The Weak Equivalence Principle states that the geodesics of a test particle in a gravitational field are independent of the particle’s constitution. To constrain violations of the Weak Equivalence Principle, we use the one-meter telescope at Table Mountain Observatory near Los Angeles to monitor the relative arrival times of pulses from the Crab Pulsar in the optical ($\lambda \approx 585$ nm) and near-infrared ($\lambda \approx 814$ nm) using an instrument that detects single photons with nanosecond-timing resolution in those two bands. The infrared pulse arrives slightly before the visible pulse. Our three analysis methods give delays with statistical errors of $\Delta t_{\text{obs}} = 7.41 \pm 0.58$, $0.4 \pm 3.6$, and $7.35 \pm 4.48$ microseconds (at most 1/4000 of the pulsar period). We attribute this discrepancy to systematic error from the fact that the visible and infrared pulses have slightly different shapes. Whether this delay emerges from the pulsar, is caused by passing through wavelength-dependent media, or is caused by a violation of the equivalence principle, unless there is a fine-tuned cancellation among these, we set the first upper limit on the differential post-Newtonian parameter at these wavelengths of $\Delta \gamma < 1.07 \times 10^{-10}$ ($3\sigma$). This result falls in an unexplored region of parameter space and complements existing limits on equivalence-principle violation from fast radio bursts, gamma-ray bursts, as well as previous limits from the Crab.

Key words: gravitation – instrumentation: miscellaneous – pulsars: individual (Crab)

1. Introduction

For decades, precise experimental tests of general relativity have been carried out using a variety of observational and laboratory techniques, ranging from the Weber bars of the 1960s to astrophysical timing measurements, atom interferometric techniques, and Advanced LIGO (Weber 1960; Shapiro et al. 1968, 1976; Taylor & Weisberg 1989; Williams et al. 2004; Dimopoulos et al. 2007; Zhou et al. 2015; Abbott et al. 2016). The parametric post-Newtonian (PPN) formalism translates the results of these diverse tests into a common language. A set of dimensionless parameters summarize the observational consequences of various alternative gravitational theories and enable different experiments to constrain new physics in a unified framework (see Will 2014 for a review). For example, a well-known general-relativistic effect occurs when a point particle experiences a time delay falling through a gravitational potential $U(r)$ from point A to B:

$$\delta t_{\text{GR}} = \frac{2}{c^3} \left[ \int_A^B U(r) \, dr \right].$$

This effect, called the Shapiro delay (Shapiro et al. 1968), is generalized by the PPN framework by the introduction of the parameter $\gamma$,

$$\delta t = \frac{1 + \gamma}{c^3} \left[ \int_A^B U(r) \, dr \right].$$

with general relativity being the special case where $\gamma = 1$. In the PPN framework, the Weak Equivalence Principle (WEP) is equivalent to the statement that $\gamma$ is constant, independent of the constituents of whatever is going from A to B through $U(r)$. In order to constrain WEP-violating theories of gravity, e.g., scalar-tensor theories, gravitational theories with nonsymmetric metrics, and non-metric theories, tests of the WEP aim to measure the absolute value of $\gamma$ (see Shapiro et al. 1976).

A way to test the WEP is to measure whether $\gamma$ varies between different choices of test particles. For example, $\gamma$ may potentially take on different values for photons of two different wavelengths $\lambda_1$ and $\lambda_2$. This manifests itself in a differing time-of-flight $\Delta t$ for the two photons along a common trajectory between arbitrary points A and B:

$$\Delta t = (\delta t_1 - \delta t_2) = (\gamma_1 - \gamma_2) \left[ \int_A^B \frac{U(r)}{c^3} \, dr \right].$$

