Can gravitational waves be detected in quasar microlensing?

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ABSTRACT

Studies of the lensed quasar Q0957 + 561A, B have shown evidence for microlensing in the brightness history of the quasar images. It had been suggested that a frequency offset between the brightness fluctuations in each of the two images might possibly be caused by gravitational radiation generated by a massive black hole binary at the center of the lensing galaxy. This paper demonstrates that the fluctuations produced by such a source of gravitational waves will be too small to account for the observed frequency offsets.

Subject headings: cosmology: gravitational lensing — microlensing — gravitation — gravitational waves — quasars: individual (Q0957+561)

1. Introduction

The Q0957 + 561A, B system was the first recognized multiple image gravitational lens (Walsh, Carswell, and Weymann 1979) and the first to have a measured time delay (Schild and Cholfin 1986). Once the time delay between the two images was measured, the brightness histories of the two images could be compared and Q0957 was the first to show evidence for a microlensing event (Vanderriest et al. 1989; Schild & Smith 1991; Pelt et al. 1998). The long brightness records accumulated to measure the time delay and microlensing at optical (Schild and Thomson, 1997 and earlier references therein) and radio (Haarsma et al., 1997) wavelengths have been analyzed by Thomson and Schild (1997) to look for other artifacts in the time series data.

A number of such artifacts were found, including evidence for multipaths, coherency in the radio and optical, weak sinusoidal behavior on timescales of weeks, and a puzzling frequency offset between the coherent brightness fluctuation in the A and B images. Since the A and B images are of the same quasar, lack of frequency coherence of the two images shifted by the measured time delay suggests that some process related to the microlensing has probably altered the frequency.

The possibility that the frequency offset might be caused by binary microlensing objects was illustrated in Schild and Thomson (1993). A more intriguing possibility has also been suggested
(Schild and Thomson 1997): the frequency offset might constitute the detection of gravitational waves radiated by a binary black hole at the nucleus of the lens galaxy. The purpose of this paper is to explore this possibility more carefully.

The possibility that a massive binary black hole might reside at the center of the lens galaxy is reinforced by what is known about the monster. It is a very luminous elliptical galaxy near the center of a cluster, suggesting it is probably a starpile type galaxy, resulting from a long history of mergers of smaller galaxies. The lens galaxy is a known radio source (Greenfield et al. 1980) so it is presumed to contain at least one black hole at the center. If the galaxy is a starpile type, then it would have accumulated one or more massive black holes from galactic mergers. Dynamical friction with the constituent stars in the merged galaxy would cause the massive black holes to settle into the central density cusp over the course of time. If one were to look for binary black holes, this is the place one would start the search. The nearest analogue to the lens galaxy would be M87, near the center of a subgroup of the Virgo cluster. Evidence for massive black hole binaries has been found in other astrophysical systems; for example a binary black hole has been inferred to exist in quasar Q1928+738 (Roos, Kaastra, and Hummel 1993).

To picture the physical configuration for a gravitational wave explanation consider a terrestrial observer looking in the direction of a distant quasar. The observer sees two images because the gravitational field of a lens galaxy near the line of sight creates two light paths to the observer. As the quasar light passes through the lens galaxy, stars within the galaxy act as microlenses that can further magnify the luminous quasar structure. Any dark matter objects would also introduce microlensing. The theory for the formation of two quasar images indicates that the surface mass density is sufficiently high that microlensing events should always be underway. If a gravitational wave originating at the center of the lens galaxy passes through the field of microlenses, it should alter the pattern of null geodesics by which light passes through the lens galaxy, and impose the wave’s periodicity on the resulting signal, suggesting the gravitational wave’s frequency should be evident in the time series record of the quasar’s brightness.

This paper is organized as follows. Section 2 summarizes the evidence for the observed Q0957 frequency offset. In Section 3, the amount that microlensing signals would be affected by propagating gravitational waves is calculated, and we conclude that no observable signature would be found. Section 4 reconsiders the origin of the observed effect in Q0957 and speculates on prospects for observing gravitational waves in other microlensed quasar systems.

Geometric units where $G = c = 1$ are used throughout; conventional units are adopted (and specified) when numerical values are quoted.

