Planet–Planet Scattering in Upsilon Andromedae

Eric B. Ford, Verene Lystad, Frederic A. Rasio

1 Department of Astronomy, University of California, Berkeley, CA, USA
2 Department of Physics and Astronomy, Northwestern University, Evanston, IL, USA

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Doppler spectroscopy has detected 136 planets around nearby stars. A major puzzle is why their orbits are highly eccentric, while all planets in our Solar System are on nearly circular orbits, as expected if they formed by accretion processes in a protostellar disk. Several mechanisms have been proposed to generate large eccentricities after planet formation, but so far there has been little observational evidence to support any particular one. Here we report that the current orbital configuration of the three giant planets around Upsilon Andromedae (υ And) provides evidence for a close dynamical interaction with another planet, now lost from the system. The planets started on nearly circular orbits, but chaotic evolution caused the outer planet (υ And d) to be perturbed suddenly into a higher-eccentricity orbit. The coupled evolution of the system then causes slow periodic variations in the eccentricity of the middle planet (υ And c). Indeed, we show that υ And c periodically returns to a very nearly circular state every 9000 years. Our analysis shows that strong planet–planet scattering, one of several mechanisms previously discussed for increasing orbital eccentricities, must have operated in this system.

The innermost planet around υ And has a very small orbital eccentricity, as expected from tidal circularization, but the two outer planets have large eccentricities, both around 0.3. It was quickly recognized after their discovery that the gravitational interaction between these two planets causes significant eccentricity evolution on secular timescales (∼ 10^4 years). In particular, in some early solutions, the middle planet appeared to have its eccentricity varying periodically with a large amplitude, from a maximum near the present value to a minimum near zero. Later fits to the data suggested that the outer two orbits had arguments of pericenter nearly equal to within about 10°. This could indicate an “apsidal resonance,” in which two elliptical orbits oscillate about an aligned configuration with a small libration amplitude.
Two possible explanations have been proposed for this peculiar orbital configuration. The first is a dynamical mechanism in which a sudden perturbation imparts a finite eccentricity to the outer planet\(^4\). The subsequent secular evolution causes the middle planet’s orbit to become eccentric and can leave the two orbits either circulating, or librating with a large amplitude. In either case, the eccentricity of the middle planet periodically returns to its initial low value. The impulsive perturbation of the outer planet would result naturally from planet–planet scattering, which was one of the earliest mechanisms proposed for inducing large eccentricities in extrasolar planets\(^8,9\). In contrast, the second explanation invokes an adiabatic perturbation of the outer planet’s eccentricity through torques exerted by an exterior gaseous disk\(^10\). As the eccentricity of the middle planet grows on a similarly long timescale, this would leave the system in an apsidal resonance by damping the libration amplitude to zero. This is a natural extension of more general “migration scenarios” in which the coupling of a planet’s orbit to a gaseous disk could both increase eccentricities\(^11\) and lead to orbital decay and the formation of planets with very short orbital periods\(^12\).

The \(\upsilon\) And system was the first extrasolar multi-planet system ever discovered by Doppler spectroscopy. Since the first announcement of the outer two planets in 1999, the California and Carnegie Planet Search team has taken over 350 new radial velocity measurements, making \(\upsilon\) And one of the systems with the tightest constraints on orbital parameters (Table 1; see also supplementary information). The secular evolution of the system is shown in Fig. 1. While the eccentricity of d remains always between 0.2 and 0.3, planet c returns periodically to a nearly circular orbit with \(e < 0.01\). As shown in Fig. 2, this is now a property of all solutions consistent with the data, in contrast to earlier suggestions that it could happen for some solutions\(^4,6\).

We have also re-examined the possible presence of apsidal resonance in the system. Remarkably, we find that the allowed solutions all lie very close to the boundary between librating and circulating configurations (Fig. 3). As a consequence, all librating systems have libration amplitudes close to 90°. As shown in Fig. 3, this behavior is confirmed by direct numerical integrations of all three planets for a large sample of systems covering the allowed parameter space of solutions.

Our results do not change significantly if the assumption of a coplanar system viewed edge-on is relaxed. Inclination angles can be constrained by requiring dynamical stability of the system\(^6,7,16,17\). Using the latest data we find that, for a coplanar configuration of three planets with the best-fit orbital parameters, the system becomes dynamically unstable when \(\sin i < 0.5\) (where \(\sin i = 1\) corresponds to edge-on). If we relax coplanarity, we find that the system becomes dynamically unstable whenever the relative inclination is greater than about 40°. Throughout the full range of allowed inclination angles we find qualitatively similar behavior for the secular evolution of the system. For example, Fig. 2 shows that the eccentricity of planet c would still return periodically to a value near zero. The secular evolution of the system should be reevaluated if future observations of \(\upsilon\) And were to discover an additional planet in a long period orbit.