A powerful way to set upper limits on this possibility is to make a differential measurement $\gamma_1 - \gamma_2 \equiv \Delta \gamma$ using high-time-resolution, multi-band electromagnetic observations of high-energy astrophysical transients. Typical candidates include blazars (Wei et al. 2016), the supernova SN1987A (Longo 1988), gamma-ray bursts (Gao et al. 2015; Nusser 2016), fast radio bursts (Nusser 2016; Tingay & Kaplan 2016), and recently, pulses from the Crab Pulsar (Zhang & Gong 2017). A relative time delay $\Delta t_{\text{obs}}$ can be interpreted as some combination of factors including intrinsic delay, delays in traversing media along the way, and WEP violation. By assuming there is no fine-tuned cancellation between these, and with a model of the gravitational potential $U(r)$ along the transient’s trajectory toward Earth, we can set an upper limit on $\Delta \gamma$ between the two observing wavelengths. This upper limit is saturated when all of the delay is due to WEP violation and still holds if the delay is due to any of the other mechanisms.

Here, we present a detailed measurement of the pulse delay between visible and near-infrared (NIR) pulses of the Crab pulsar using fast single-photon detectors. Folding $\sim 2 \times 10^5$ Crab pulses to obtain a high signal-to-noise ratio enables us to measure the difference in arrival times in these two wavelength bands to within microseconds. We can translate
our measurement of the arrival time difference into an upper bound on $\Delta \gamma$ between visible and NIR wavelengths, using the model of the galactic gravitational potential from Zhang & Gong (2017).

Golden (2000), Massaro et al. (2000), Rots et al. (2004), Kuiper et al. (2003), Oosterbroek et al. (2006), and Molkov et al. (2010) have all conducted extensive studies of wavelength-dependent Crab pulse delays, measuring the delay with respect to the main radio pulse. Many of these measurements have also been incorporated into the strong upper limits on $\Delta \gamma$ set by Zhang & Gong (2017). In addition, the Crab pulsar has been timed at optical wavelengths with nanosecond-timing resolution detectors (Germanà et al. 2012). However, to the best of our knowledge, our study is the first that combines nanosecond-timing resolution with simultaneous observations in multiple bands to derive an upper limit on violations of the weak equivalence principle as parameterized by $\Delta \gamma$. This work provides a complement to existing bounds from several high-energy astrophysical phenomena, including several from the Crab pulsar, as mentioned earlier.

### 2. Observations of the Crab Pulsar

For our observations, we utilize a custom instrument, described in Leung et al. (2018) and similar to those in Handsteiner et al. (2017), which uses avalanche photodiodes and a time-tagging unit to record the arrival times of single photons from the Crab pulsar with nanosecond-timing resolution in two observing bands simultaneously. We made two observations of the Crab pulsar on the nights of 2016 December 21–22 using the 1-meter telescope at Table Mountain Observatory near Los Angeles, when Crab was at an elevation of $\approx 75^\circ$ in the sky (airmass $X \approx 0.74$ at our altitude above sea level). The first night had clearer observing conditions, but on the second night, we were able to record a 1 pulse-per-second signal from a TM-4 GPS unit, which gave us 25 ns absolute long-term stability referenced to UTC and $10^{-11}$ relative stability over one second. Applying three analyses methods to these two data sets, we obtain new bounds on the variation of the post-Newtonian parameter $\gamma$ between our observing wavelengths, as summarized in Table 1.

To fit a timing model for the pulsar, we follow a procedure very similar to Germanà et al. (2012), digitally combining our two lists of detections from the two bands. We determine absolute site arrival times (SATs) by first computing the complex periodogram of our list of $\approx 2 \times 10^6$ photon detections and maximizing its modulus over possible pulse frequencies $\nu$ to obtain an approximate reference frequency $\nu_{ref} = 29.646635033$ Hz. This reference frequency differs from the pulsar’s true rotation frequency by a few parts in $10^5$, primarily due to the Doppler shift induced by the Earth’s radial motion toward or away from the pulsar. Folding our data on this reference frequency enables us to compute the light curve of the pulsar, as shown in Figure 1, by binning the photon detections into 1000 histogram bins. The combined light curves generated are added together and used as a composite template in order to determine SATs for individual pulsar pulses.

