Eccentricity Excitation and Apsidal Resonance Capture in the Planetary System Upsilon Andromedae

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ABSTRACT

The orbits of the outer two known planets orbiting Upsilon Andromedae are remarkably eccentric. Planet C possesses an orbital eccentricity of $e_1 = 0.253$. For the more distant planet D, $e_2 = 0.308$. Previous dynamical analyses strongly suggest that the two orbits are nearly co-planar and are trapped in an apsidal resonance in which $\Delta \tilde{\omega}$, the difference between their longitudes of periastron, undergoes a bounded oscillation about $0^\circ$. Here we elucidate the origin of these large eccentricities and of the apsidal alignment. Resonant interactions between a remnant circumstellar disk of gas lying exterior to the orbits of both planets can smoothly grow $e_2$. Secular interactions between planets D and C can siphon off the eccentricity of the former to grow that of the latter. Externally amplifying $e_2$ during the phase of the apsidal oscillation when $e_2/e_1$ is smallest drives the apsidal oscillation amplitude towards zero. Thus, the substantial eccentricity of planet C and the locking of orbital apsides are both consequences of externally pumping the eccentricity of planet D over timescales exceeding apsidal precession periods of order $10^4$ yr. We explain why the recently detected stellar companion to $\upsilon$ And is largely dynamically decoupled from the planetary system.

Subject headings: planetary systems — celestial mechanics — stars: individual ($\upsilon$ Andromedae, HD168443, 47 UMa)

1. INTRODUCTION

The outer two known planets orbiting Upsilon Andromedae ($\upsilon$ And) possess remarkably large orbital eccentricities (Butler et al. 1999). Planet C has a mass of $m_1 = (1.83/\sin i_1) M_J$

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(where $i_1$ is the angle between the orbit pole of planet C and our line of sight, and $M_J$ is the mass of Jupiter), an orbital semi-major axis of $a_1 = 0.805$ AU, and an orbital eccentricity of $e_1 = 0.253$. For planet D, the corresponding quantities are $m_2 = (3.79/\sin i_2) M_J$, $a_2 = 2.48$ AU, and $e_2 = 0.308$. These orbital parameters were kindly supplied by D. Fischer (2002, personal communication), and represent more up-to-date values than those employed by previous works. Studies of the dynamical stability of the system (Rivera & Lissauer 2000; Stepinski, Malhotra, & Black 2000; Lissauer & Rivera 2001; Chiang, Tabachnik, & Tremaine 2001) strongly suggest that the two planets execute approximately co-planar trajectories that are observed nearly edge-on, so that $\sin i_1 \approx \sin i_2 \gtrsim 0.5$.

That $m_2$ likely exceeds $m_1$ while $e_2 > e_1$ stands at odds with the idea that gravitational interactions between planets D and C excited both $e_2$ and $e_1$ to their present-day values. Close encounters between planets (Rasio & Ford 1996; Weidenschilling & Marzari 1996; Ford, Havlickova, & Rasio 2001) and mean-motion resonance crossings between planets on divergent orbits (Chiang, Fischer, & Thommes 2002) tend to impart the greater eccentricity to the less massive body. Thus, we are led to the conclusion that an external agent—another planet, a star, or the circumstellar disk from which the planets formed—must have played a direct role in exciting the eccentricity of the most massive planet, D. Of these three candidates, the latter is the most promising, as we explain below.

An additional clue to the origin of $\upsilon$ And lies in the apsidal resonance that obtains if $i_{21}$, the mutual inclination between the orbits of planets C and D, is less than $\sim 20^\circ$.\textsuperscript{3} The observation today that the arguments of periastron of the two orbits, $\omega_1$ and $\omega_2$, differ by only $\sim 12^\circ$ has been used by Chiang, Tabachnik, & Tremaine (2001, hereafter CTT) to argue that the orbits are indeed nearly co-planar.\textsuperscript{4} If $i_{21} \lesssim 20^\circ$, then $\Delta \omega \equiv \omega_2 - \omega_1$ librates about $0^\circ$ with a semi-amplitude of $\sim 38^\circ$. This apsidal libration and the eccentricity evolution of both planets are displayed in Figure 1.