Our analysis clearly confirms that the \(\upsilon\) And system is evolving exactly as would be expected after an impulsive perturbation to \(\upsilon\) And d\(^4\). The initial sudden change in eccentricity for
the outer planet would be naturally produced by a close encounter with another planet, which
got ejected from the system as a result. Using our knowledge of planet–planet scattering from
several previous studies\cite{2,18–20}, we determined plausible initial conditions for the original,
unstable system. The early dynamical evolution of such a system is illustrated in Fig. 4. After a
brief period of strongly chaotic evolution, lasting \(\sim 10^3\) years, the outer planet is ejected, and
the remaining two planets are left in a dynamical configuration closely resembling that of \(\upsilon\) And
(see supplementary discussion for a more detailed discussion).

While several other mechanisms (e.g., perturbations in a binary star\cite{22}, resonances\cite{10}, inter-
action with a gaseous disk\cite{11}) have been proposed to explain the large eccentricities of extrasolar
planets, only planet–planet scattering naturally results in an impulsive perturbation, as is nec-
essary to explain the \(\upsilon\) And system. All other mechanisms operate on much longer timescales
and would also affect the eccentricity of planet c, erasing the memory of its initial circular orbit
(see supplementary discussion for a more detailed discussion).

Our results have other implications for planet formation. Given the difficulty of forming
giant planets at small orbital distances, it is generally assumed that the \(\upsilon\) And planets migrated
inward to their current locations via interactions with the protoplanetary disk\cite{12}. If this is correct,
then the small minimum eccentricity of \(\upsilon\) And c also provides evidence that its eccentricity at
the end of migration had not grown significantly, in contrast to what some theories predict\cite{11}.
However, the possibility of formation in situ\cite{23} cannot be excluded by our results.

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Correspondence and requests for materials should be addressed to F.A.R. (rasio@northwestern.edu).

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Masses and orbital parameters for the three planets in $\upsilon$ And.

| Planet | $P$ (d)          | $e$      | $\omega$ (deg) | $m \sin i$ ($M_J$) |
|--------|------------------|----------|-----------------|--------------------|
| b      | 4.617146(56)     | 0.016(11)|                 | 0.6777(79)         |
| c      | 241.32(18)       | 0.258(15)| 250.2(4.0)      | 1.943(35)          |
| d      | 1301.0(7.0)      | 0.279(22)| 287.9(4.8)      | 3.943(57)          |