To compute our SATs, we cut our list of photon timestamps into 80 consecutive observations, each lasting for $\approx 30$ s. We empirically find that this choice balances the trade-off between having more closely spaced observations and better photon statistics for each observation. Following Germanà et al. (2012), we convolve our combined visible and NIR template with each individual light curve to determine the value of the phase delay $\Delta \phi$ that maximizes the value of the convolution, thereby defining a (pointlike) SAT for a pulse of nonzero width. Though there exists substantial diversity in the literature with respect to how to do this, with many groups using a least-squares fit of a Lorentzian or a Gaussian function to the pulse’s main peak (Kuiper et al. 2003; Rots et al. 2004; Oosterbroek et al. 2006), we find consensus with Germanà et al. (2012) that the aforementioned convolution method is less sensitive than a function fit to the number of histogram bins and is also robust against a fluctuating signal-to-noise ratio. Because the overall shapes of the template and the light curve are very similar, the convolution of the two is to a very good approximation an even function, which we notice is very well described by a Lorentzian function. Fitting a Lorentzian to the peak of the aforementioned convolution defines the best-fit delay between the composite template and each individual observation to a statistical precision of $\sim 10^{-4} - 10^{-3}$ in pulse phase.

We used TEMPO2 (Hobbs et al. 2006) to convert our SATs into (solar system) barycentric arrival times (BATs), and then fit for the pulsar’s frequency and spindown rate. The inputs to TEMPO2 are the GPS coordinates of our telescope, determined to within $\pm 2$ m as well as our list of SATs provided in MJD. We note that cloudy weather obscured the pulsar in several of our 30 s chunks, making peak determination algorithm imprecise due to a poorly resolved pulse or lack of a pulse altogether. Thus, we post-selected 70/80 of our SATs on the basis of the successful convergence of our peak-finding algorithm to acceptable precision (uncertainty of $<1 \times 10^{-3}$ in pulse phase).

Our 2429 s observation starting on MJD = 57743.67833 recorded less than 10 photons per second from the Crab pulsar. The best-fit pulsar period and period derivative of

$$1/\nu = P = 0.0337302721 \pm 2.1 \times 10^{-10} \text{s}$$

$$\dot{P} = (6.92 \pm 4.2) \times 10^{-13} \text{s}/\text{s}$$

Table 1

| MJD   | Duration (s) | Flux ($s^{-1}$) | Timing | Analysis | $\Delta t_{\text{ref}}$ (µs) | $\Delta \gamma$ (µs) | $\gamma$ | $m_\gamma$ (g) |
|-------|--------------|----------------|--------|----------|----------------------------|----------------------|---------|--------------|
| 57742 | 6680         | 824            | Geocentric | Method 1 | $-7.41 \pm 0.58$ | $<1.07 \times 10^{-10}$ |         |              |
| 57742 | 6680         | 824            | Geocentric | Method 2 | $-0.4 \pm 3.6$ | $<1.30 \times 10^{-10}$ |         |              |
| 57743 | 2429         | 763            | Barycentric | Method 3 | $-7.35 \pm 4.48$ | $<2.4 \times 10^{-10}$ |         |              |

Note. Roughly half of the reported flux is pulsed, with the remaining photons from a combination of skyglow, detector dark counts, and unpulsed flux from the pulsar/nebula. We are also able to derive an upper limit on the photon mass for one of our data sets. See the main text for a more detailed description of our analysis methods.
led to an average pulse arrival time residual of \( \text{rms} = 19.9 \, \mu s \)
over our 70 observations. The lack of precision in measuring the
spindown \( P \) is due to our short observation duration.

