Dynamical Stability of the PSR1257+12 and HD83443 Extrasolar Planetary Systems

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ABSTRACT

We present the results of long-term integrations of the three extrasolar planets orbiting the pulsar PSR1257+12, and also of the two planets detected around the star HD83443. Simulations of the pulsar planets with masses up to ten times their minimum values remained stable for 100 million years when the planets were begun at low inclinations. Systems with the inner planet at a high relative inclination also remained stable, as did planar systems with the inner planet initially at a high eccentricity. However, systems in which the outer planets were highly inclined relative to one another lasted for less than 300,000 years. The planets in the HD83443 system are quite stable, even for masses 20 times as large as the measured lower bounds.

Subject headings: celestial mechanics, stellar dynamics, extrasolar planetary systems

1. Introduction

The first extrasolar planets discovered were found to orbit the 6.2 millisecond period radio pulsar PSR1257+12 (Wolszczan & Frail 1992; Wolszczan 1994). This system is comprised of three terrestrial-mass planets which orbit a neutron star, whose mass is estimated at 1.4 solar masses ($M_{\odot}$). Other multi-planet systems include three giant planets that have been detected around the F8 V star Upsilon Andromedae (Butler et al. 1999), and two Saturn-mass planets discovered to orbit the K0 V star HD83443 (Mayor et al. 2000).

PSR1257+12 was discovered with the Arecibo radio telescope in 1990, and the planetary companions were detected two years later by precise pulse timing measurements. Since this discovery, more than 50 extrasolar planets have been confirmed. Most of these planets orbit main-sequence stars and have been detected using radial velocity measurements, including the two planets in orbit around HD83443, whose mass is estimated at $0.79M_{\odot}$ (Mayor et al. 2000).

The dynamics of the Upsilon Andromedae planetary system have been studied extensively (Laughlin & Adams 1999; Rivera & Lissauer 2000; Lissauer & Rivera 2001; Stepinski et al. 2000; Ito & Miyama 2000). Preliminary integrations of the remaining multi-planet systems have shown that these systems are stable for at least 10^5 years (Malhotra et al. 1992; Mayor et al. 2000). Here we present our results of long-term integrations of both the PSR1257+12 and HD83443 multi-planet systems. Section 2 describes our numerical integration methods. In Section 3 we describe our results of the PSR1257+12 simulations. Section 4 discusses our HD83443 integrations, and we summarize our results in Section 5.

2. Method

Our numerical integrations were performed with the mixed-variable symplectic (MVS) integrator of the *Mercury5* integration package (Chambers 1999). This algorithm, based on the symplectic mapping technique of Wisdom & Holman (1991), treats each planet as a point mass subject to gravitational forces of the central star and the other planets. We have modified this code to include the effects of general relativity (see Lissauer & Rivera 2001 for details).

The initial orbital parameters for the pulsar planets are given in Table 1. Here, $M\sin i$ is the product of the planet's mass and the sine of the inclination of the normal to its orbital plane relative to the line of sight, P is the orbital period, e is the eccentricity, $\tilde{\omega}$ is the longitude of pericenter, and T_p is the time of periastron passage in Julian days. The amplitude of the radial velocity, K, was calculated for the pulsar planet simulations by:

$$K = \frac{2\pi a}{P} \frac{M_j}{M_* + M_j} \frac{1}{\sqrt{1-e^2}} \tag{1}$$

where a is the semimajor axis determined from Kepler's Third Law (assuming the nominal masses for the planets) (Lissauer & Rivera 2001), M_j is the mass of the j^{th} planet, and M_* is the sum of the masses of the star and planets interior to the j^{th} planet. $M\sin i$, P, and T_p for all three planets, as well as e and $\tilde{\omega}$ for the outer two planets, were based on measurements taken from the 305 meter Arecibo radio telescope until December 1994, and data taken from the 100 meter Effelsberg radio telescope through March 1998 (Wolszczan 2000). The other parameters (listed in italics in Table 1) were assumed. The pulsar planet simulations were begun at epoch JD2448754.3, the time of periastron passage of the inner planet given in Konacki & Maciejewski (1999).

The HD83443 system initial parameters, given in Table 2, were taken from CORALIE planet-search data (http://obswww.unige.ch/~udry/planet/hd83443_syst.html). The integrations of this system were begun at epoch JD2451625, which was midway through the radial velocity observations for this system.

