Testing the Binary Hypothesis Pulsar Timing Constraints on SMBHB Candidates

Rich Ormiston

April 20, 2017

University of Minnesota Twin Cities

Background

Pulsar Timing Arrays

- Pulsars are very stable clocks (B1937+21 is accurate to 10^{-18} s)
- Generally consider millisecond pulsars
- Gravitational waves will alter the timing of the pulses on the nanosecond scale
- Use several pulsars (arrays) to detect the GW background when it passes along the line of sight

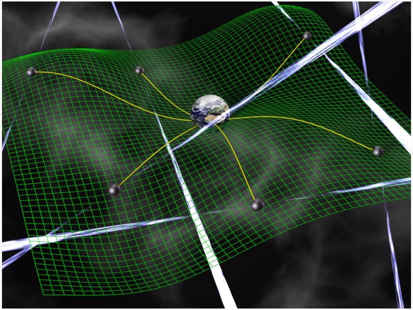


Figure 1: GW background affecting pulsar timing

Pulsar Timing Arrays

Some people (McWilliams *et. al* [1] and R.N Manchester [2]) believed that PTAs would allow for a detection of GWs before LIGO. They predicted a strain of $h_0 \approx 2 \times 10^{-15}$. Although LIGO made the discovery first, they still have great reason to be optimistic and can contribute to GW backgrounds with excellent sensitivity.

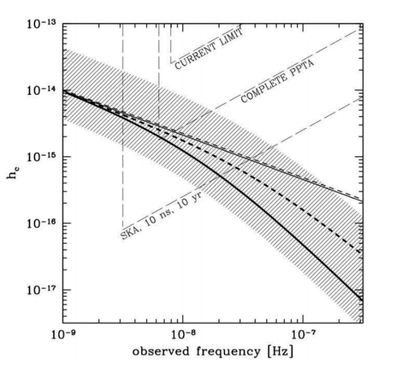


Figure 2: Predicted sensitivities [2]

Testing the SMBHB Hypothesis

- Sesana *et. al* sought to compute the expected SMBHB merger rate and extract from this the expected GWB.
- To do this they examined 250k quasars from CRTS (111 candidates) and 33k from PTF (33 candidates)
- Found that the GWB should *exceed* the current PTA upper limits by a factor of at least 2–15!
- Either need $\approx$ 90% false positives or assume that the black hole mass is overestimated by $\gtrsim 4$

Setup

Assumptions

1. AGNs with periodic variability are viable candidates for SMBHB
2. The reason that the candidates all *individually* fit with the PTA upper limits is because the residuals are too small and the GW are above 10^{-8} Hz and the PTA detection is most sensitive at $\approx 10^{-8.3}$ Hz.
3. When the datasets are extrapolated to lower frequencies, they are inconsistent with the PTA limits
4. Standard ΛCDM constants: $h = 0.679$, $\Omega_M = 0.306$, $\Omega_\Lambda = 0.694$

Preliminary Observations

1. The majority of the GW signal comes from sources with $z < 1.3$ so this gives a redshift cutoff
2. The GW sources have a mass larger than $\approx 3 \times 10^8 M_\odot$
3. Of the 111 sources in the CRTS catalogue, only those with a reported mass (98 total) will be considered.

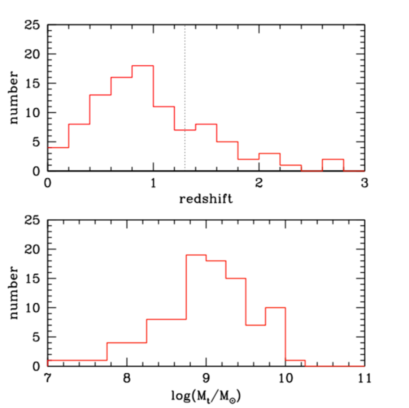


Figure 3: Redshift and mass distributions of SMBHB candidates

Parameters

We care quite a lot about the mass ratio of the BBH system. Define $q = M_2/M_1$ (which maximizes around 0.1). The merging system will change its frequency and we can write this rate as [3]

$$\frac{df}{dt} = \frac{5}{96\pi^{8/3}} \left(\frac{G\mathcal{M}}{c^3}\right)^{-5/3} f^{-11/3} \tag{1}$$

where $\mathcal{M}$ is the chirp mass which is defined as

$$\mathcal{M} = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}} = M_1 \frac{q^{3/5}}{(1+q)^{1/5}} \tag{2}$$

