Complex Planetary Systems
Proceedings IAU Symposium No. 310, 2014
Z. Knežević & A. Lemaitre, eds.

doi:10.1017/S1743921314007881

Orbital fitting of Fomalhaut b and subsequent interaction with the dust belt

Hervé Beust[1], Virginie Faramaz[1] and Jean-Charles Augereau[1]

[1]Univ. Grenoble Alpes, CNRS, IPAG, B. P. 53, F-38041 Grenoble, France
email: Herve.Beust@obs.ujf-grenoble.fr

Abstract. Fomalhaut harbours a moderately eccentric dust belt with a planet candidate (Fom b) imaged near its inner edge. MCMC-based orbital determination of Fom b shows that the orbit is highly eccentric ($e \simeq 0.9$), nearly apsidally aligned with the belt. We study the secular interaction between the planet and the dust ring. We show that only if it is a small mass object, Fom b can perturb the belt without destroying it. But Fom b's perturbing action inevitably drives the belt to high eccentricity and apsidal misalignment. This behaviour is due to the planet's high eccentricity.

This dynamical outcome contradicts both observations and orbital determination. We conclude that another, more massive and less eccentric planet (Fom c) is required to dynamically control the belt. We show that Fom b is likely to have been formerly trapped in mean-motion resonance with Fom c and that subsequent eccentricity increase caused it to cross Fom c's orbit and to jump on its present day orbit via a scattering event.

Keywords. Stars: Fomalhaut – Planetary systems – Planet-disk interactions – Methods: numerical – Celestial mechanics

1. Introduction

Fomalhaut A (αPsa) is a 440 Myr old (Mamajek (2012)) A3V star, located at 7.7 pc. As revealed by HST, Fomalhaut A is surrounded by an eccentric dust ring ($e = 0.11 \pm 0.01$) with a sharp inner edge at 133 AU and extending up to 158 AU (Kalas *et al.* (2005)). Afterwards, a companion near the inner edge of the belt, Fomalhaut b (herafter Fom b) was directly imaged (Kalas *et al.* (2008)). The nature of Fom b is controversial (Kalas *et al.* (2008), Marengo *et al.* (2009), Janson *et al.* (2012)). It is viewed today as a low mass planet surrounded by a population of dust (Kennedy & Wyatt (2011), Kenyon *et al.* (2014)). Further observations of this body led to the detection of its orbital motion (Graham *et al.* (2013), Beust *et al.* (2014)).

The purpose of this paper is to summarize the orbital fit process and the most recent subsequent dynamical studies (Beust *et al.* (2014), Faramaz *et al.* (2014)).

2. Orbital fit

Four astrometric points of Fom b are available between 2004 and 2012 (Kalas *et al.* (2013)). We use a Markov-Chain Monte Carlo (MCMC) approach to fit the orbit, assuming $d = 7.7$ pc and $M = 1.92\,M_\odot$ for the distance and the mass of Fomalhaut. The result of the fit is described in Beust *et al.* (2014). We display in Fig. 1 the posterior distribution of the eccentricity. The semi-major axis (not shown here) peaks as expected around $\sim$ 110–120 AU, but surprisingly, the eccentricity is very high, peaking above 0.9. The distributions of the inclination, longitude of ascending node and argument of periastron (not shown here) also favour coplanarity and apsidal alignment with the disk.

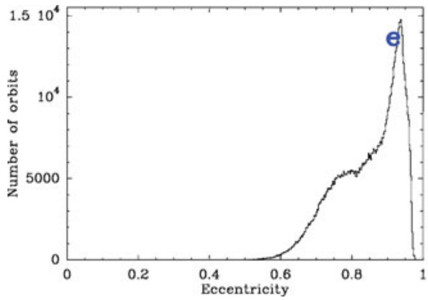

Figure 1. Resulting MCMC posterior distribution of the eccentricity of Fom b's orbit.

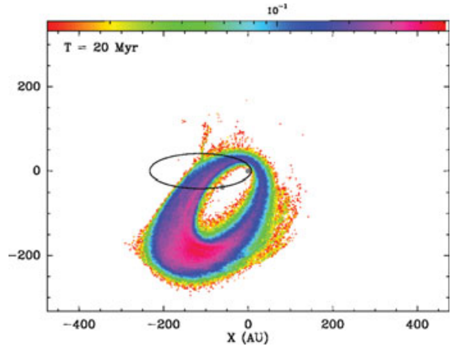

Figure 2. Example of result of the numerical investigation : upper view of the particle disk as perturbed by a super-Earth sized Fom b, after 20 Myr of evolution.