The radial velocity and pulse timing detection methods provide $M\sin i$, rather than the actual planetary masses. We thus multiplied the minimum planetary masses by a range of mass factors, $m_f \equiv 1/\sin i$, for our simulations. Maximum integration times were set between 1 and 100 million years, and simulations were stopped if a planet fell into the central star or was ejected from the system (when either its eccentricity reached one or the planet traveled beyond 100 AU).

3. PSR1257+12 Results

Our first set of simulations involved multiplying the planetary masses by 1, 2, 4, or 10, and integrating each system for 100 million years with a time step of 1 day. Each of these four systems remained stable for the duration of the integration. Note that observational constraints on the mutual planetary perturbations have led to limits on the planetary masses such that $m_f = 1/\sin i \lesssim 2/\sqrt{3}$ (Wolszczan 1997).

For our next set of runs, we set $m_f = 2/\sqrt{3}$ and set the initial inclination of one planet's orbit at either 30°, 45°, or 60° relative to the plane containing the other two planets. Simulations with one planet inclined at 30° resulted in stable systems for the entire integration time of 100 million years. Systems with the inner planet inclined by 45° or 60° also remained stable (Fig. 1). However, systems with the middle or outer planet inclined at 45° or 60° self-destructed in less than 300,000 years. Our next set of runs included systems with $m_f = 2$, and the middle or outer planet inclined at 30°. Both systems remained stable for 100 million years, although the eccentricity of the inner planet was excited throughout the integration in the case of the inclined outer planet.

We next performed a set of runs in which we increased the eccentricity of the innermost planet (which is not well constrained by the observations) to $e = 0.5$. Two coplanar systems, with $m_f = 1$ and the argument of periapse at either 0° or 180°, remained stable for 100 million years. Two similar systems, but with $m_f = 2/\sqrt{3}$ and the inclination of the inner planet at 60° and the argument of periapse at either 0° or 90°, also remained stable. In the case where the inner planet is inclined at 60° and its initial argument of periapse is 0°, the apoastron of the inner planet appears to overlap with the periastron of the middle planet (Fig. 2). The two bodies are prevented from close approaches by a coupling of the inner planet's eccentricity and argument of periastron (Fig. 3).

4. HD83443 Results

We examined the stability of the HD83443 planetary system by first integrating the planets with $m_f = 1$ through 20. These simulations were performed with a timestep of 0.119412 days (4.7% of the orbital period of the inner planet), and each system remained stable for 1 million years. The system with $m_f = 20$ (Fig. 4) also remained stable when continued for 100 million years. To examine how inclinations would affect the stability, we varied the mutual inclination for the $m_f = 2$ case between 30° and 180°. The systems with a mutual inclination of 30° or 180° were stable for the entire 100 million years simulated. Systems with a mutual inclination at 60°, 90°, 120°, or 150° all became unstable in less than 150,000 years.

5. Discussion

In both the PSR1257+12 and the HD83443 planetary systems, high relative inclinations cause each system to quickly destabilize. Low to moderate relative inclinations, however, do not cause the systems to self-destruct. The two planets around HD83443 appear to be highly stable for mass factors of up to 20 in planar systems. Better observational constraints of the planetary parameters are needed, however, to determine whether the planets are actually locked in mean-motion resonances.

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REFERENCES

Butler, R. P., Marcy, G. W., Fischer, D. A., Brown, T. W., Contos, A. R., Korzennik, S. G., Nisenson, P., and Noyes, R. W. 1999. Evidence for Multiple Companions to Upsilon Andromedae. *Ap. J.* **526**, 917-927.

Chambers, J. E. 1999. A Hybrid Symplectic Integrator that Permits Close Encounters Between Massive Bodies. *Mon. Not. R. Astron. Soc.* **304**, 793-799.

Ito, T., and Miyama, S. M. 2000. An Estimation of Upper Limit Masses of Upsilon Andromedae Planets. *Proceedings of the 32nd Symposium on Celestial Mechanics*, 194-205.

Konacki, M. and Maciejewski, A. J. 1999. Resonance in PSR B1257+12 Planetary System. *Ap. J.* **513**, 471-476.

Laughlin, G., and Adams, F. C. 1999. Stability and Chaos in the Upsilon Andromedae Planetary System. *Ap. J.* **526**, 881-889.

