Upsilon Andromedae: A Rosetta Stone in Planetary Dynamics

E. I. Chiang

University of California at Berkeley, Berkeley CA 94720

Abstract. We review the orbital dynamics exhibited by the first extrasolar planetary system discovered, Upsilon Andromedae. This system is unique in combining all of the surprising architectural features displayed individually by extrasolar planetary systems found today: (1) a hot Jupiter, (2) two planets on highly eccentric orbits, and (3) a stellar companion. We discuss the system’s stability properties and its possible origin. Planet-disk interactions seem critical to the emerging story.

1. Introduction

Upsilon Andromedae (υ And) is a Sun-like star harboring at least three planetary companions (Butler et al. 1999). Definitions and current fitted values of planetary orbital parameters are listed in Table 1, as supplied by D. Fischer and G. Marcy (2002, personal communication).

Table 1. Fitted Orbital Parameters of Upsilon Andromedae

| Planet | P (days) | Tperi (JD) | e | ω (deg) | m sin i (M_J) | a (AU) |
|--------|---------|-----------|---|---------|--------------|--------|
| b      | 4.6170  | 12088.710 | 0.0167 | 47.864  | 0.64         | 0.057  |
| c      | 241.2473| 10157.675 | 0.2525 | 245.826 | 1.83         | 0.805  |
| d      | 1298.5614| 13947.615  | 0.3080 | 258.114 | 3.79         | 2.475  |

Based on fitting N = 207 radial velocity points.

The quantity ω in Table 1 is a given planet’s argument of pericenter referred to the plane of the sky. For an illustration and more details, see Chiang, Tabachnik, & Tremaine (2001, hereafter CTT). Curiously, the ω’s of the outer two planets, c and d, are presently nearly identical: ∆ω = ω_d − ω_c = 12° ± 5° (1σ). Let us define Θ to be the mutual inclination between the two orbit planes of planets c and d. If we assume for the moment that Θ = 0°, then the observation that |∆ω| ≪ 1 rad implies the near perfect alignment of orbital pericenters.

In this review, we address four questions: (1) Is the near equality of ω_d and ω_c coincidental, or does a dynamical mechanism exist to lock the apsidal
lines together? (2) If a locking mechanism is present, how did it come to be? (3) What is the origin of the large eccentricities of planets c and d? (4) What effect does the stellar companion to $\upsilon$ And (Lowrance, Kirkpatrick, & Beichman 2002) have on the dynamics of the planetary system? Questions (3) and (4) are addressed simultaneously in §3.

2. Existence of Secular Resonance

The answer to question (1) is that if $\Theta \lesssim 20^\circ$, then the two planets are trapped in an apsidal resonance for which $|\Delta \omega| \lesssim 38^\circ$ (CTT; Chiang & Murray 2002). If, however, $\Theta \gtrsim 20^\circ$, then the pericenters are unlocked and today’s observation of the smallness of $\Delta \omega$ is accidental.

Figure 1 summaries the results of 855 numerical orbit integrations, each of duration $10^6$ yr, of $\upsilon$ And c and d. The innermost planet, b, is neglected in these integrations; its time-averaged potential acts mainly as a small, static quadrupole moment. Each integration begins with a different set of five orientation angles consistent with the Doppler velocity data: $\Theta_0, \Omega_0, \chi_0$—the initial inclination, initial longitude of ascending node, and initial argument of pericenter, respectively, of the orbit of planet d referred to that of planet c—and $\phi, \delta$—the location of the observer on the celestial sphere centered on $\upsilon$ And. Simulated systems that begin with $\Theta_0 \lesssim 20^\circ$ tend not only to be stable but also spend the most time with their $\omega$’s nearly equal. Such systems inhabit a so-called secular resonance for which $\Delta \omega$ librates about $0^\circ$ with an amplitude of $\sim 38^\circ$. This behavior can be described analytically by the Laplace-Lagrange equations (CTT). Those systems that are stable have $\sin i_c, \sin i_d \gtrsim 0.5$ (data not shown). Systems at $\Theta_0 \gtrsim 20^\circ$ are characterized by circulating $\Delta \omega$. Those for which $40^\circ \lesssim \Theta_0 \lesssim 140^\circ$ are rendered unstable by the Kozai resonance, by which $e_c$ is driven by planet d to near unity (CTT).

We submit Figure 1 as our best plausibility argument that the outer two planets of $\upsilon$ And occupy nearly co-planar orbits that are seen nearly edge-on and that will remain nearly apse-aligned. This conclusion, in turn, would argue that these planets formed from a flattened circumstellar disk. Verification of the smallness of $\Theta$ will probably have to wait for astrometric measurements of the proper motion of $\upsilon$ And. These measurements are currently in progress with the Hubble Space Telescope.

