main pulse for each energy band. The squares indicate the centroid of a Lorentzian fit to the pulse profile for each energy band. The energies plotted are the median energy for each band; the diamonds are shifted slightly in energy for clarity. The dashed line is the centroid of a Lorentzian fit to the pulse profile for all energies above 70 MeV.

It is apparent from the figure that there is no statistically significant variation in pulse arrival time with energy. To place an upper bound on any energy dependence in the speed of light, we compare the arrival time for photons with energies above 2 GeV (median energy 2.93 GeV) to that for the 70–100 MeV band (median energy 82.8 MeV). The 95% confidence upper limit on the difference of the arrival times is 0.35 ms. Adopting a distance to the Crab of 2.2 kpc (Zombeck 1990), this leads to a lower limit on the energy scale of quantum gravity effects on the speed of light of $E_{QG} > 1.8 \times 10^{15}$ GeV (95% confidence). This limit lies below the range of interest, but within an order of magnitude of some predictions in the context of string theory (Witten 1996).

3. Discussion

Other effects which could also produce an energy dependent delay in photon arrival times include energy dependent dispersion due to the strong gravitational field near the neutron star, purely electromagnetic dispersion, an energy dependence in the emission location, or an intrinsic energy dependence in the emission time. The effect of any energy dependent dispersion due to the strong gravitational field near the neutron star is likely to be small because, even if emitted from the neutron star surface, photons traverse the region of high gravitational fields within about 0.1 ms. Allowing a fractional change in the speed of light equal to the dimensionless field strength at the neutron star surface, $GM/Rc^2 \approx 0.2$, where $M \approx 1.4\,M_{\odot}$ is the neutron star mass and $R \approx 10\,\mathrm{km}$ is the neutron star radius, the difference in arrival times would be only 0.02 ms. The actual energy dependent change in the speed of light is likely to be much smaller than 0.2. Any significant purely electromagnetic dispersion at MeV energies and above can be excluded based on the dispersions measured at lower energies.

An energy dependence in the photon emission location or intrinsic emission time could produce a significant energy dependent time delay. While the possibility that precise tuning of the emission locations or times for various energy photons could cancel an energy dependent dispersion arising from quantum gravity effects, we consider such a coincidence unlikely, although not excluded, and interpret our lack of detection of any energy dependence in arrival times as constraining both the energy dependent dispersion and the emission location and time. In this case, the average emission location, projected along our line of sight, for photons at energies in the 70–100 MeV band must lie within 110 km of that for photons above 2 GeV, within 50 km of that for 0.5–1.0 GeV photons, and within 150 km of that for radio photons.

It is encouraging that the analysis shows that it is possible to time the Crab pulsar at gamma-ray energies to an accuracy of 0.07 ms (95% confidence) given adequate statistics. Detection of pulsations from the Crab at 50–100 GeV could improve the limit on E_{QG} by two orders of magnitude. The key question is whether the pulsations of the Crab and other gamma-ray pulsars continue to such high energies. Observations of the Crab near 1 TeV show only unpulsed emission (Vacanti et al. 1991) and the cutoff energy of the pulsed emission is unknown. If the Crab does pulse at 50–100 GeV, detection of the pulses may be possible in the near term with low energy threshold atmospheric Cherenkov telescopes (ACTs), such as STACEE (Bhattacharya et al. 1997) and CELESTE (Giebels et al. 1998), or in the longer term with a space-borne gamma-ray detector such as GLAST (Gehrels et al. 1998). The Crab pulsed signal may extend only to the lowest energies accessible with the ACTs. Thus, measurement of a timing difference between two energy bands might require contemporaneous measurements at other wavelengths. Both optical (Smith et al. 1978) and x-ray timing (Rots et al. 1998) can exceed the accuracy of gamma-ray timing. However, the emission location for x-ray and optical photons may differ from that of gamma-ray photons. If quantum gravity does produce a first order correction to the dispersion relation for electromagnetic waves, then measurement of the pulse arrival time of the Crab at 50 GeV with an accuracy of 0.1 ms could be used to place a lower bound on $E_{QG} > 1.1 \times 10^{17}\,\mathrm{GeV}$. This is within the range, 10^{16}–$10^{18}\,\mathrm{GeV}$, for the energy scale for quantum gravity effects preferred in string theory (Witten 1996).

If future measurements do reveal an energy dependence in pulsar photon arrival times, then it will be difficult to distinguish an energy dependent dispersion from an intrinsic energy dependence in the emission location or emission time. This problem is common to all of the suggested astronomical tests of quantum gravity effects. Convincing proof for quantum gravity effects will likely require detection of energy dependent time delays in at least two different classes of objects, preferably at vastly difference distances, i.e. pulsars versus AGN or gamma-ray bursts, with all of the detections compatible with the same value of E_{QG}.

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