This paper lays the groundwork for understanding the origin of the large eccentricities and the apsidal alignment exhibited by the orbits of planets C and D in $\upsilon$ And. Our main result is that the eccentricity of planet C and the locking of orbital apsides are both consequences of the slow growth of the eccentricity of planet D. The latter eccentricity, in turn, was driven by an external agent—plausibly a primordial circumstellar disk lying

\textsuperscript{3}The mutual inclination, $i_{21}$, does not necessarily equal $i_2 - i_1$; see, e.g., Stepinski, Malhotra, & Black (2000).

\textsuperscript{4}The argument of periastron, $\omega$, as fitted by Doppler velocity measurements is referred to the plane of the sky (see, e.g., CTT). The longitude of periastron, $\hat{\omega}$, may be referred to any fixed line in inertial space for the purposes of this paper. When $i_{21} = 0^\circ$, we can take $\hat{\omega} = \omega$. 

Fig. 1.— Time evolution of orbital eccentricities of planets C (denoted 1) and D (denoted 2), and the difference in their apsidal longitudes, as computed using linear secular theory for $\sin i_1 = \sin i_2 = 1$ and $i_{21} = 0^\circ$. The maximum in $\tilde{\omega}_2 - \tilde{\omega}_1$ is $38^\circ$; this differs from the preferred value cited in CTT because of the inclusion of more recent Doppler velocity measurements. The system spends more time at small $e_2/e_1$ than at large $e_2/e_1$, a fact that is important for understanding the damping of apsidal libration.
exterior to the orbit of planet D—that acted over timescales exceeding $10^4$ yr. We play our scenario out and explain the mechanics of apsidal resonance capture in §2. We also discuss in that section why the recently detected companion star to $\upsilon$ And is not likely to be dynamically relevant. A summary is provided in §3.

2. Secular Growth of $e_1$ and Apsidal Resonance Capture

2.1. Basic Model

We take planets C and D to occupy co-planar, nearly circular orbits at time $t = 0$. The dynamics exhibited by the system is qualitatively the same over the range $0^\circ \lesssim i_2 \lesssim 30^\circ$ (CTT). We adopt current observed values for the orbital semi-major axes, and minimum values for the planetary masses ($\sin i_1 = \sin i_2 = 1$).

We introduce an external force only on planet D that smoothly amplifies that planet’s eccentricity over a finite time interval. The equations governing the eccentricities and apsidal longitudes ($\bar{\omega}$) of the orbits of planets C and D read as follows (cf. Murray & Dermott 1999):

\[
\dot{h}_1 \equiv \frac{d}{dt}(e_1 \sin \bar{\omega}_1) = +A_{11}k_1 + A_{12}k_2
\]

\[
\dot{k}_1 \equiv \frac{d}{dt}(e_1 \cos \bar{\omega}_1) = -A_{11}h_1 - A_{12}h_2
\]

\[
\dot{h}_2 \equiv \frac{d}{dt}(e_2 \sin \bar{\omega}_2) = +A_{21}k_1 + A_{22}k_2 + Eh_2
\]

\[
\dot{k}_2 \equiv \frac{d}{dt}(e_2 \cos \bar{\omega}_2) = -A_{21}h_1 - A_{22}h_2 + Ek_2
\]

where

\[
A_{11} = \frac{n_1}{4} \frac{m_2}{m_* + m_1} \left( \frac{a_1}{a_2} \right)^2 b_{3/2}^{(1)} \left( \frac{a_1}{a_2} \right)
\]

\[
A_{12} = -\frac{n_1}{4} \frac{m_2}{m_* + m_1} \left( \frac{a_1}{a_2} \right)^2 b_{3/2}^{(2)} \left( \frac{a_1}{a_2} \right)
\]

\[
A_{21} = -\frac{n_2}{4} \frac{m_1}{m_* + m_2} \left( \frac{a_1}{a_2} \right)^1 b_{3/2}^{(2)} \left( \frac{a_1}{a_2} \right)
\]

\[
A_{22} = \frac{n_2}{4} \frac{m_1}{m_* + m_2} \left( \frac{a_1}{a_2} \right)^1 b_{3/2}^{(1)} \left( \frac{a_1}{a_2} \right)
\]
\[ E = \exp(-t/\tau_E)/\tau_e. \]  

(9)

Here \( n_j \) is the mean motion of planet \( j \), \( m_* = 1.3M_\odot \) is the central stellar mass, \( b_{3/2}^{(1)} \) and \( b_{3/2}^{(2)} \) are the usual Laplace coefficients, and \( 1/E \) is the timescale over which exponential growth of \( e_2 \) occurs, where \( \tau_E \) and \( \tau_e \) are fixed time constants.