Mass Models

- **Model 1**: q peaked at $\log(q) = 0$ and consider only $\log(q) < 0$ (biased high)
- **Model 2**: q taken from blue curve with minimum cutoff at $q = 0.05$ (accretion induced periodicity)
- **Model 3**: q taken from red curve without cutoff (Doppler boosting)

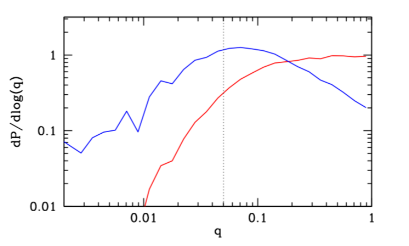


Figure 4: Probability distribution of the mass ratio of merging SMBHB. Red line assumes previous redshift and mass limits. Blue line is a selected frequency range

Populating the Sky

The CRTS data is only sensitive to binaries with observed periods shorter than ~ 300 weeks which corresponds to a rest frame GW frequency $\tilde{f}_r \approx (1+z)P_{orb}^{-1}$. Assuming a circular orbit, then the coalescence time-scale is

$$T_c(\tilde{f}_f) \propto \left(\frac{G\mathcal{M}}{c^3}\right)^{-5/3} \tilde{f}_r^{-8/3} \tag{3}$$

Therefore, for N binaries (with $f_r > \tilde{f}_r$) the merger rate can be written as

$$\dot{N} = \frac{dN}{dt_r} = \frac{N(f_r > \tilde{f}_r)}{T_c(\tilde{f}_r)} \tag{4}$$

Populating the Sky

The argument was now generalized to include different chirp masses and redshifts. In the continuous form, they calculate

$$\frac{dt_r}{df}\frac{\partial^2}{\partial\mathcal{M}\partial z}\left(\frac{dN}{dt_r}\right) \tag{5}$$

Integrating this over the redshift (from $0 < z < 1.3$) gives the plot on the right. The merger rate *is* consistent with the CRTS data but the mass distributions, at least at 95% confidence are not.

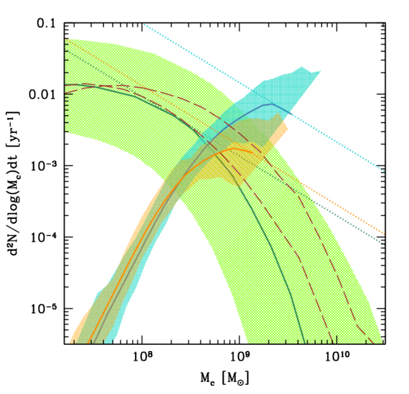


Figure 5: Merger rate as a function of chirp mass. Green is theory. Blue and orange are Models 1b and 3a respectively

Is it Reliable?

The comparison of the mock population of SMBHB candidates and the 98 CRTS candidates shows good agreement between the models suggesting that the estimates of the merger rates are likely reliable

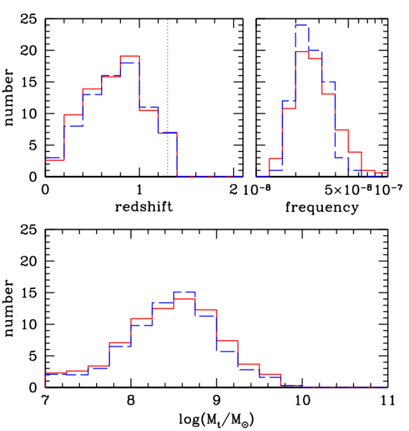


Figure 6: Red lines are the actual CRTS data. Blue lines are from Model 1b

GW Signals

Calculating the strain

Using the merger rate (which *is* consistent with the data), the GW signal is found by the following (assuming $n = N/V$)

$$h_c^2(f) = \frac{4}{\pi f^2} \int_0^\infty dz \int_0^\infty d\mathcal{M} \frac{\partial^2 n}{\partial \mathcal{M} \partial z} \frac{1}{1+z} \frac{dE_{GW}(\mathcal{M})}{d\log(f_r)} \tag{6}$$

