Limits on the Gravity Wave Background From Microlensed Quasars

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Abstract

The double quasar 0957+561 is a very long baseline, highly stable system with an "instrumental resolution" of order μas thanks to its microlensing caustics. The system is therefore an excellent "device" for detecting the gravitational wave background. I show that observations to date can be used to place limits on this background of $\Omega_\omega \lesssim 10^{-12}(\omega\,\mathrm{yr})$ for $\omega^{-1} \lesssim 10\,\mathrm{yr}$ and $\Omega_\omega \lesssim 10^{-14}(\omega\,\mathrm{yr})^{-1}$ for $\omega^{-1} \gtrsim 10\,\mathrm{yr}$. Here ω is the frequency of the radiation and Ω_ω is its density in units of the closure density. These limits are $\sim 10^5$ lower than those obtained from pulsar timing. A scale-free spectrum of gravitational waves is therefore ~ 1000 times weaker than the microwave background fluctuations. It is possible that gravitational waves are being detected at one or two orders of magnitude below the current limit. I discuss future observations which could help resolve this issue.

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1. Introduction

Gravitational waves propagate almost freely through media which are opaque to photons and even to neutrinos. This makes gravitational radiation a unique probe of matter in the most extreme conditions such as those that prevail during the collision or collapse of compact objects or in the early universe. However, the same property that allows gravitational waves to emerge freely from these hostile environments also makes them difficult to detect. While the existence of gravitational waves has been clearly demonstrated from pulsar timing (Taylor et al. 1992), the prospect of using them as a direct astrophysical probe appears to be at least several years (and substantial technological improvements) away. The problem is that the very small scale of the effect demands an extremely stable system preferably extended over a long baseline, and with a very sensitive detector. Interferometers have been seen as the instrument of choice.

Thus, I was more than a bit startled when Rudy Schild (private communication 1995) told me a few days ago that he thought he might have detected gravitational waves with a 1.2 m telescope. Schild has been engaged in long term monitoring of 0957+561, the double quasar. The original object of this campaign was to determine the time delay between the two images A and B. Image B sits directly behind the lensing galaxy and image A is offset by $6''$. One hopes that by measuring the time delay, one can determine the Hubble constant H_0.

Even by the standards of Hubble constant determinations, the level of controversy surrounding the 0957+561 time delay has been high. The controversial aspects of this work have, of course, engendered the most discussion. As I will show, however, it is actually the non-controversial aspects that yield the most spectacular result: strong limits on the cosmological background of gravitational radiation at all wavelengths.

The basic facts are these. Both images A and B have been observed to vary over the 15 years that they have been monitored. This is not in itself surprising since many if not all quasars vary. However, the images have varied differently.

Image B has shown a long term rise and then fall of several tenths of a mag, while image A has shown only a long term (and more gradual) rise. Although there is controversy about the length of the time delay, all sides agree that it is ~ 1.1–1.5 yr. Hence the difference in the behavior of the two light curves over ~ 10 yr cannot be from looking at the same quasar during different epochs. The most likely explanation is microlensing of the B image. For typical stellar masses of a few tenths of a solar mass and for typical expected transverse speeds $\sim 600\,\mathrm{km\,s^{-1}}$, a $\sim 10\,\mathrm{yr}$ event is to be expected. Moreover, since the B line of sight passes right through a galaxy, microlensing by the galaxy's stars should occur every ten years or so. Thus, in all respects the microlensing hypothesis is extremely plausible.

Radio observations have not confirmed the B microlensing event, but this is also to be expected. The quasar radio emission region is thought to be much larger than the optical region, so that it cannot all be lensed at once by the typical stellar masses of the galaxy. This insensitivity to microlensing is thought by radio observers to be a substantial advantage in determining the time delay. Another advantage is the possibility of all-year monitoring. On the other hand, quasars show greater intrinsic variability on short time scales in the optical and this should allow a more precise measurement of the time delay provided that the microlensing effects can somehow be removed.