We emphasize that only the eccentricity of planet D is directly amplified by our external force. Our equations are intended to represent the following physical picture, staged just after the formation epoch of the planets. Interior to and between the orbits of planets C and D, circumstellar disk gas is absent. Only exterior to the orbit of planet D lies disk gas whose resonant interaction with that planet excites the planet’s eccentricity. Our scenario is consonant with most current thinking on planet-disk interactions. Gas between the two planets is plausibly driven out of this region by planet-induced torques, as numerical simulations by Kley (2000) and Bryden et al. (2000) find. Such gas either tunnels past both planets into the innermost and outermost disks, or is accreted by the planets (Bryden et al. 2000). Viscous accretion may drain away the disk that lies interior to both planets onto the central star, as has been invoked by Snellgrove, Papaloizou, & Nelson (2001). The disk outside \( \sim 3 \) AU may be prevented from accreting inwards by shepherding torques exerted by the outermost planet. Goldreich & Sari (2002) have discovered that disk gas can excite a planet’s eccentricity; eccentricity-amplifying Lindblad resonances can defeat eccentricity-damping co-rotation resonances provided the planet’s initial eccentricity exceeds a critical threshold. While the nonlinear outcome of their finite amplitude instability remains to be worked out, it may be that a planet’s eccentricity ceases to grow when the planet’s orbit begins to overrun the gap edge, i.e., when \( e \sim 0.3 \). For a dimensionless disk viscosity of \( \alpha = 10^{-4} \) and a disk mass of \( 40M_J \), we compute an eccentricity amplification timescale, \( e_2/\dot{e}_2 \), of \( 7 \times 10^4 \) yr, and a radial migration timescale, \( |a_2/\dot{a}_2| \), of \( 4 \times 10^6 \) yr [Goldreich & Sari 2002; their equations (18) and (19)]. Since the latter can exceed the former, we fix the semi-major axes of both planets in our analysis.\(^5\)

We are aware that certain details underlying our scenario are not well understood. Gas between planets C and D might be shepherded rather than driven out (Bryden et al. 2000), in which case its effects on D and C would need to be accounted for. Numerical simulations by Papaloizou, Nelson, & Masset (2000) of interactions between Jupiter-mass planets and their parent disks result in eccentricity damping and have yet to be reconciled with the predictions of Goldreich & Sari (2002). Uncertainties in the plausibility of our scenario notwithstanding, the key features of equations (1)–(4) are that (a) the eccentricity evolution

\(^5\)We have verified by direct numerical simulations that relaxing this assumption changes none of our conclusions.
of planet D is directly driven by an external influence, and (b) the eccentricity and apsidal evolution of planet C are not, i.e., planet C feels only the gravitational potential of planet D. These minimal requirements are sufficient to understand the origin of the eccentricity of planet C and the origin of the curious apsidal alignment of the orbits of C and D, as we now demonstrate.

If $E = 0$, equations (1)–(4) yield the classical Laplace-Lagrange (L-L) solution. One solution, fitted with initial conditions appropriate to observations of $\nu$ And today, is embodied in Figure 1. A variety of L-L solutions, differing only in initial eccentricities and apsidal longitudes, are mapped in the space of $\Delta \tilde{\omega} = \tilde{\omega}_2 - \tilde{\omega}_1$ and $e_2/e_1$ in Figure 2a. The dashed separatrix divides circulating solutions from librating solutions. Librating solutions all have $|\Delta \tilde{\omega}| < 90^\circ$. Today planets C and D live on a contour of libration characterized by $\max|\Delta \tilde{\omega}| \approx 38^\circ$.