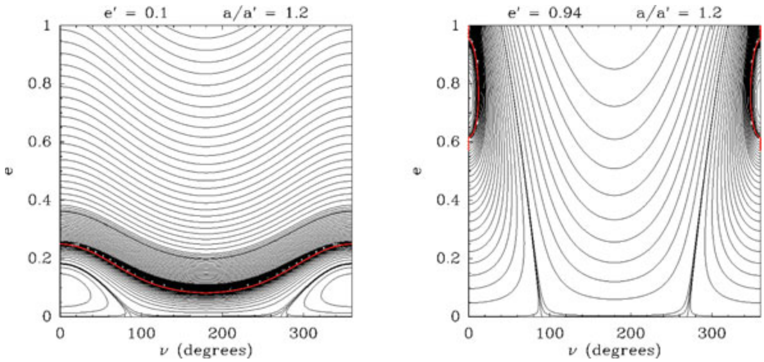

Figure 3. Phase portraits in (ν, e) space of secular averaged Hamiltonian for different values of the perturber's eccentricity e' and a fixed semi-major axis ratio $a/a' = 1.2$. The red curves separate regions where the orbits actually cross from regions where they do not.

3. Dynamical study

The conclusion of the orbital fit is that Fom b very probably has high eccentricity, is nearly coplanar with the dust belt and apsidally aligned. It is thus expected to be disk crossing. The potential effect of this planet on the dust belt needs to be investigated.

We present a numerical study of the Fomalhaut system, taking an initial ring of 10^5 massless particles between 110 AU and 170 AU, adding a planet orbiting on an orbit corresponding to our best fit: $a = 120$ AU and $e = 0.94$. We ran several N-body simulations changing Fom b's mass from sub-Earth to Jupiter size.

Our integrations first showed that with a Jovian-sized Fom b, the disk is quickly destroyed (see Beust *et al.* (2014) for details), thus excluding this mass range. For lighter planets the disk does not erode so much, but Fig. 2 shows that it is stirred up to a highly eccentric shape misaligned by $\sim 70°$ with respect to Fom b's periastron. This obviously does not match the observation.

This behaviour difference can be understood via a semi-analytical study. In Fig. 3, we display phase portraits of the secular doubly averaged interaction Hamiltonian for a test particle orbiting a star, and perturbed by a coplanar planet, assuming a semi-major axis 1.2 times that of the planet. The phase protrait is done in (ν, e) space, where ν is the longitude of periastron of the particle with respect to that of the planet. The left plot

https://doi.org/10.1017/S1743921314007881 Published online by Cambridge University Press

is done assuming that the planet's eccentricity is $e' = 0.1$, while the right one is done for $e' = 0.94$. In the $e' = 0.1$ case, we see that particles starting at low eccentricity are expected to remain so, having their maximum eccentricity at $\nu = 0$. In the $e' = 0.94$ case, all particles are nearly subject to evolve up to $e \simeq 1$, and most of the eccentricity growth is done around $\nu = 70°$. This explains our simulation results.

4. The need for another planet

The perturbations triggered on the disk by Fom b do not match the observation. We thus have two conclusions. First, Fom b is very likely to be a low mass planet (∼Earth or super-Earth sized), otherwise the dust belt would not survive more than a few Myrs. Second, Fom b is not responsible for the shaping of the dust ring. Subsequently, there must be another, more massive planet shepherding the dust ring. Chiang *et al.* (2009) and Kalas *et al.* (2013) also came to the same conclusion. Given its high eccentricity, Fom b's orbit will inevitably cross that of that additional planet (hereafter called Fom c), which raises the issue of its dynamical stability.

We conclude that Fom b is presently on a moderately unstable orbit. We suggest that Fom b could have resided initially closer to the star, and it would have been put more or less recently on its present orbit by a scattering event. The likelihood of this scenario is related to the evolution and survival timescales of the transient configuration, as compared to Fomalhaut's age. This requires a dedicated study.

5. Dynamical history of Fomalhaut b

We investigate the past history of Fom b, assuming that it formed inside Fom c's orbit and was furthermore scattered by a close encounter. Considering the constraints given by Chiang *et al.* (2009), we first chose a mass of $m_c = 3\,M_{Jup}$ for Fom c, a semi-major axis $a_c = 108$ AU, and an eccentricity $e_c = 0.1$.