Lissauer, J. J., and Rivera, E. J. 2001. Stability Analysis of the Planetary System Orbiting Upsilon Andromedae. II. Simulations Using New Lick Observatory Fits. Submitted to *Ap. J.*

Malhotra, R., Black, D., Eck, A., and Jackson, A. 1992. Resonant Orbital Evolution in the Putative Planetary System of PSR1257+12. *Nature* **356**, 583-585.

Mayor, M., Naef, D., Pepe F., Queloz, D., Santos, N., Udry, S. and Burnet, M. 2000. HD 83443: a System with Two Saturns. *Planetary Systems in the Universe, Observation, Formation and Evolution; ASP Conference Series,* in press.

Rivera, E. J., and Lissauer, J. J. 2000. Stability analysis of the planetary system orbiting Upsilon Andromedae. *Ap. J.* **530**, 454-463.

Stepinski, T. F., Malhotra, R., and Black, D. C. 2000. The Upsilon Andromedae System: Models and Stability. *Ap. J.* **545**, 1044-1057.

Wisdom, J. and Holman, M. 1991. Symplectic Maps for the N-body Problem. *Astron. J.* **102**, 1528-1538.

Wolszczan, A., and Frail, D. A. 1992. A Planetary System around the Millisecond Pulsar PSR1257+12. *Nature* **355**, 145-147.

Wolszczan, A. 1994. Confirmation of Earth Mass Planets Orbiting the Millisecond Pulsar PSR1257 + 12. *Science* **264**, 538.

Wolszczan, A. 1997. Searching for Planets around Neutron Stars. *Celest. Mech. & Dynam. Astron.* **68**, 13-25.

Wolszczan, A., Doroshenko, O., Konacki, M., Kramer, M., Jessner, A., Wielebinski, R., Camilo, F., Nice, D. J., and Taylor, J. H. 2000. Timing Observations of Four Millisecond Pulsars with the Arecibo and Effelsberg Radiotelescopes. *Ap. J.* **528**, 907-912.

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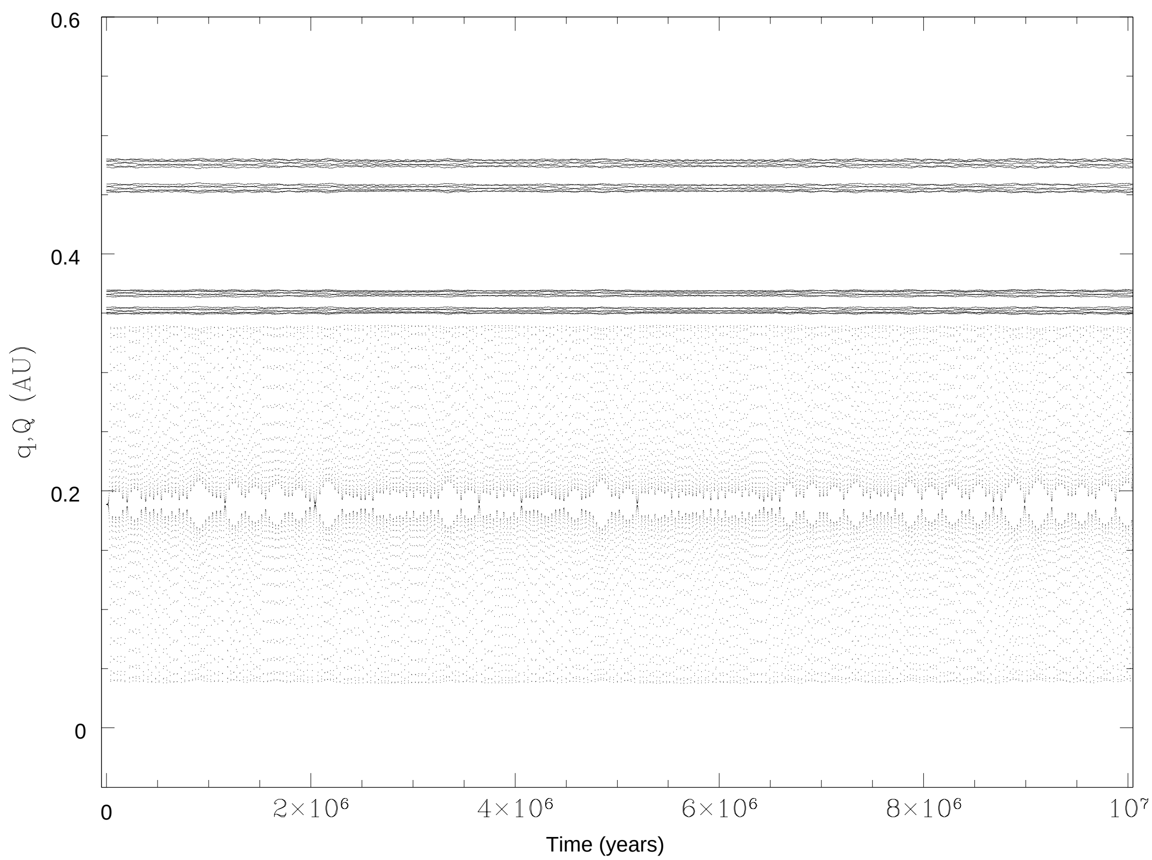