If $O(E) \ll O(A_{jk})$, or equivalently if $1/E$ is longer than apsidal precession timescales of order $10^4$ yr, then the system evolves adiabatically through a series of L-L solutions. Figure 2b follows the evolution of a system for which $e_1(t = 0) = e_2(t = 0) = 0.05$, $\Delta \tilde{\omega}(t = 0) = 180^\circ$, $\tau_e = 7.0 \times 10^4$ yr, and $\tau_E = 1.5 \times 10^5$ yr. The final time of the calculation is $t_f = 1 \times 10^6$ yr, at which time the eccentricity driving term, $E$, is effectively zero. Each point represents the position of the system in $\Delta \tilde{\omega} - e_2/e_1$ space at a particular time; the solution was obtained by numerically integrating equations (1)–(4) using a standard fourth-order Runge-Kutta routine (Press et al. 1992). A set of points highlighted by a symbol of a given type indicates the trajectory over a time interval of 8400 yr. Comparison of Figure 2a with 2b indicates that the system morphs smoothly through a series of L-L contours. What is noteworthy is that the system is captured into libration and thereafter evolves towards smaller libration amplitude.

The mechanics underlying apsidal resonance capture and the damping of apsidal libration is as follows. The introduction of our eccentricity driving term amplifies $e_2$, i.e., it pushes the system to the right in Figure 2. Thus, a system initially occupying a contour of circulation is eventually pushed past the separatrix onto a contour of libration. It remains to explain the evolution towards smaller libration amplitude. A librating system executes an elliptical trajectory in $\Delta \tilde{\omega} - e_2/e_1$ space. While the system traces out the left-hand side of an elliptical contour, external amplification of $e_2$ pushes the system to the right, i.e., towards contours of smaller libration amplitude. While the system traces out the right-hand side of the ellipse, external amplification of $e_2$ also pushes the system to the right, but now towards contours of larger libration amplitude. Which half of the interaction dominates depends on how much time the system spends on each half of the ellipse. It is clear from Figure 1 that the system spends more time near the minimum value of $e_2/e_1$ than near the maximum
Fig. 2.— (a) Solutions of equations (1)–(4) for $E = 0$. Each contour represents one possible solution. The dashed contour closes at infinite $e_2/e_1$; it is the separatrix dividing apsidally circulating solutions from apsidally librating ones. (b) Solution of equations (1)–(4) for $e_1(t = 0) = e_2(t = 0) = 0.05$, $\Delta \omega(t = 0) = 180^\circ$, $\tau_c = 7.0 \times 10^4$ yr, and $\tau_E = 1.5 \times 10^5$ yr, over a time span of $1 \times 10^6$ yr. Each point marks the instantaneous position of the system in phase space. Open circles denote the trajectory over a 8400 yr interval starting at $t_s = 0$; +’s, $t_s = 5.1 \times 10^4$ yr; X’s, $t_s = 1.2 \times 10^5$ yr; and filled circles, $t_s = 2.8 \times 10^5$ yr. The system is captured from circulation into libration and evolves towards smaller libration amplitude. Damping of libration results from increasing $e_2$ when $e_2/e_1$ is smallest [filled arrows in (a)]. Increasing $e_2$ when $e_2/e_1$ is largest excites libration [open arrows in (a)], but this effect is small because the system spends less time at large $e_2/e_1$ than at small $e_2/e_1$. 
value of $e_2/e_1$. The same behavior can be seen from Figure 2b; the points, plotted at equal time intervals, cluster more strongly near small $e_2/e_1$ than near large $e_2/e_1$. The reason for this is that the apsides of low eccentricity orbits tend to precess more quickly than those of high eccentricity orbits; for the same perturbative acceleration, $\dot{\omega} \propto \sqrt{1 - e^2}/e$ by Gauss’s equation; and thus when $e_1$ is minimal ($e_2/e_1$ maximal), the orbital apsides of planet C precess more rapidly past the apsides of planet D than when $e_1$ is maximal ($e_2/e_1$ minimal). Variations in $e_2$ can be ignored in this analysis; they are characteristically smaller than variations in $e_1$ because planet D carries the lion’s share of the orbital angular momentum of the system (see, e.g., CTT and Figure 1). Thus, external driving of $e_2$ on the leftmost half of an elliptical contour dominates the driving of $e_2$ on the rightmost half, and the system spirals deeper into apsidal lock—all without the need for any explicit dissipation of energy!