Table 1: Results of our new analysis of the $\upsilon$ And radial velocity data$^{2,3,13}$. We have used the entire Lick Observatory data set, kindly provided to us by D. Fischer. For conciseness, we present only the means and standard deviations on the last two digits (indicated in parenthesis) after marginalizing over all other parameters. We list the orbital period ($P$) in days, the orbital eccentricity ($e$), the argument of pericenter ($\omega$) in degrees, and the planet mass times the sine of the inclination of the orbital plane to the line of sight ($m \sin i$) in units of Jupiter masses ($M_J$). More details on our analysis are presented in the supplementary information.
Figure 1: Secular evolution of the planetary system around \( \upsilon \) And. The top panel shows the semimajor axes (thick lines), as well as the periastron and apastron distances (thin lines), for the outer two planets. The lower panel shows the evolution of the orbital eccentricity for each planet. Note that both planet c (dashed) and planet d (dotted) have a significant eccentricity at the present time \((t = 0)\), but that the eccentricity of c returns periodically to very small values near zero. The results shown here were obtained by direct numerical integration using our best-fit parameters. All direct \( N \)-body integrations presented in this paper were performed using Mercury\textsuperscript{14}, version 6.1.
Figure 2: Probability distribution for the minimum eccentricity of planet c. We draw initial orbital elements for planets b, c, and d from their posterior probability distribution and evolve each system according to classical second-order secular perturbation theory. We find that all allowed orbital solutions have the eccentricity of planet c oscillating from a maximum value slightly larger than the present value to very nearly zero. The solid curve corresponds to coplanar orbits viewed edge-on. The dotted curve shows the result for orbits with random orientations to the line of sight, but requiring dynamical stability. This implies relative inclinations $< 40^\circ$. Note that systems with relative inclinations $> 140^\circ$ are also dynamically stable. Although such retrograde orbits are unlikely on theoretical grounds, our conclusions are robust to this possibility. Since the secular perturbation theory averages over the orbits, it is also valid for retrograde orbits. The fact that all allowed solutions result in the eccentricity of planet c returning to a very small value can be understood easily from lowest-order secular perturbation theory,\textsuperscript{4,15} where the eccentricity vector of each planet can be described as the sum of three rotating eigenvectors in the $(e \cos \omega, e \sin \omega)$ plane. The eigenvector representing the effects of planet b on planet c has a very small amplitude and can be neglected. For the particular configuration of $\nu$ And, the two dominant eigenvectors describing planet c have very nearly the same length. Depending on whether the eigenvector with the faster rotation (higher eigenfrequency) has a slightly larger or smaller length than the other, the vector sum will be rotating around $360^\circ$ (circulation) or oscillating with an amplitude close to $90^\circ$ (libration), respectively. Whenever the two vectors are anti-aligned, the magnitude of their sum, i.e., the eccentricity of the planet, is very close to zero; when they are aligned, the eccentricity is maximum.
Figure 3: Observational constraints on the secular evolution parameters. The eccentricity ratio is plotted as a function of the difference between arguments of pericenter for planets c and d, all at the present epoch. We show the 1-, 2-, and 3-σ contours for the posterior probability distribution function marginalized over the remaining fit parameters. The thick contours assume that the radial velocity variations are the result of three non-interacting Keplerian orbits viewed edge-on, while the dotted contours include the mutual gravitational interactions of the planets when fitting to the radial velocity data (only 1- and 2-σ contours are shown). The thin solid line shows the separatrix between the librating (upper left) and circulating (lower right) solutions according to the classical second-order perturbation theory (neglecting the inner planet b). The dotted lines on either side show the variation in the location of the separatrix due to the uncertainty in the remaining orbital elements. The data points show the results of our direct numerical integrations for the full three-planet system: triangles (squares) indicate that the system was found to be librating (circulating). Note that, regardless of the assumptions, the separatrix runs right through the 1-σ contours. We find the median libration amplitude of the librating systems to be about 80°.
Figure 4: Dynamical evolution of a hypothetical planetary system similar to $\upsilon$ And. After a brief period of dynamical instability, one planet is ejected, leaving the other two in a configuration very similar to that of $\upsilon$ And c and d. The innermost planet was not included, as it plays a negligible role. All planets were initially on nearly circular orbits. The initial periods of the two inner planets were 241.5 days (equal to the period of $\upsilon$ And c) and 2100 days. An additional planet (solid), of mass $1.9 M_J$, was placed on an orbit of period 3333 days, so that the outer two planets were close to their dynamical stability limit. The fourth planet (solid) interacted strongly with the third (dotted), while the second planet (dashed) maintained a small eccentricity. After the ejection, the two remaining planets evolve secularly just like $\upsilon$ And c and d (cf. Fig. 1). While this simulation illustrates a case in which $\upsilon$ And had only one extra planet, our results do not preclude the existence of even more planets at larger distances. In fact, the presence of another planet in an even longer-period orbit could be responsible for triggering the instability after a long period of seemingly "stable" evolution and help raise more quickly the pericenter of the planet which perturbed $\upsilon$ And d. Note that the timescale to completely eject the outer planet from the system (after $\sim 9000$ years in this particular simulation) is much longer than the timescale of the initial strong scattering. After this initial brief phase of strong interaction, the perturbations on the outer planet are too weak to affect significantly the coupled secular evolution of $\upsilon$ And c and d. Thus, the "initial" eccentricity of $\upsilon$ And c for the secular evolution is determined by its value at the end of the strong interaction phase, rather than at the time of the final ejection.
Supplementary Methods

We model the observations as resulting from three planets on independent Keplerian orbits. We use a Bayesian framework, to constrain the orbital elements and masses with the radial velocity observations, as well as the "stellar jitter" (radial velocity variations due to stellar phenomena such as convection, star spots, and rotation). We assume priors uniform in the logarithms of orbital periods, velocity semi-amplitudes, and the stellar jitter. Initially, we assume that the orbits are coplanar and viewed edge-on. (Later, we relax this assumption by adopting instead an isotropic distribution of inclinations but rejecting configurations that are not dynamically stable.) We assume uniform priors for the eccentricities and the remaining angles.