Fig. 1.— The periastron (q) and apoastron (Q) for the three planets in the PSR1257+12 system, with a mass factor of $2/\sqrt{3}$, are shown for the first ten million years of a simulation in which the inner planet was initially inclined 60° relative to the plane of the other two planets. The system remained stable for the entire 100 million years simulated.

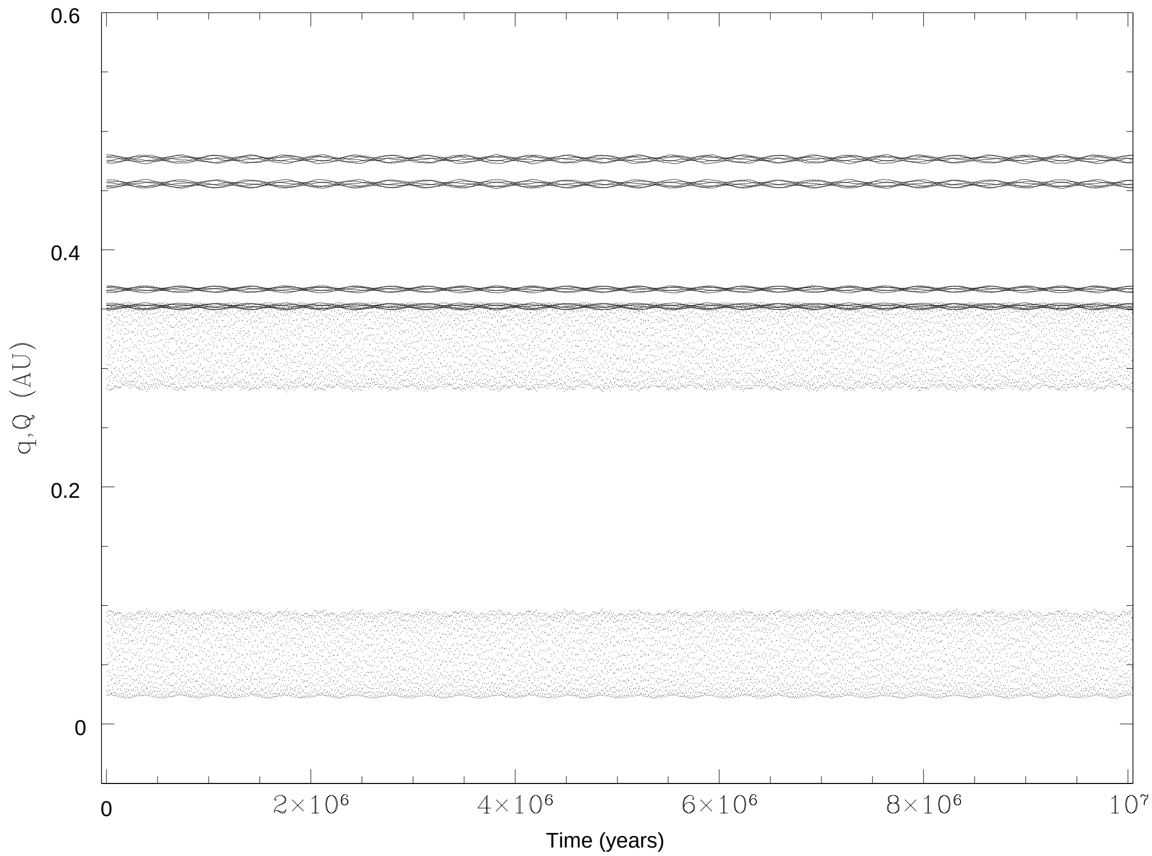

Fig. 2.— The periastron (q) and apoastron (Q) for each of the three planets in a simulation of the PSR1257+12 system are shown for ten million years. The masses assumed $m_f = 2/\sqrt{3}$ and the inner planet was initially