The celestial mechanical considerations described above are general and we have verified by numerous integrations of equations (1)–(4) that apsidal resonance capture and the subsequent damping of apsidal libration occur under a wide variety of initial conditions. The input parameters employed for the trajectory shown in Figure 2b were chosen so that the end state of our calculation yielded system parameters that resemble those of $\upsilon$ And today. Figure 3 portrays the same model, displaying the eccentricity and apsidal evolution as explicit functions of time, and should be compared with Figure 1.

2.2. Refinements and Extensions

2.2.1. Disk-induced Precession

In addition to exciting the eccentricity of planet D, an external disk would also cause the orbits of both planets to precess at rates different from those due solely to the planets’ mutual gravity. We may model disk-induced precession by adding extra terms to $A_{11}$ and $A_{22}$ that decay on timescales characterizing the dissipation of the disk (by, e.g., photoevaporation). This procedure can account for the disk’s temporary resonant and secular contributions to planetary precession rates. We have experimented by adding various transient terms to $A_{11}$ and $A_{22}$ and find that none of our conclusions changes qualitatively. Faced with extra, disk-driven differential precession, we may still reproduce the observed parameters of $\upsilon$ And by appropriately re-adjusting our input parameters (e.g., initial eccentricities and $\tau_e$).
Fig. 3.— Solution of equations (1)–(4) using input parameters listed under 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.

\[
\begin{align*}
\tau_e &= 7.0 \times 10^4 \text{ yr} \\
\tau_E &= 1.5 \times 10^5 \text{ yr}
\end{align*}
\]
A stellar companion to $\upsilon$ And has recently been reported by 2MASS (Two Micron All-Sky Survey; Lowrance, Kirkpatrick, & Beichman 2002). The mass of the companion is $m_E \sim 0.2 M_\odot$ and the projected separation between it and the primary is 750 AU. 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 (see, e.g., Holman, Touma, & Tremaine 1997) can only operate if (1) the plane of the planetary system is sufficiently inclined with respect to the plane of the stellar binary, and (2) the apsidal precession rate of the planet due to the stellar companion dominates other contributions to that precession rate. The latter condition fails to be satisfied, by a wide margin. We define $e_E$ and $a_E$ to be the (unknown) orbital eccentricity and semi-major axis, respectively, of the companion star. Then the precession period of planet D, as induced solely by the stellar companion, is of order $\sim 2\pi n_2^{-1}(m_*/m_E)(a_E/a_2)^3(1 - e_E)^{3/2} \sim 2.5 \times 10^8(0.2 M_\odot/m_E)(a_E/750\text{ AU})^3[(1 - e_E)/0.5]^{3/2}\text{ yr}$ (Holman, Touma, & Tremaine 1997). This greatly exceeds the precession periods set by the mutual interaction between planets C and D, which are of order $10^4\text{ yr}$.

If the plane of the stellar binary has a small inclination with respect to the plane of the planetary system, we may treat the stellar companion as a third, massive body in our linearized equations of motion. It is not difficult to show that the companion star would then induce an eccentricity of order $(a_2/a_E)e_E$ in the orbit of planet D. For the same parameters employed above, this secularly forced eccentricity is of order $10^{-3}$.