2. Frequency Shifts in the Q0957 Coherence

Frequency shift effects in Q0957 were first discussed in Thomson and Schild (1997), who noted that (p. 188) “Analyzing the A and B light curves jointly, we find a frequency shift between them.
This shift is one-sided, so it is not the result of a simple modulation, and has about the same value as the periodicity seen in the microlensing.” A more comprehensive discussion and a plot of the unexpected behavior is given in Schild and Thomson (1997), who plot the dual-frequency cross coherence between the delayed A and the B light curves for a 3286-day time interval. Their surprising result is that although the two images originate in the same quasar, the brightness records have almost no cross-coherence over the frequency band 1.5 – 5.0 cy/yr. Instead, the coherency seems to be shifted up to higher frequencies, commonly 2 to 3 cy/yr higher than the expected frequency. Because the quasar’s random brightness fluctuations appear to be phase coherently shifted to higher frequency over a restricted frequency band, the effect might be thought of as a kind of blueshift that operates over only a limited frequency band. Several such blue shifting frequencies are found, and it is not yet clear whether a single such blueshift operates over only a limited time interval (a limited range of Julian dates). In this report we focus on the dominant frequency offset, 0.29 cycles/year. Because the affected frequency band was shown by Schild (1996) to be dominated by microlensing effects, it seems likely that the shift of frequency coherence results from the microlensing.

For modulation of the microlensing signal by gravitational waves to be observable, two conditions must be met. First, the amplitude of the gravitational wave at the microlensing field must be large enough to alter the microlensing amplitude, implying the amplitude must be a significant fraction of the Einstein radius of a microlensing particle. Second, the quasar source must also have sufficiently fine structure that the background to the wave-altered geodesics produces the periodically modulated brightness changes.

While the quasar accretion disc is usually taken to be quite large and structureless, a study of the Q0957 statistics by Schild (1996) showed that fluctuations were seen to be so rapid that they evidenced dark matter in the form of condensed objects (rogue planets) having approximately terrestrial mass and cosmologically significant numbers. They also evidenced compact quasar structure, which seemed surprising at the time but has since been confirmed in the observation of an apparent cusp crossing in quasar Q2237. These Q0957 and Q2237 observations place important constraints on the size of the emitting quasar source. For the brightness profile illustrated in Schild’s (1996) Fig. 5, a time scale of 60 days is evidenced, about the same as the peak of the power spectrum illustrated in his Fig. 4. Thus quasar structure on size scales less than the accretion disc diameter seems to be indicated by the microlensing data for two quasars.

Because the B quasar image passes 5 times closer to the lens galaxy nucleus than A, we presume that gravitational waves would be greatest in B, and compute the spacing of the microlensing masses to determine the amplitude of gravitational wave that would be needed. The normalized surface mass density for the B image was defined in Schmidt and Wambsganss (1998) and shown to be equal to 1.17. Schmidt and Wambsganss also show that for standard cosmology, the angular size diameter of a solar mass Einstein ring projected to the quasar source is $3 \times 10^{13}$ cm. The calculated

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1See the data at website http://www.astro.princeton.edu/~ogle/ogle2/huchra.html
1.17 surface mass density means that along any line of sight, on average an observer sees one microlensing mass magnifying the background quasar source, so on average the Einstein rings are adjacent to one another (they touch each other with 17% overlap, loosely speaking). Because the distance to the lens is nearly half the distance to the quasar in a correct calculation of the angular diameter distances, the separation of the microlenses projected onto the plane of the sky at the distance of the lens galaxy is about half the Einstein ring diameter, or about $10^{13}$ cm.

From these numbers we wish to estimate an amplitude scale for which the gravitational waves emanating from the putative black hole at the center of the lens galaxy would periodically influence the microlensing. We presume that the gravitational waves passing the network of microlenses alter the null geodesics of the quasar beams periodically, and cause the observed periodic changes in the microlensing magnification. The microlensing magnification is usually illustrated as the pattern of high magnification cusps that the masses impose upon the light beam from the distant source. Such cusp patterns have been illustrated, for example, by Wambsganss (1992) and Seitz, Wambsganss, and Schneider (1994), who show that for optical depths near 0.1 the cusps have a characteristic size scale about the same as the Einstein ring diameter, but for higher optical depths, such as 1.17 appropriate for Q0957, the cusp scale is about a factor of ten smaller, especially when the random motions of the field microlenses are taken into account (Wambsganss & Kundic, 1995). Thus we take the characteristic size scale for the brightness amplification cusps to be $10^{12}$ cm. We are aware that this is also approximately the size of the putative black hole at the center of the quasar.

Because the brightness fluctuations observed are small, only 3% or so, it may not be justified to assume that the gravitational wave induced alteration of the quasar light’s path is the full amplitude of the cusp pattern; even an alteration of the propagation path by 10% of the characteristic cusp spacing should produce an effect of the small amplitude observed. If the predicted amplitude of the propagation path alteration were $10^{11}$ cm, we would feel obliged to model this and sharpen this estimate, but we shall see that the predicted effect falls short of this amplitude by several orders of magnitude. In this sense, we take the fiducial amplitude for any gravitational wave alteration of the pattern of null geodesics through the pattern of microlensing masses to be $10^{11}$ cm.