3. The Crab Pulsar’s Spectrum

We estimate the number distribution of photons detected as a
function of wavelength in order to determine our effective
observing wavelength. The spectrum of the Crab Pulsar at
optical and near-infrared wavelengths is known to follow an
empirically measured power law (Carramiñana et al. 2000).
Using MODTRAN (Berk et al. 1987) to estimate the transmis-
sion of the atmosphere due to Rayleigh scattering and telluric
absorption, and taking into account the manufacturer-provided
transfer functions of each optical component (two achromatic
lenses, a detector quantum efficiency curve, as well as a pair of
dichroic beamsplitters), we are able to compute up to an overall
multiplicative constant the underlying number distribution
versus wavelength of the Crab photons detected. Due to the
sharp cutoff of our dichroic beamsplitters, the overlap between
sensitivity bands is at the level of \( \sim 10^{-3} \), minimizing cross-
contamination between observing bands. The calculated
distribution of detected photons as a function of wavelength
arriving in our instrument’s two observing bands is plotted in
Figure 2. Photons in our visible and near-infrared bands have
average wavelengths and FWHMs of \((585 \pm 180) \, \text{nm}, \)
\((815 \pm 177) \, \text{nm}, \) respectively. Our data contain 1.01 near-
infrared photons per visible photon, which is roughly consistent
with our spectral model, which predicts 0.94.

4. Delay between Visible and Infrared

We measure the delay between pulse arrival times in our
visible and infrared observing bands with three different
methods.

Method 1 is a point estimate of the delay between the red
and blue pulses. This does not incorporate any time dependence or
require an absolute timing model of the pulsar. We simply fold
our list of detections on our chosen reference period and
determine a “phase of arrival” \( \phi_{\text{vis}} \) by fitting a Lorentzian to
the convolution of the infrared light curve with our combined
template. Repeating this with our visible light curve gives us
\( \phi_{\text{vis}} \) from which we can determine that the infrared pulse
arrives slightly before the visible one, with
\[
\Delta t_{\text{obs}} = (\phi_{\text{vis}} - \phi_{\text{NIR}})/v_{\text{ref}} = 7.41 \pm 0.58 \, \mu s
\]
where the statistical error is estimated by parameter uncertainty
on the peak of the Lorentzian fit.

Method 2 is a slightly more sophisticated method but also
does not require conversion of SATs to barycentric arrival times. We break our infrared and visible data into 50
consecutive observations for each band. We measure the same
quantity as in Method 1 in a time-dependent way. We
determine \( \phi_{\text{vis}}(t_i) \) and \( \phi_{\text{NIR}}(t_i) \) for each observation taken at time
\( t_i \) and fit a parabola to the quantity
\[
\phi_{\text{vis}}(t) - \phi_{\text{NIR}}(t) = a t^2 + b t + c.
\]
Due to the long-term stability of the pulse profile, we can interpret the constant term \( c \) as a phase delay between the blue
and red pulses, enabling us to decouple the effects of slow time
dependence introduced from uncorrected systematics. We find
the best-fit parabola
\[
\phi_{\text{vis}}(t) - \phi_{\text{NIR}}(t) = (2.1 \pm 3.0) \times 10^{-11} (t - t_0)^2
+ (4.2 \pm 4.8) \times 10^{-8} (t - t_0) + (1.2 \pm 10.6) \times 10^{-5}
\]
where time \( t \) is measured with respect to the middle of our
observation time \( t_0 \) in seconds. Note that the quadratic and linear coefficients \( a \) and \( b \), which absorb time-dependent pulse
delays, are consistent with zero. The constant term corresponds to
a delay of
\[
\Delta t_{\text{obs}} = 0.4 \pm 3.6 \, \mu s.
\]
Method 3 involves using the TEMPO2 timing model described
earlier. We input a list of visible SATs and infrared SATs,
determined with the same method described earlier, using the
same timing model parameters, and use TEMPO2 to fit for a
time delay (or a “jump”) between infrared BATs and visible
BATs. We find a delay of
\[
\Delta t_{\text{obs}} = 7.35 \pm 4.48 \, \mu s.
\]
It is interesting that all of our measurements suggest that the IR
pulse arrives before the visible one. However, within our three
analysis methods there remains ~2σ of statistical tension. We suspect that the tension is caused by the pulse’s shape differing slightly in our infrared and visible bands, as reported in several works (Percival et al. 1993; Eikenberry et al. 1997; Sollerman et al. 2000). This systematic effect will be most prevalent in Method 1, which suffers from the least statistical noise. Also, we emphasize that Methods 1 and 2 were carried out with our first data set with a bad (time-tagging module) clock and a good (clear) sky, whereas Method 3 was only possible using our second data set with a good clock (GPS 1pps) and a bad (partly cloudy) sky. We hope to resolve this tension with future observations in order to simultaneously obtain precise pulsar timing, as well as more sophisticated data analysis procedures that can possibly mitigate the systematic effect of different pulse shapes.