We use the techniques of Markov chain Monte Carlo (MCMC) and the Metropolis-Hastings algorithm with the Gibbs sampler to sample from the posterior probability distribution for the masses and orbital parameters. Since our Bayesian analysis closely follows the methods developed for single-planet systems with no stellar jitter by Ford, here we only discuss the generalizations to the algorithm which were necessary to apply it to multiple-planet systems and to allow for an unknown stellar jitter. Each state of the Markov chain includes the five fit parameters for each planet (orbital period, $P$, velocity semi-amplitude, $K$, orbital eccentricity, $e$, argument of pericenter, $\omega$, and mean anomaly at the specified epoch, $M_o$), the unperturbed stellar velocity, $C$, and the magnitude of the stellar jitter, $\sigma_j$. The jitter is assumed to be Gaussian and uncorrelated from one observation to the next. We use the Gibbs sampler and Gaussian candidate transition functions which are centered on the parameter values from the current state in the Markov chain. The scales of the candidate transition functions were chosen based on a preliminary Markov chain so as to result in acceptance rates of nearly 40%. The computational efficiency of MCMC can also be significantly affected by correlations between variables. To improve the computational efficiency we added candidate transition functions which were based on several auxiliary variables based on combinations of the fit parameters. These auxiliary variables are $e \sin \omega$, $e \cos \omega$, $\omega + M_o$, $\omega - M_o$, $P^{2/3}(1 - e)$, and $P^{2/3}(1 + e)$, for each planet, as well as $\omega_b \pm \omega_c$ and $\omega_c \pm \omega_d$ (where $\omega_b$, $\omega_c$, and $\omega_d$ are the arguments of pericenter for planets b, c, and d, respectively). The acceptance ratio was determined according to the Metropolis-Hastings algorithm to reflect our choice of priors described in the previous paragraph. The use of this enlarged set of candidate transition functions significantly improved the mixing and hence efficiency of our Markov chains. It is important to note that our sampling procedure does not make any assumptions about the posterior distribution for the orbital elements or masses. Therefore, our approach allows us to take into account correlations between various orbital parameters, in contrast to previous simpler analyzes.

We have computed five Markov chains, each of which contains over one million states. We have performed several checks to verify the reliability of our Markov chains. The acceptance rates were between 0.37 and 0.45 for trail states generated by the candidate transition functions for each variable or auxiliary variable in each chain. We have also verified that the resulting distributions show excellent agreement across all five chains. For example, the Gelman-Rubin test statistic, $\hat{R}$, approaches 1 from above as a Markov chain approaches convergence. While
sets of Markov chains with $\hat{R}$ less that 1.1, or even 1.2, are frequently used for inference, for the Markov chains used in this analysis, $\hat{R}$ was less than 1.001 for each fit parameter and auxiliary variable, and for the predictions of the radial velocity at 40 future epochs. Thus, we are very confident in the reliability of our Markov chains.

We use the results from our Markov chains as the basis for our dynamical analyzes. When considering non-coplanar cases, we independently draw the inclinations from isotropic distributions and the longitude of ascending node from a uniform distribution. For each state in the Markov chain, we calculate the planet masses and semi-major axes iteratively and treat them as Jacobi elements. Finally, we have performed direct $N$-body integrations of systems sampled from our Markov chains. For these integrations, we chose a variety of initial epochs varying by several times the orbital period of planet d. By comparing the $\chi^2$ of the fit determined by the analytic and $N$-body models, we have determined that our results are not affected by including the effects of mutual planetary perturbations in the fitting procedure.

**Additional References for Supplementary Methods**

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Supplementary Discussion

Choice of Initial Conditions for Figure 4

We have adopted this simple two–planet configuration for computational convenience. In this configuration (two planets on circular orbits perturbing each other significantly, with the other planets distant enough to be negligible), the dynamical stability limit is known analytically and is sharply defined\textsuperscript{21}. Therefore we place the two planets very near that limit in our initial condition. As discussed in previous papers, a variety of scenarios would lead naturally to two planets approaching this limit\textsuperscript{8,17,18}. For example, the outer planet might be migrating inward through coupling with an outer gaseous disk. Once the stability limit is reached, the system evolves quickly (on the orbital timescale) until the strong scattering occurs and one planet is ejected, while the gas becomes irrelevant (as the viscous timescale is much longer).

