EXPLORING MINOR PLANETS BY GRAVITATIONAL WAVE DETECTIONS WITH PULSAR TIMING ARRAYS Xihao Deng[1], Lee Samuel Finn[1,2], [1]Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA; xud104@psu.edu; [2]Department of Astronomy & Astrophysics, The Pennsylvania State University,University Park, PA 16802, USA

Introduction: High precision pulsar timing arrays are used to determine planet masses by accurately measuring the periods of many pulsars [1]. The measured pulsar period is constant with respect to the solar system barycenter. Any error in the planets' masses leads to an inaccurate solar system barycenter, which causes a systematic variation in the measured pulsar period. This technique has determined the masses of planets such as Jupiter within 1 part in 10^9, which is comparable to the accuracy obtained by the *Galileo* spacecraft [1]. For the smaller minor planets, their contributions to the systematic variations in the measured pulsar periods are usually smaller than the systematic error introduced by the pulsar's transverse Doppler effect [2]. In order to remove such systematic error, we have to measure the pulsar distances with accuracies that can hardly be achieved by the standard parallax measurement. However, in anticipation of gravitational wave detections by pulsar timing arrays in the near future, which searches for a characteristic quadrupolar spatial sinusoidal variation in the pulsar period induced by gravitational waves [3], we have found that the information of pulsar distances is embedded in the gravitational wave signals. By extracting them from the pulsar timing data, we will be able to determine the pulsar distances with adequate accuracy to remove the systematic error induced by pulsar's transverse Doppler effect. Therefore, pulsar timing arrays will be able to measure the masses of small and distant minor planets within 1% to 10%. This technique will be able to offer valuable background information of the minimum mass solar nebula, planet formation, protoplanetary disk and debris-disk.

Signal and Noise: The systematic variation induced by a minor planet in the pulsar period P (also called timing residual) is

$$\Delta P = \frac{m}{c\mathrm{M}_\odot}\,(\mathbf{b}\cdot\mathbf{R})$$

where m is the mass of the minor planet, c is the light velocity, $M_\odot$ is the solar mass, $\mathbf{b}$ is the vector position of the minor planet relative to the solar system barycenter (SSB) and $\mathbf{R}$ is the unit vector from SSB toward the pulsar. So minor planets with larger masses (m) and farther distances ($\mathbf{b}$) will lead to larger variation or timing residual and will be easier to explore.

The systematic error caused by the pulsar's transverse Doppler effect is propotional to V^2/L (V is the traverse velocity of pulsars and L is the pulsar distance). Removing this noise requires an accurate determination on pulsar distances.

Table 1 lists the comparison between the systematic variations induced by 38628 Huya in the pulsar periods (Signal) and the systematic errors caused by the transverse Doppler effects four stable pulsars (Noise). The systematic errors caused by Doppler effect are usually larger than the systematic variations induced by 38628 Huya. If we try to determine its mass within 1% to 10%, we have to measure the pulsar distances within 0.1% to 1%, which is hard to achieve by standard parallax measurement.

Pulsar	Signal	Noise
J1713+0747	83 ns	170 ns
J0437-4715	110 ns	1.2 μs
J02145-0750	31 ns	350 ns
J1012+5307	22 ns	380 ns

Table 1: Comparison between pulsar period variations induced by Huya (Signal) and systematic errors caused by pulsar's Doppler effect (Noise).

Our Technique and Result: Pulsar timing arrays will also be able to detect gravitational waves by searching for a characteristic quadrupolar spatial sinusoidal variation in pulsar period induced by gravitational waves. Taking advantage of this, we have discovered that gravitational wave signals contain information on pulsar distances. The detected gravitational wave signal can be written as [4]:

$$\tau_{GW} = A\sin(2\pi fL)\cos(2\pi ft + \phi - 2\pi fL)$$

where A is the gravitational wave (GW) amplitude, f is the GW frequency, ϕ is the initial phase and L is the pulsar distance. Because f is of the order yr^{-1} but L is of the order Kpc, so the quantity $2\pi fL$ in the argument of the sine function is of the order $10^3 - 10^4$, which means the signal is very sensitive to pulsar distances. Therefore, we can precisely extract pulsar distances from gravitational wave signals. For the four pulsars described above, gravitational wave detections will be able to determine their distances within 0.01% to 0.1%, so that we can remove the systematic errors induced by pulsar's transverse Doppler effect.

Figure 1 and Figure 2 and illustrates the measured period variation of the pulsar PSR J0437-4715 before (Fig. 1) and after (Fig. 2) removing the systematic error by our technique. The pulsar period variation in the left plot is dominated by the systematic error, but that in the right plot shows the variation induced by 38628

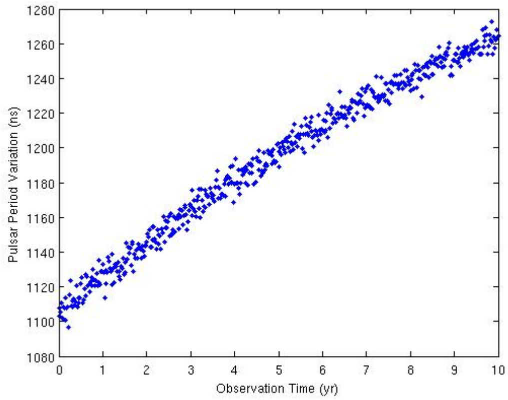

Figure 1: measured period variation of the pulsar PSR J0437-4715 *before* removing the systematic error by our technique.

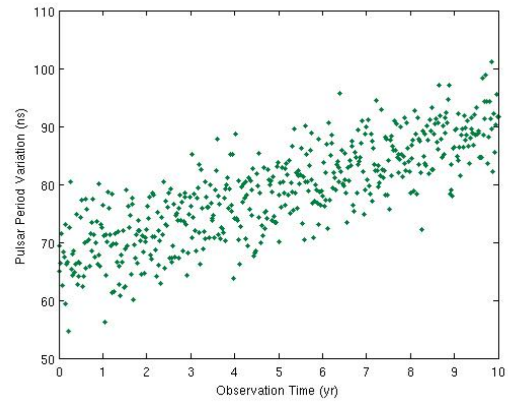

Figure 2: measured period variation of the pulsar PSR J0437-4715 *after* removing the systematic error by our technique.

Huya. By the four pulsars described above, the mass of 38628 Huya will be determined with the uncertainty of 5%, which is precise enough.

Impact: In this manner, our technique can be used to precisely determine the masses of the distant and/or small minor planets such as trans-Neptunian ojects, Kuiper belt objects, Oort Cloud objects, etc., which are usually poorly determined by conventional methods. The accuracy achieved by our method can help provide invaluable information on the minimum mass solar nebula, planet formation, protoplanetary disk and debris-disk.

References: [1] Champion D.J. *et al*, ApJ, L201-L205, 2010 [2] Lyne, A. and Graham-Smith, F., *Pulsar Astronomy*. Cambridge University Press, 2005. [3] Hobbs, G, *et al*, Class.Quant.Grav.27, 084013, 2010 [4] Deng, X. and Finn, L.S., to be submitted.