I will not review here the numerous conflicting measurements of the time delay using both optical and radio data. The important point from the present perspective is that this controversy has led to an increase in the amount of monitoring. In particular Schild & Thomson (1995) have observed 0957+561 every clear night over the last three ($\sim 9\,$month) seasons. They find (R. Schild private communication, 1995) that no matter what time delay is adopted the A/B light curve has power at the level of several hundredths of a mag on several time scales from days to years. Schild (1992; private communications 1993, 1995) regards this power as evidence for microlensing on very short time scales, a view which is not widely shared because these short time scales would correspond to masses $\sim 10^{-3}$–$10^{-7}M_\odot$. In response to criticism along these lines, Schild (1995 private communication) has raised the possibility that gravitational radiation from discrete events causes shimmering of the images over the caustic structure of the lens. This in turn would generate fluctuations in the light curve.

While these claims and suggestions have seemed to me to be fairly outrageous, the data on which they are based appear sound. I was therefore led to investigate whether gravitational radiation could be detected by quasar monitoring. In brief, I find that while discrete events could in principle be detected, the greatest sensitivity is to an ambient cosmological background. In fact, the experiment is a factor $\sim 10^5$ more sensitive to the gravitational wave background than any previous test. To actually confirm that gravitational radiation is being detected would require substantial additional observations. I believe that such observations would be very important and I discuss them further in § 4. However, because the experiment is so sensitive, one can already obtain very strong upper limits at all wavelengths on the cosmological background. These limits are derived in the following section and are the principal result of this *Letter*.

Quasar monitoring is a good detector of gravitational waves for the same reasons that interferometers are: long baseline ($\sim$ horizon scale), stable system (quasar–galaxy–Earth), and sensitivity to minute changes (microlensing caustics with μas resolution).

2. Limits

Consider gravitational radiation with characteristic frequency ω and amplitude h_ω in both components. The energy density is $h_\omega^2\omega^2/16\pi$ (G=c=1) (Misner, Thorne, & Wheeler 1973), which may be expressed as a fraction of the critical density $\Omega_\omega = h_\omega^2\omega^2/6H_0^2$. Consider now a light ray passing through a region of size ω^{-1} containing such radiation. It will suffer a deflection $\delta\theta \sim h_\omega$. Over a distance D, the ray will encounter $D\omega$ such regions incoherently, so that the total deflection is $\delta\theta_\omega \sim h_\omega\sqrt{D\omega}$.

Since the B/A light curve of 0957+561 is not changing by order unity on time scales $\lesssim 10$ yr, one can infer that $\delta\theta_\omega \lesssim l_*/D$ where D is the characteristic distance of the observer-lens-quasar system and l_* is the typical projected distance between stars in the galaxy superposed on the B image. Because the images are macrolensed, the surface density Σ of these stars must be near critical, $\Sigma \sim D^{-1}$. Assuming that they have characteristic masses like the local population $M \sim 0.3\,M_\odot$, then $l_* \sim 0.03\,\mathrm{pc}$. Combining these results yields a limit $\Omega_\omega \lesssim l_*^2\omega/6H_0^2D^3$ or

$$\Omega_\omega \lesssim 10^{-12}\omega\,\mathrm{yr} \qquad (\omega^{-1} \lesssim 10\,\mathrm{yr}), \tag{2.1}$$

where I have adopted $l_*/D \sim 10^{-11}$, $H_0 D \sim 0.5$, $H_0^{-1} \sim 13\,\mathrm{Gyr}$, and where I have dropped factors of order unity.

The argument leading to equation (2.1) breaks down if ω^{-1} is smaller than the crossing time (a few days) of the optical emission area, but the equation itself remains valid. In this case, different parts of the source would be deflected incoherently so that the effective size of the image would be larger than the typical distance between the microlensing stars. The larger effective source size would prevent optical microlensing from taking place (as is the case for the bigger radio source). Since microlensing of the B image is actually observed, these short time scale fluctuations are ruled out.

Finally consider gravitational waves with time scales longer than the span of observations, $\omega^{-1} \gtrsim 10\,\mathrm{yr}$. One would not in this case have had the opportunity to see the effects of the image jumping around the microlensing caustic surface. Instead, the image would move across the caustic network at a steady angular rate $d\theta/dt \sim h_\omega\omega\sqrt{D\omega}$, implying that microlensing events would occur at a rate $\sim (D/l_*)h_\omega\omega\sqrt{D\omega}$. Since in fact events are not being observed at a rapid rate, but only at $\sim (10\,\mathrm{yr})^{-1}$, this implies a limit

$$\Omega_\omega \lesssim 10^{-14}(\omega\,\mathrm{yr})^{-1} \qquad (\omega^{-1} \gtrsim 10\,\mathrm{yr}). \tag{2.2}$$