3. The expected gravitational wave amplitude

To explicitly compute the effect of a gravitational wave on photons propagating through a symmetric Schwarzschild gravitational lens, consider the geometry shown in Figure 1. An Earth-bound observer and a distant source of photons are situated about a thin gravitational lens, with the source lying at a misalignment angle $\beta$ from the line of sight to the lens. The Einstein radius is given by

$$\eta = \sqrt{\frac{2M}{L}},$$

where $M$ is the lens mass and $L$ is the separation between the lens and observer (or lens and source).
If one wants to consider the effect of the wave on photons propagating through the lens and toward a distant observer, one approach is to consider the superposition of a linearized Schwarzschild metric (describing the lens) and a linearized metric describing gravitational plane-waves. Consider the case of a gravitational wave with amplitude $h$, frequency $\omega$ and + polarization propagating through a Schwarzschild lens down the $+x-$axis. The spacetime metric may be written as

$$ds^2 = \left(1 - \frac{2M}{r}\right)dt^2 - \left(1 + \frac{2M}{r}\right) (dx^2 + dy^2 + dz^2) + h \cos \omega(t - x) \left(dy^2 - dz^2\right),$$

(2)

where $r$ is the radial coordinate from the lens. Note that in the limit $h \to 0$, this becomes the Schwarzschild metric in isotropic coordinates.

A standard (but computationally intensive) approach to studying photon trajectories in the spacetime described by the metric of Eq. (2) is to write out and solve the null geodesic equations. Such a study would allow one to ascertain what, if any, observable effect the gravitational wave might have on an observed microlensing signal.

A simpler approach may be used in the thin lens approximation, where the photon trajectories may be approximated as straight lines deflected when they pass through the lens plane. In this case, an application of Fermat’s principle can be used to extremize the time of flight through the lens in lieu of solving the geodesic equations. The condition that the time of flight be an extremum will provide the necessary geometrical information to consider how the microlensing signal is affected by the gravitational wave.

Fermat’s principle in non-stationary spacetimes has been discussed in the specific context of gravitational lensing (Kovner 1990; Nityananda and Samuel 1992), and has been used to examine the effect of cosmological gravitational waves on the time delay between lensed quasar images (Frieman, Harari and Surpi 1994, hereafter FHS). The conclusion of FHS was that for long wavelength gravitational waves, any time delay between the images due to the gravitational wave would be interpreted by observers as part of the misalignment angle $\beta$. We will follow the example of FHS, using Fermat’s principle to compute the apparent misalignment angle $\beta(h)$ as a function of the gravitational wave amplitude.

FHS showed that for the lens/gravitational wave system described by the metric in Eq. (2) the time of flight may be written

$$\tau \simeq \int_{-L}^{+L} dz \left[1 + \frac{1}{2} \left(\frac{dx}{dz}\right)^2 + \frac{1}{2} h \cos \omega(t - x) + \frac{2M}{r}\right],$$

(3)

where $(dx/dz)$ characterizes the photon paths in Fig. 1.

Extremizing the time of flight in Eq. (3) leads to an expression for the deflection angle $\alpha$ in the lens plane:

$$\alpha = 2 \left(\theta - \beta_g\right),$$

(4)
where $\theta$ is the apparent location of the image, and $\beta_g$ is the apparent misalignment angle in the presence of the gravitational waves, which was found by FHS to be

$$\beta_g = -\frac{h}{\omega L} \sin^2 \left(\frac{\omega L}{2}\right) \sin \omega (t_e + L). \quad (5)$$

This expression for $\beta_g$ is valid so long as $\eta L \ll 1/\omega$ (i.e., as long as the wavelength of the gravitational wave is much larger than the typical size of the Einstein radius of the microlens).

In general, increasing the misalignment angle reduces the lensing effect. In microlensing, the lens mass is small enough that individual images are unresolvable, and increasing the misalignment angle reduces the microlens amplification. In the presence of gravitational waves, the apparent misalignment angle is given by Eq. (5). The condition that $\eta L \ll 1/\omega$ amounts to requiring that the gravitational wave vary on a timescale much less than the time of flight for photons through the vicinity of the lens. This suggests that over a long period of time, the microlensing amplification may change due to the fact that $\beta_g$ is a slowly varying function of time.