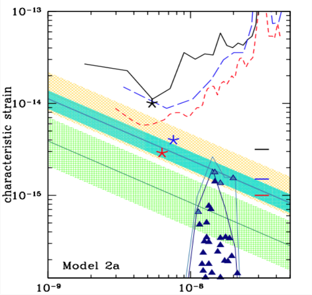
where the radiated energy E_{GW} per unit frequency is given by

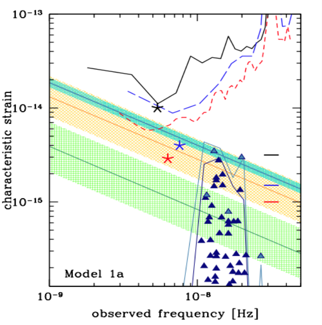
$$\frac{dE_{GW}(\mathcal{M})}{d\log(f_r)} = \frac{\pi^{2/3}}{3} \mathcal{M}^{5/3} f_r^{2/3} \tag{7}$$

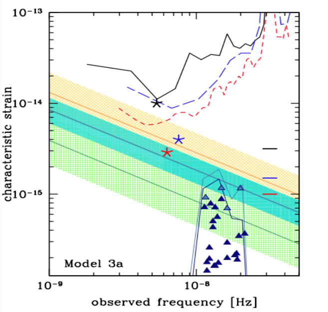
Note that $h_c = A \left(\frac{f_r}{1\,yr^{-1}} \right)^{-2/3} \propto f_r^{-2/3}$.

Comparison of GW Amplitudes

Current model gives $-15.1 < \log(A) < -14.7$ at 68% confidence, but best current upper limit (at 95% confidence) has $\log(A) < -15$ [4]. Figures show frequency vs. amplitude for each model (type "a").







Comparison of GW Amplitudes

- Model 1a is inconsistent with the CRTS data
- Including uncertainties in the mass broadens the distribution of the amplitude giving $\log(A) \approx -14.5$ for all three models which makes them all inconsistent with the CRTS data
- Even considering only $z < 1.3$, the SMBHB candidates cannot be reconciled with the PTA upper limits

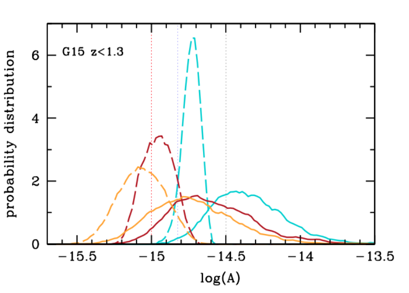


Figure 7: SGWB distribution for six model variation. Model 1 is blue, Model 2 is red, Model 3 is orange.

Comparison of GW Amplitudes

- Considering all redshifts and removing the loudest contributors (high mass $\rightarrow$ short merger time-scales $\rightarrow$ higher merger rate), most of the distributions are still inconsistent with PTA upper limits.
- Misclassification can have a large impact on GW predictions
- Even so, would have to assume 30 misidentifications in order to reconcile the SMBHB data with the CRTS data
- Accounting for the "incompleteness" of the sample only makes this worse by at least a factor of two

Conclusions

- SGWB is dominated by $z > 1.3$ giving a factor of $\sim$ 2–8 inconsistency with PTA upper limits
- Nearly 70% of the signal comes from 11 particularly loud sources
- Accounting for sky coverage makes the PTA limits off by another factor of 2
- Environmental couplings can get this down by a factor of two roughly, leaving roughly a factor of 2–5 discrepancy
- Reconciliation would require a 90% misidentification rate or a factor of 4 overestimation of the BH mass
- The SMBHB hypothesis for the CRTS data is not tenable!

Thanks!