We characterize our instrumental contribution to this delay to be (5.2 ± 0.5) × 10^{-10} s. The largest contribution is relative delay in the two arms of our instrument caused by a small optical path-length difference, and detector/electronics delays. This was quantified by periodically driving a broadband LED at ~700 nm to simulate a pulsar’s periodic flashing in both of our channels; the total measured latency between the two detection channels was determined to be (4.8 ± 0.5) × 10^{-10} s. In addition, the difference of the index of refraction of air at our two observing wavelengths under our observing conditions is n(585 nm) - n(815 nm) = 2.2 × 10^{-6} (Stone & Zimmerman 2001) and corresponds to a relative time delay of ≈4.4 × 10^{-11} s through our line of sight (≈6 km) through the atmosphere. Hence, the precision of our time delay measurements are not limited by instrumental delays or uncertainty.

5. Constraining Violations of the Weak Equivalence Principle

To translate our observed time delays into a measure of WEP violation, we follow recent works (Longo 1988; Gao et al. 2015; Wei et al. 2015; Nusser 2016; Tingay & Kaplan 2016; Zhang & Gong 2017) in conservatively assuming that the observed delay Δt is larger in magnitude than any delay due to a WEP violation. We note that this crucial assumption admits the possibility that a large WEP violation delay is being hidden by an almost equal intrinsic pulse delay in the opposite direction. It is possible to decouple Lorentz-violating WEP delays from astrophysical ones with multiple observations of astrophysical transients coming from different directions (Yu et al. 2017), but to our knowledge is not possible to isolate the WEP violation from delays intrinsic to the Crab pulsar or caused by its surrounding nebula for our single observation.

Finally, to calculate Δγ, we employ a model of the gravitational potential U(r) experienced by the pulses as they travel across the Milky Way. We directly employ the model and parameters of Zhang & Gong (2017) who formulated it to derive similar limits for the Crab pulsar. The potential U(r) is modeled with two components, a Miyamoto–Nagai disc (Miyamoto & Nagai 1975) and a Navarro–Frenk–White (Navarro et al. 1996) dark matter halo, and it is integrated from the Crab pulsar to Earth. This results in a single conversion factor between time delay measurements and Δγ:

\[ \Delta \gamma = 1.167 \times 10^{-5} \text{s}^{-1} \Delta_{\text{wpv}}. \]

For our three analysis methods, we obtain 3σ upper limits of

\[ \Delta \gamma_{\text{vis,nir}} < 1.07 \times 10^{-10}, 1.30 \times 10^{-10}, 2.4 \times 10^{-10}. \]

We suspect the large discrepancy between Method 3 versus Methods 1 and 2 is due to the different observing conditions in the two data sets used.

6. Upper Limit on Photon Mass

In addition to constraining the WEP, it is possible to obtain a robust upper limit on the photon mass through our observation of a frequency-dependent time delay (Schaefer 1999). While global fitting techniques with multiple pulsars can be used to decouple the effects of a nonzero photon mass from plasma dispersion (which induces a similar functional dependence as a function of frequency; Wei & Wu 2018), our measurement of a single pulsar at optical frequencies is largely intrinsically free from that particular systematic effect at µs levels of precision.

