Constraining the Properties of the Proposed Super-Massive Black Hole System in 3C66B: Limits from Pulsar Timing

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Abstract. Recent VLBI observations suggest the presence of a supermassive black hole binary system in the core of the radio galaxy 3C 66B. The proposed system would emit high amplitude, low-frequency gravitational wave radiation. This radiation would induce detectable periodic fluctuations in the arrival times of individual pulses from a radio pulsar. The signature of this radiation was searched for in seven years of timing data from the pulsar PSR B1855+09. No evidence for gravitational waves was detected in this data set and limits were placed on the mass and eccentricity of the proposed system.

1. Introduction

This work summarizes the search for gravitational wave (G-wave) emission from the recently proposed Supermassive Binary Black Hole (SBBH) system in 3C66B (Sudou et al. 2003, hereafter S03) using 7 years of timing data from the radio pulsar PSR B1855+09. A more detailed account of this analysis which includes expressions for the expected timing residuals induced by G-wave emission from a slowly evolving, eccentric, binary black hole system may be found in Jenet et al. (2004).

The S03 observations suggest the existence of a nearby (z = 0.02) SBBH system. Such a system is remarkable in that the emitted G-waves could be detected in pulsar timing data. The proposed binary system has a current period of 1.05 years, a total mass, M_t, of $5.4 \times 10^{10} M_\odot$, a mass ratio, q, of 0.1, and a lifetime of about 5 years. Such a system has a "Chirp Mass," M_c, equal to $1.4 M_\odot$, where the chirp mass is given by $M_c = M_t q^{3/5}/(1+q)^{6/5}$. Since G-wave emission is not detected, limits are placed on the possible mass and eccentricity of the system.

The analysis of these data demonstrate two interesting properties of a gravitational wave detector made up of radio pulsars. First, the amplitude of the observed signature increases with decreasing gravitational wave frequency. Second, the light travel time
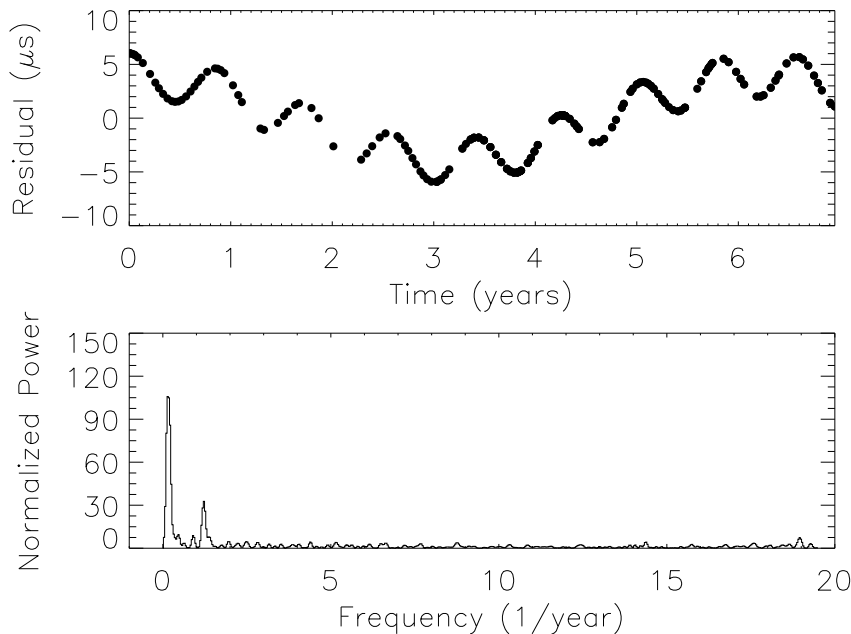
Figure 1.   Top panel: Theoretical timing residuals induced by G-waves from 3C66B. The timing points are chosen to coincide with the actual timing residuals of B1855+09. Bottom panel: The corresponding normalized Lomb periodogram.

delay between the Earth and the pulsar can, depending on the geometry, allow one to observe the gravitational wave source at two distinct epochs of time simultaneously. For example, if the pulsar is 4000 light-years away and the Earth-pulsar line-of-sight is perpendicular to the G-wave propagation vector, then the observed timing residuals will contain information about the source both at the current epoch and 4000 years ago. If the G-wave emitter is a binary system, slowly inspiraling due to G-wave emission, then the observed residuals will contain both low and high frequency components. The difference in the frequencies of these components will depend on how quickly the system is evolving. Since pulsar timing is more sensitive to lower frequencies, the highest amplitude oscillations in the timing residuals will be due to the delayed (i.e., 4000 year old) component. This effect, referred to as the "two-frequency response," is analogous to the three-pulse response occurring in spacecraft Doppler tracking experiments (Estabrook, & Wahlquist 1975) and the multi-pulse response from time-delay interferometry used in the proposed Laser Interferometer Space Antenna (LISA) mission (Armstrong, Estabrook, & Tinto 1999).