References

References i

- S.T McWilliams, J.P Ostriker, F. Pretorius *The imminent detection of gravitational waves from massive black-hole binaries with pulsar timing arrays*
  https://arxiv.org/pdf/1211.4590v1.pdf
  arXiv:1211.4590v1 [astro-ph.CO] 19 Nov 2012
- R.N Manchester *Detection of Gravitational Waves Using Pulsar Timing*
  https://arxiv.org/pdf/1004.3602.pdf
  arXiv:1004.3602v1 [astro-ph.HE] 21 April 2010

References ii

- A. Sesana, A. Vecchio, C.N Colacino *The stochastic gravitational-wave background from massive black hole binary systems: implications for observations with Pulsar Timing Arrays*
  https://arxiv.org/pdf/0804.4476.pdf
  arXiv:0804.4476v2 [astro-ph.CO]
- R.M Shannon *et. al Gravitational waves from binary supermassive black holes missing in pulsar observations*
  https://arxiv.org/pdf/1509.07320.pdf
  arXiv:1509.07320 [astro-ph.CO]

References iii

- A. Sesana, Z. Haiman, B. Kocis, L.Z Kelley *Testing the Binary Hypothesis Pulsar Timing Constraints on SMBHB Candidates* https://arxiv.org/pdf/1703.10611.pdf arXiv:1703:1061v1 [astro-ph.HE]
- S. Babak *et. al European Pulsar Timing Array Limits on Continuous Gravitational Waves from Individual Supermassive Black Hole Binaries* https://arxiv.org/pdf/1509.02165.pdf arXiv:1509.02165v2 [astro-ph.CO]

Extra Slides

Plots i

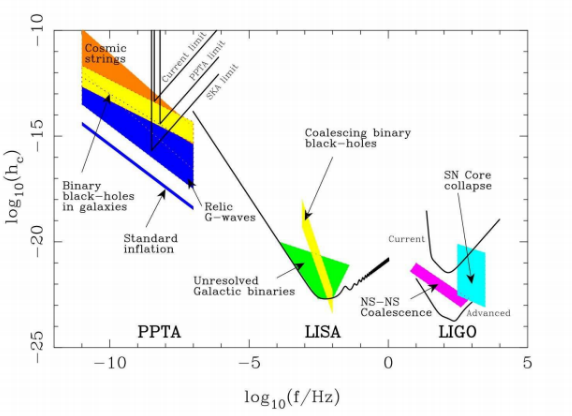


Figure 8: Sensitvity curves and GW spectra [2]

Plots ii

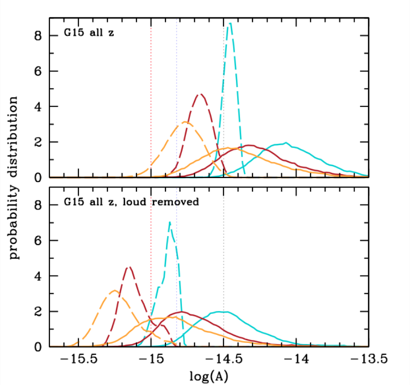


Figure 9: SGWB distribution including all redshifts. Model 1 is blue, Model 2 is red, Model 3 is orange. [1]

Plots iii

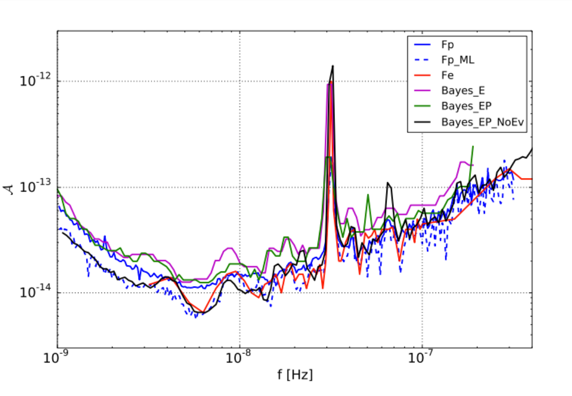


Figure 10: Bayesian and frequentist analysis on SGWB amplitude using EPTA data. Limits of $6 \times 10^{-15} < A < 1.5 \times 10^{-14}$. [6]