In addition, the chaotic evolution of a multi–planet system (with more than two planets perturbing each other significantly) can also easily lead to strong scattering, sometimes after a long period of seemingly “stable” evolution\textsuperscript{20,21}. Although equally plausible, this is less convenient computationally since, with more than two planets, the stability limit is not known analytically and not sharply defined, so numerical experimentation would be needed to find a case that could produce a final state resembling the current \( \upsilon \) And configuration, possibly after a very long dynamical integration.

With more than two planets, the timescale for growth of the instability and the occurrence of a strong scattering involving \( \upsilon \) And d can be arbitrarily long\textsuperscript{21,49} and could easily exceed the \( \sim 10^7 \) yr timescale on which the gas is expected to be lost from the protoplanetary disk. If gas were still present when the scattering occurs, the final outcome would be modified, but only the details of the dynamical evolution would change. For example, if gas drag produces some damping of the eccentricity, then a slightly stronger scattering may be needed to produce the same final eccentricity for the retained planet.

Finally, we want to emphasize that, while reproducing the exact parameters of any particular observed system always requires “fine tuning” in an obvious sense, what is important here is that our mechanism can — naturally and without any fine tuning — provide the very short timescale required for the initial perturbation that left \( \upsilon \) And d on an eccentric orbit while leaving \( \upsilon \) And c on a perfectly circular orbit.

Perturbations Due to a Gas Disk

The possibility that the impulsive perturbation to \( \upsilon \) And d was delivered by a massive exterior gaseous disk with a large viscosity was mentioned in a previous study\textsuperscript{4}. However, we can show that this possibility is now firmly excluded for this system. If the eccentricity of \( \upsilon \) And d had been induced by an outer disk, the eccentricity growth time would have to be considerably shorter than the secular timescale. In addition, if the eccentricity grew to \( \sim 0.3 \), the perturbation must stop suddenly. Otherwise the eccentricity of the middle planet, \( \upsilon \) And c, would also start growing and its “initial” value would no longer be compatible with the minimum we derive in the secular solution.
Quantitatively, this is a very stringent requirement. We have performed additional numerical integrations for the outer two planets, starting with their current masses and orbital periods, but on circular orbits. In addition to the mutual gravitational perturbations, we include a simple semi–analytic model of angular momentum dissipation acting on $\upsilon$ And d only. The dissipation rate ($\dot{J}$) is constant for a time $\Delta t$ and then disappears (completely and instantaneously). We have performed multiple simulations holding the product $\dot{J} \Delta t$ fixed to reproduce the current eccentricity of $\upsilon$ And d. If we impose the constraint that the eccentricity of $\upsilon$ And c must remain $\lesssim 0.01$ (the current best–fit value of the minimum is 0.005) after $\Delta t$, then this model provides an upper limit of $\Delta t \lesssim 100$ years. Thus, it is not sufficient to impose an eccentricity growth time shorter than the secular period of $\sim 10^4$ years.

A timescale for eccentricity growth by viscous coupling to a disk as short as $\lesssim 100$ years would require both an implausibly massive disk and a very high effective viscosity. The possibility of eccentricity growth caused by interactions with a disk is rather controversial\textsuperscript{4}, particularly for planets less massive than $10 - 20 M_J$. Nevertheless, we have estimated the timescale for eccentricity using the only detailed theory of eccentricity excitation by viscous coupling to a disk in the astrophysical literature\textsuperscript{5}. We find that a timescale for eccentricity growth as short as $\sim 100$ years would require a mass in the relevant part of the disk, $\Sigma r^2 \sim 40 M_J$, ten times more than the mass of the planet, even with an implausibly large disk viscosity parameter, $\alpha \sim 0.1$. Instead, using more typical parameters\textsuperscript{5} (for a $1 M_J$ planet at 1 AU, with disk parameters $r/h = 25$, $\alpha = 0.001$, and $w/r = 0.5$), it would require $\sim 10^7$ years for the eccentricity to grow from 0.01 to 0.3. Eccentricity growth on this very long timescale would instead lead to apsidal resonance between $\upsilon$ And c and d with a small amplitude libration\textsuperscript{10}, which we have ruled out in the main text. In addition, neither this theory\textsuperscript{5} nor any other published theory of eccentricity excitation due to a gas disk provides a mechanism for making the perturbation cease quickly ($\lesssim 100$ years) after a phase of very rapid eccentricity growth.

What is truly unique about planet–planet scattering is that it provides both a very short timescale for eccentricity growth (the dynamical timescale on which the instability develops) and the same very short timescale for removing the perturbation (since the extra planet gets ejected as a result of the scattering).

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**Additional References for Supplementary Discussion**

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