3. Implications

The limits obtained in the previous section constrain Ω in gravitational waves to be smaller than that of the microwave background over the range $H_0 \lesssim \omega \lesssim 1\,\mathrm{Hz}$. The limits are strongest near $\omega^{-1} \sim 10\,\mathrm{yr}$ where they are a factor 10^5 more severe than the best previous limits which were obtained from pulsar timing (Stinebring et al. 1990). The earlier limits constrained some cosmological models, particularly those containing cosmic strings. The new limits (2.1) and (2.2) have substantially wider implications. For example, for models with equal power per logarithmic interval, the limit on the overall normalization is set by the regime where the experiment is most sensitive, $\omega^{-1} \sim 10\,\mathrm{yr}$ where $\Omega_\omega \lesssim 10^{-13}$, about 9 orders of magnitude smaller than the microwave background (CMB) and 3 orders smaller than the CMB fluctuations. Gravitational radiation therefore plays no role in the CMB in such models.

4. Future Detections

While upper limits are important, the detection of the gravitational wave background would be far more exciting. The A/B light curve has power of order a few per cent on time scales of days to years. This is what would be expected from gravitational waves with 1–10% of the limit on Ω_ω set by equation (2.1). However, one can easily imagine several alternative sources for this power including time-dependent extinction in the lens or in the Galaxy, microlensing by very small masses, or subtle systematic effects in the observations. Moreover, there may be other sources of power that are more difficult to imagine. What is required to make a definitive detection, or at least to limit the alternative interpretations?

The first and most important step is to remove uncertainties about possible instrumental problems by observing the system simultaneously from two observatories at substantially different locations (with different air masses and weather conditions).

A second major step would be to measure the time delay with reasonable precision, to a day or perhaps less. It goes without saying that the power spectrum of the residuals cannot be measured on shorter time scales than the error in the time delay. By measuring this spectrum as a function of photon wavelength one could look for a key signature of a gravitational wave background: a break in the spectrum on scales of the light crossing time of the source. Since the quasar X-rays are generally believed to originate from a much smaller volume than the optical light, this break should occur at a substantially shorter time scale for X-rays.

The reason for the break can be understood from the arguments of § 2. For gravitational waves that are long compared to the source size, the image will "dance" over the caustic structure giving rise to variable magnification. But for waves that are smaller than the source size, the image will simply be smeared out with no changes in magnification.

Refining the time delay measurements is primarily a matter of acquiring more and better data and of making duplicate measurements from different observatories to remove artifacts. A key test is to achieve agreement between the radio and optical measurements. Better time sampling will also remove a major theoretical uncertainty in modeling the observations which arises from the necessity to interpolate between data points when comparing two time-shifted light curves. This problem was highlighted by Press, Rybicki, & Hewitt (1992a,b) who were the first to give a clear theoretical model for the random processes over which the interpolation is carried out. Nevertheless, in as much as these random processes are not known *a priori* and are difficult to extract from the data, it would be far better simply to decrease the sampling time to scales that are much shorter than the observed variability and so avoid interpolation altogether. Finally, I should note that one's ability to measure the time delay depends not only on there being variability in the quasars on sufficiently short scales, but also on one's ability to recognize this variability against other noise (whether from gravitational waves, microlensing, or other sources). Whatever this fundamental limit is, it cannot be achieved without a major campaign to obtain the best possible data.

As mentioned above, the controversy surrounding the time delay has led to a significant improvement in the sampling rate and also the quality of the data. Schild has been obtaining new optical data every clear night, some of which is published (Schild & Thomson 1995), and Hewitt and her collaborators have improved their program of radio observations with measurements at an additional frequency (to track down anomalous data points that may be due to scintillation) and by doubling the sampling rate to fortnightly during some key periods.

It should be noted, however, that the dominant opinion in the general community is that 0957+561 is unlikely to yield any useful information about H_0 regardless of how well the time delay is determined. In the long run, this opinion cannot but dampen the enthusiasm of the observers for carrying out these campaigns. The unique value of determining the time delay is in its role in probing for gravitational radiation and not in measuring H_0 which can in any event be measured by many other methods. Thus, the observational campaigns should be intensified, not slackened.

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