The speed of a massive photon with mass \( m_\gamma \), is

\[ v/c = \sqrt{1 - \frac{m_\gamma^2 c^4}{E^2}} \]

where the photon energy \( E = h \nu \) introduces a wavelength dependence on the speed of light. The observed color-dependent time delay between the arrival times of two photons, to leading order in the observation frequencies \( \nu_1 \geq \nu_2 \), is

\[ \Delta t_{\text{obs}} = \frac{m_\gamma^2 c^3 d}{2 h^2} (\nu_1^2 - \nu_2^2). \]

Where \( d \) is the light travel distance. For the Crab pulsar, we adopt a distance of \( d = 2 \text{kpc} \) for consistency with previous upper limits in Schaefer (1999). It is important to note that this effect, unlike our delay direction-independent test of WEP violation, predicts that bluer photons arrive before redder ones. This corresponds to \( \Delta t_{\text{obs}} < 0 \), which is in statistical tension with two out of our three observations (Method 1 and 3), which suggests strongly that \( \Delta t_{\text{obs}} > 0 \), refuting altogether the possibility of a photon mass under the crucial assumption that another systematic effect is not canceling the time delay induced by a massive photon. However, we can still derive a quantitative upper limit on the photon mass with our Method 2 result that is consistent within statistical error with a timing measurement of \( \Delta t_{\text{obs}} \approx 0 \); we obtain an upper bound of

\[ m_\gamma < 3.7 \times 10^{-44} \text{g} \]

under the assumption that \( \Delta t_{\text{obs}} < 3 \times 3.6 \mu \text{s} \) (the uncertainty of our Method 2 result). While this is not a numerically superlative upper bound on the photon mass, we emphasize that our complementary method of observing at optical frequencies is subject to different systematics and provides a robust check against other limits. For example, recent photon mass constraints using pulsar timing at radio frequencies (Wei & Wu 2018) must carefully remove the systematic effects of plasma dispersion. Plasma dispersion not only exhibits the same functional dependence on observing frequency as a nonvanishing photon mass but also is estimated by assuming a vanishing photon mass in the first place. In contrast, for our relative timing measurements at optical frequencies to be affected by plasma dispersion at the level of microseconds, the dispersion measure would need to be six orders of magnitude higher than that which is currently measured (Lyne et al. 1993), a highly unlikely possibility.
Due to our choice of wavelength bands, this upper limit lies in a region of parameter space that makes it complementary to similar photonic tests of WEP violation (Gao et al. 2015; Wei et al. 2015; Tingay & Kaplan 2016; Zhang & Gong 2017). We summarize $3\sigma$ upper limits from a variety of recent astrophysical tests in Figure 3.

In this work, we have used a specialized instrument with nanosecond-timing resolution to measure the light curve of the Crab pulsar in two adjacent but disjoint wavelength bands. We first determined the period of the Crab pulsar to sub-nanosecond accuracy with less than an hour-long observation. We set a new upper limit on the differential value of the post-Newtonian parameter $\Delta \gamma$ at visible and $\gamma$ wavelengths to conduct similar WEP tests.

Our upper bound on the photonic WEP violation is the first of its kind at the relevant wavelengths. We emphasize that the precision of our measurement is currently limited not by any instrumental uncertainty but rather by the intrinsic ambiguity of assigning a definite value of a delay between two functions with the same period and different profile shapes. The absence of instrumental effects in our equipment at the ns level may pave the way to further applications in precise photonic timing measurements. Even though there are only seven known optical pulsars, they can potentially act in tandem with pulsar timing arrays. Unlike radio pulsars, optical pulsar timing measurements are essentially free of plasma dispersion delays. It may be possible to improve our current limits by leveraging the moon’s retroreflectors and using strong pulsed lasers at various wavelengths to conduct similar WEP tests.

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