Sigurdsson (1992) has shown that the mean induced eccentricity and inclination of a planet orbiting a $1.4 M_\odot$ star exceed $10^{-3}$ and $10^{-2}$, respectively, if a $0.7 M_\odot$ companion approaches the primary to within a distance of $\sim 5$ times the semi-major axis of the planet. These are mean induced orbital parameters, averaged over 25,000 different possible encounter geometries. For the stellar companion having $a_E \approx 750\text{ AU}$ to come within $5a_2 \sim 13\text{ AU}$ of the primary, $e_E \gtrsim 0.98$. This is an underestimate of the eccentricity required for the companion star to be dynamically relevant because $m_E \approx 0.2 M_\odot < 0.7 M_\odot$. In any case, we consider such large eccentricities to be improbable. Moreover, if such large eccentricities were to obtain, the consequent violent forcing of the planetary system over the orbital period of the star would threaten the stability of the system.
2.2.3. Other Planetary Systems

We are aware of two other extrasolar two-planet systems whose present-day dynamics may be primarily secular: HD168443 (Marcy et al. 2001) and 47 UMa (Fischer et al. 2002). In the first system, the less massive, inner planet occupies the more eccentric orbit. This is consistent with the idea that both planets excited each other’s eccentricities by, e.g., divergent resonance crossings (Chiang et al. 2002). Alternatively, each planet’s eccentricity may have been excited by local disk material (Goldreich & Sari 2002), independently of the presence of the other planet. In HD168443, the separation in semi-major axis between the two planets is greater than that between planets C and D in υ And, increasing the likelihood that disk gas was confined between the two planets in the former system. In the absence of an innermost disk, ring confinement is necessary for the resonant excitation of the inner planet’s eccentricity, either by divergent resonance crossings or local disk-planet interaction. Both scenarios are consistent with the fact that HD168443 does not exhibit an apsidal lock; there is no reason to expect the ratio $e_{outer}/e_{inner}$ to be driven to large values.

In the case of 47 UMa, the eccentricity of the less massive, outer planet is constrained by observation to be less than 0.2 (Fischer et al. 2002). If said eccentricity is less than 0.1, we find that the apsides of the two planets are locked about 0°, consistent with the findings of Fischer et al. (2002). Can we apply our theory for υ And to 47 UMa? The eccentricities in 47 UMa are so low that it is not clear how the system was driven by an external influence, if at all. Moreover, the phase space of possible trajectories in $\Delta\bar{\omega}-e_{outer}/e_{inner}$ space is qualitatively different from the case of υ And, because most of the angular momentum of the system is carried by the inner planet. This causes an island of libration about $\Delta\bar{\omega} = 180^\circ$ to appear at $e_{outer}/e_{inner} \gtrsim 1$. An important feature of 47 UMa is the proximity of this system to a 5:2 mean-motion resonance; if future Doppler velocity data place the system in this resonance, then the apsides circulate (Fischer et al. 2002). Whether or not the system inhabits this mean-motion resonance, it seems that our theory for υ And cannot be applied to 47 UMa in a straightforward manner.

3. Summary

We have sketched an evolutionary scenario that explains the origin of the eccentricities and the apsidal alignment exhibited by the orbits of planets C and D in the extrasolar planetary system, Upsilon Andromedae. In our picture, the eccentricity of the outermost planet, D, grows smoothly via resonant interaction with a circumstellar disk of gas remaining from the formation of planets C and D. Provided the external, disk-driven amplification of the eccentricity of planet D occurs over a timescale that is long compared to apsidal
precession timescales set by the planets’ mutual gravity, the orbits of planets C and D evolve adiabatically through a series of classical Laplace-Lagrange solutions. Increasing the ratio of the eccentricity of planet D to that of planet C eventually forces apsidal circulation to give way to apsidal libration. Continued pumping of this eccentricity ratio during the phase of the libration when this ratio is smallest drives the libration amplitude to zero. The resonantly excited eccentricity of planet D is secularly shared with that of planet C. In short, the substantial eccentricity of planet C and the apsidal resonance are both consequences of the growth of the eccentricity of planet D which, in turn, was driven by a third agent, most likely a remnant circumstellar disk lying exterior to the orbits of both planets. The companion M4.5V star to υ And recently detected by 2MASS is likely dynamically decoupled from the planetary system.

Our mechanism for capture into apsidal resonance and damping of apsidal libration is, to our knowledge, novel. Moreover, it enjoys complete independence from energy dissipation mechanisms that are normally required to damp libration amplitudes as in, e.g., the case of the Laplace resonance inhabited by the Galilean satellites (see, e.g., Murray & Dermott 1999). The gravitational interactions between planets C and D are, to excellent approximation, secular and therefore energy-conserving.

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