3. Eccentricity Excitation and Secular Resonance Capture

That $m_d$ likely exceeds $m_c$ while $e_d > e_c$ stands at odds with the idea that gravitational interactions between planets D and C excited both $e_d$ and $e_c$ to their present-day values. We are led to the conclusion that an external agent—another planet, a star, or the circumstellar disk from which the planets formed—directly excited $e_d$. We favor the third candidate.

Goldreich & Sari (2002) describe a finite-amplitude instability by which a planet’s eccentricity can be resonantly excited by the disk. The timescale for eccentricity amplification is $e/\dot{e} \sim 7 \times 10^4 (10^{-4}/\alpha)^{4/3} (40M_J/M_D)\text{yr}$, where $\alpha$ is the usual dimensionless viscosity of the disk, and $M_D$ is the mass of disk material occupying first-order Lindblad resonances established by the planet.
Figure 1. Alignment probability and stability (CTT). *Open circles, left-hand ordinate:* Fraction of time that surviving, sampled, 2-planet scenarios spend with $|\Delta \omega| \leq 10^\circ$. *Solid line, right-hand ordinate:* Fraction of 2-planet scenarios that survive the $10^6$ yr duration of the integration.

Figure 2. Externally driving the eccentricity of planet d amplifies the eccentricity of planet c and locks the system into apsidal resonance. At the end of the integration, the eccentricities and apsidal longitude difference match those of $\upsilon$ And today (Chiang & Murray 2002).
Suppose a circumstellar disk sits just exterior to planet d and excites $e_d$. Provided $\tau_e \equiv e_d/\dot{e}_d$ exceeds apsidal precession timescales ($\sim 8000$ yr), the (nearly co-planar) system morphs adiabatically through a series of classical Laplace-Lagrange solutions. Chiang & Murray (2002) calculate that the resulting probability of apsidal resonance capture is 100%, that $e_c$ grows by siphoning off $e_d$, and that continued eccentricity driving damps the apsidal libration amplitude towards zero. Figure 2 illustrates one sample evolution, in which $e_d$ is grown from 0 to its present-day value of $\sim 0.3$ over a timescale of $\tau_e \sim 10^5$ yr.

Note that slow, adiabatic growth of $e_d$ is not guaranteed. The viscosity profile of protoplanetary disks is poorly understood. If we adopt $\alpha = 10^{-2}$ instead, then the evolution is impulsive. Malhotra (2002) computes the evolution in the impulsive limit and calculates a probability of capture into apsidal resonance of approximately 50%. Impulsive driving may also result from violent planet-planet scattering, though the details have yet to be elucidated.

4. Ups And B: Nemesis or Benign Companion?

Sitting at a projected separation of 750 AU from $\upsilon$ And A is $\upsilon$ And B, a proper motion companion of mass $m_B \sim 0.2M_\odot$ (Lowrance et al. 2002). Could this companion star be responsible for exciting the observed eccentricities of planets c and d? The answer is almost certainly no. The usual Kozai mechanism for pumping planetary eccentricities probably cannot operate because apsidal precession rates of the planets due to planet-planet interactions are likely $\sim 10^4$ times faster than those induced by the star (Chiang & Murray 2002). The star can never “get a handle” on the apses of the planets.

Close encounters between $\upsilon$ And B and planet d are not important unless the eccentricity of the former’s orbit exceeds 0.98, an unlikely possibility that would threaten the stability of the entire system.

The impotence of Kozai-type forcing by the star also implies that it is not the route by which the innermost planet, b, attained its current close orbit. We cannot, however, rule out Kozai-type forcing of $e_b$ by planets c and d, though this would require that the orbit plane of b be once inclined with respect to those of c and d by more than $\sim 40^\circ$. “Type II” migration of planet b induced by a viscous protoplanetary disk seems a more natural hypothesis (Ward 1997).

References

Butler, R.P., et al. 1999, ApJ, 526, 916
Chiang, E.I., & Murray, N. 2002, ApJ, 576, 473
Chiang, E.I., Tabachnik, S., & Tremaine, S. 2001, AJ, 122, 1607 (CTT)
Goldreich, P., & Sari, R. 2002, ApJ, submitted (astro-ph:0202462)
Lowrance, P., Kirkpatrick, D., & Beichman, C. 2002, ApJL, 572, 79
Malhotra, R. 2002, ApJL, 575, 33
Ward, W. 1997, ApJL, 482, 211