inclined 60° relative to the other two planets and had a 0.5 initial eccentricity and zero argument of periastron. The system remained stable for 100 million years. The apoastron of the inner planet overlaps the periastron of the middle planet frequently throughout the simulation.

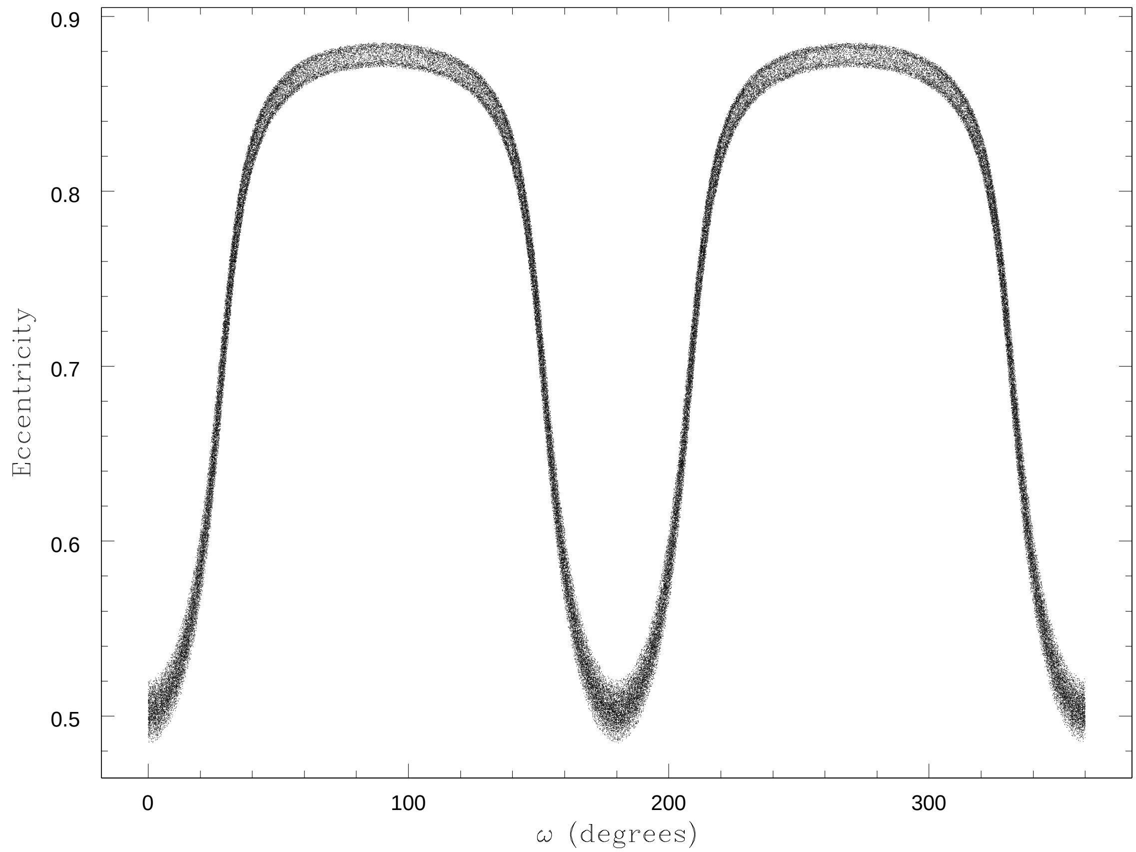

Fig. 3.— The inner planet's eccentricity plotted against its argument of periastron for the system whose periastra and apoastra are shown in Figure 2. Although the orbits of the inner and middle planets cross, the two planets do not suffer close approaches because of this $e-\omega$ protection mechanism.