Any change in $\beta_g$ over the course of time amounts to a change in the impact parameter of a given photon trajectory which passes through the lens. The misalignment angle subtends an arclength

$$s = L \beta_g = -\frac{h}{\omega} \sin^2 \left(\frac{\omega L}{2}\right) \sin \omega (t_e + L) \quad (6)$$

for a lens which lies a distance $L$ from the observer. Eq. (6) can be separated into a scaling amplitude (given by $h/\omega$) multiplied by a periodic function which varies between $-1$ and $+1$. The quantity of interest is the maximum value of $s$, which we take to be

$$s_{\text{max}} \sim \frac{h}{\omega}. \quad (7)$$

$s_{\text{max}}$ represents the maximum deflection of a null geodesic (passing through a thin gravitational lens) by a gravitational wave of amplitude $h$ and frequency $\omega$.

The gravitational wave amplitude can be estimated by assuming the case of an equal mass circularized binary source. At a distance $r$ from a system with total mass $2m$, and gravitational wave frequency $\omega$, the amplitude is well approximated by

$$h \sim \frac{(2m)^{5/3} \omega^{2/3}}{r}. \quad (8)$$

Combining this with Eq. (7) yields

$$s_{\text{max}} \sim \frac{(2m)^{5/3}}{r \omega^{1/3}}. \quad (9)$$

Eq. (9) may be evaluated for the case of Q0957. Assuming the anomalous frequency shift in the brightness history is caused by gravitational waves, the 3.4 yr period implies a gravitational
wave frequency\(^2\) of \(\omega \sim 8 \times 10^{-8}\) Hz. The separation between the microlens and the source of gravitational waves is taken to be the linear distance between the quasar image which is being microlensed and the center of the primary lensing galaxy. For the Q0957 system, the distance between the B image and the nucleus of the lens galaxy has been measured to be 1.045 arcsec (or \(r \sim 5\) kpc for a lensing galaxy at a redshift of \(z \sim 0.37\), assuming a flat cosmology with a Hubble parameter of 75 km s\(^{-1}\) Mpc\(^{-1}\)) (Bonometti, 1985). If the typical mass of a central galactic black hole is \(m \sim 10^8 M_\odot\), then the maximum deflection is

\[ s_{\text{max}} \sim 10^6 \text{cm} . \]  

(10)

4. Discussion

This calculation of the maximum deflection of the pattern of null geodesics due to a gravitational wave from a putative binary black hole at the center of the lens galaxy shows that no observable effects would be expected. The gravitational wave deflects the propagation paths by \(10^6\) cm, whereas a deflection of order \(10^{11}\) cm (the smallest size scale expected to be found in quasar source structure) would be required to explain the frequency offset between the A and B images.

Might the effects be observable in a different lens system having different parameters? Our Eq. (9) shows that the deflection amplitude is a weak function of the gravitational wave source frequency \(\omega\), which is presumed known for the Q0957 system; other lens systems with a factor 100 higher binary black hole frequency are certainly possible (they would have a lifetime shorter than a Hubble time). The Q0957 system has the widest image separation of all known lens systems, so most other lenses would have a smaller value of \(r\), the impact parameter of the quasar beam passing the binary black hole; thus an effect might be slightly favored in other gravitational lens systems (Eq. (9)). An effect would be strongly favored by a more massive black hole binary, but we have already used large values for the orbiting masses. We conclude that the detection of gravitational waves with quasar microlensing seems not to be possible for any known system.

We are left to speculate about the nature of the periodicity observed in the microlensing (Schild and Thomson 1997). A microlensing explanation seems essential because the observed effect is asymmetrical; the frequency offset seems to affect the B image most strongly, and the B image has the hugest optical depth to microlensing. With the gravitational wave explanation excluded it seems most likely that the source of the periodic activity is orbital effects in the microlensing objects themselves. This would literally mean that the planetary mass objects found by Schild (1996) to dominate the mass of the lens galaxy are in some (or most) cases binaries. Heretofore we have disfavored this explanation because a simple calculation of the transverse velocities predicts that the microlens’ orbital velocity would be much less than such cosmological velocity components

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\(^2\)This value for \(\omega\) is the frequency of the emitted gravitational radiation (given by the observed 3.4 yr period), corrected for the redshift of the source galaxy, \(z = 0.37\).
as the motion of the sun around the center of the galaxy (220 km/sec), or the motion of the source quasar or lens galaxy relative to its local Great Attractor (600 km/sec). Nevertheless it would be possible for some orbital effects to be introduced into the microlensing, and more intricate microlensing simulations might be necessary to explore an orbital explanation.

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Fig. 1.— The geometry of image formation for the QSO’s B image, past a hypothetical microlens situated 10 kpc from the center of the G1 lens galaxy. The microlensing produces a doubling of the quasar’s B image with an image separation of $10^{-6}$ arcsec, so the images are not resolved; however the passage of a gravitational wave causes periodic fluctuations in the deflection angle $\beta_g$ which might cause variations in the lens magnification and thus impose a periodic frequency offset in the observed pattern of quasar brightness fluctuations.