2.   The Signature of Gravitational Waves from 3C66B

The orbital motion of a SBBH system will generate gravitational radiation. The emitted G-waves are described by two functions of spacetime, h_+ and $h_\times$ which correspond to the gravitational wave strain of the two polarization modes of the radiation field. As these waves pass between the Earth and a pulsar, the observed timing residuals, $R(t)$,
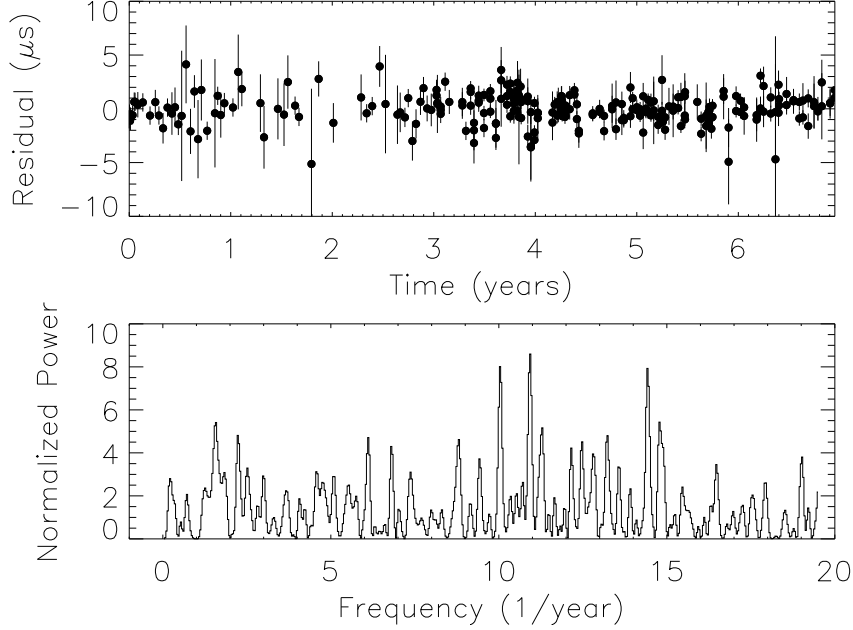
Figure 2.   Top Panel: Timing residuals for B1855+09. Bottom Panel: The corresponding normalized Lomb periodogram.

will vary as (Estabrook, & Wahlquist 1975; Detweiler 1979):

$$R(t) = \frac{1}{2}(1 + \cos(\mu))(r_+(t)\cos(2\psi) + r_\times(t)\sin(2\psi)), \tag{1}$$

where t is time, μ is the opening angle between the G-wave source and the pulsar relative to Earth, ψ is the G-wave polarization angle, and the "+" and "×" refer to the two G-wave polarization states. The functions r_+ and $r_\times$, referred to collectively as $r_{+,\times}$, are related to the gravitational wave strain by

$$r_{+,\times}(t) = r^e_{+,\times}(t) - r^p_{+,\times}(t) \tag{2}$$

$$r^e_{+,\times}(t) = \int_0^t h^e_{+,\times}(\tau)d\tau \tag{3}$$

$$r^p_{+,\times}(t) = \int_0^t h^p_{+,\times}(\tau - \frac{d}{c}(1 - \cos(\mu)))d\tau, \tag{4}$$

where $h^e_{+,\times}(t)$ is the gravitational wave strain at Earth, $h^p_{+,\times}(t)$ is the gravitational wave strain at the pulsar, τ is the time integration variable, d is the distance between Earth and the pulsar, and c is the speed of light. Note that the pulsar term, $h^p_{+,\times}$, is evaluated at the current time minus a geometric delay which encodes the time it takes the G-waves to propagate from the source to the pulsar plus the time it takes the pulses from that instant to propagate from the pulsar to Earth. For the case of a binary black hole system, expressions for $r_{+,\times}(t)$ in terms of the orbital parameters are given in Jenet et al. (2004). Figure 1 shows a possible set of timing residuals for the system proposed by S03. Note the large amplitude (5 μs) and the presence of two distinct

frequencies. Figure 2 shows the actual timing residuals for PSR B1855+09. These data were taken from Kaspi, Taylor, & Ryba (1994). These data do not show the expected signature of G-wave radiation from the system proposed in S03. Since the amplitude of the emitted G-waves depends on the precise geometry of the binary system which is unknown, a Monte Carlo simulation was used to determine the probability of not detecting a system with a given chirp mass, M_c, and eccentricity, e. Its was determined that a system with $M_c = 1.4 \times 10^{10} \, M_\odot$ and $e < 0.03$ could be ruled out at the 98% level. Any system with $M_c < 0.7 \times 10^{10} \, M_\odot$ could not be ruled out regardless of the eccentricity. For a detailed discussion of the constraints these observations place on the chirp mass and eccentricity of the proposed binary system in 3C66B, see Jenet et al. (2004).

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