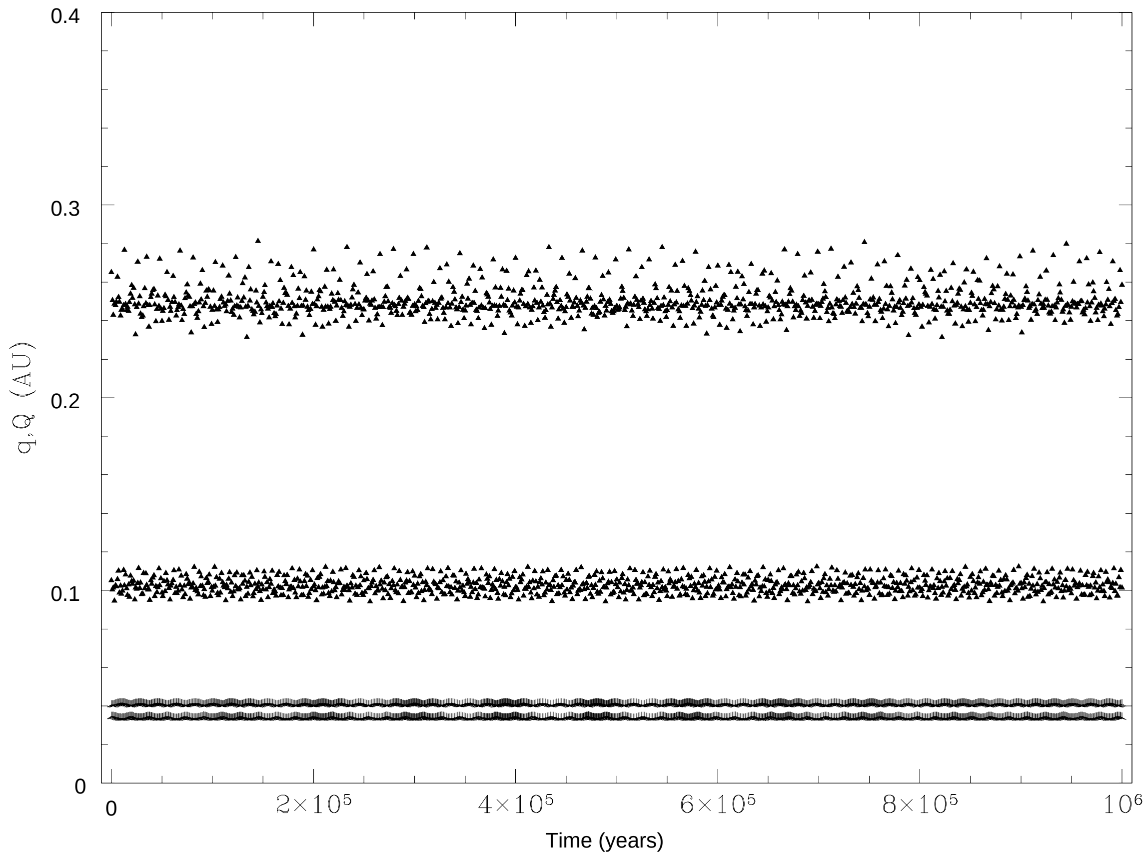

Fig. 4.— The periastron (q) and apoastron (Q) of the two planets in the HD83443 system, with a mass factor of 20, are shown as a function of time. The system also remains quite stable for all mass factors less than 20.

Table 1. PSR1257+12 Planets' Orbital Parameters.

Parameter	Inner Planet	Middle Planet	Outer Planet
$M\sin i$ ($M_\oplus$)	0.015	3.4	2.8
P (days)	25.3144	66.5352	98.2228
e	*0.0*	0.0183	0.0264
$\tilde{\omega}$ (deg)	*0.0*	249.698	106.857
T_p (JD)	2447994.4288	2448104.5391	2448096.3240
K (m/s)	0.002610	0.428821	0.310202

Table 2. HD83443 Planets' Orbital Parameters.

Parameter	Inner Planet	Outer Planet
$M\sin i$ (M_J)	0.34	0.16
P (days)	2.9853	29.83
e	0.08	0.42
$\tilde{\omega}$ (deg)	300.0	337.0
T_p (JD)	2451386.50	2451569.60
K (m/s)	56.0	14.0