We must guess where Fom b could have initially resided before undergoing a significant eccentricity increase to cross Fom c's chaotic zone. Mean-motion resonances (MMRs) are good dynamical routes to achieve this. It has been indeed demonstrated (Yoshikawa (1989), Beust & Morbidelli (1996)) that some inner MMRs can trigger important eccentricity increases provided the perturbing planet is moderately eccentric (∼ 0.1).

To test this scenario, we ran several simulations over 500 Myr with different initial sets of particles chosen close the major MMRs. In each case, we monitor the number of particles that are put on Fom b-like orbits, and how long they survive there. We define Fom b-like orbits as orbits with semi-major axis $a > 80$ AU and eccentricity $e > 0.7$. The

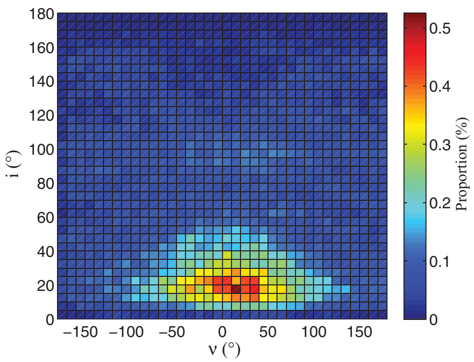

Figure 4. Distribution in inclination i and longitude of periastron ν with respect to that of Fom c of Fom b-like orbits produced in the case of the and 5:2 MMR

https://doi.org/10.1017/S1743921314007881 Published online by Cambridge University Press

3:1, 7:3, 5:2 and 2:1 MMRs all appear to be sources of Fom b like orbits, the most efficient one being the 5:2 (Faramaz *et al.* (2014)) with 3.8% of the initial particles moving to Fom b-like state. It takes approximately 2 Myrs for particles to reach this state, but their survival time in a Fom b-like state is also a few Myrs, which is clearly too short. If we assume a Saturn-sized Fom c, then the number of particles becoming Fom b-like decreases down to ∼0.1%, but it takes now more than 100 Myrs to get there and they are able to stay there for several 10^7 yrs, which makes them good candidates.

Figure 4 shows the distribution of 5:2 MMR originating Fom b-like particles in (ν, i) space (ν having the same definition ans above, and i accounting for the inclination). It reveals that the particles concentrate around $\nu = 0$ and $i = 0$, i.e., coplanar and apsidally aligned orbits, which is in agreement with the observation ! This behaviour is however not due to the encounters, but rather to post-encounter evolution. Considering the near conservation of the Tisserand parameter in encounters, we can show (Faramaz *et al.* (2014)) that particles initially trapped in inner MMRs hardly reach the $e = 0.7$ threshold characteristic for Fom b-like orbits after encounter, and even less easily $e = 0.9$.

Once a particle has been scattered, it is no longer trapped in a MMR, but it keeps evolving secularly as perturbed by Fom c. This evolution can be viewed in the left plot of Fig. 3, which shows the non-resonant phase-space diagram of particles perturbed by a $e' = 0.1$ planet. One must consider that after the encounter, a Fom b progenitor appears somewhere in this diagram around $e \simeq 0.6$ and starts evolving following one of the curves. If it appears around $\nu = 0$ (i.e., apsidally aligned), it naturally evolves towards lower eccentricity at $\nu = 180°$. It never becomes Fom b-like. Conversely, if it appears around $\nu = 180°$, its secular evolution inevitably drives it to higher eccentricity, i.e., Fom-b-like state, when reaching $\nu = 0$. Post-encounter evolution can thus drive particles towards higher eccentricity, but naturally selecting apsidally aligned (and also coplanar) orbits. This scenario explains all characteristics of Fom b. Faramaz *et al.* (2014) show examples of particles out of our simulation following this 3-step dynamical route : Resonant eccentricity increase, then scattering by close encounter, and finally post-encounter evolution that drives it to apsidal alignment with the current eccentricity.

Further work will investigate the effect of this scenario on the dust belt and aid the search for the hypothetical Fom c exoplanet.

References

Beust, H. & Morbidelli, A. 1996, *Icarus* 120, 358

Beust, H., Augereau, J.-C., & Bonsor, A., *et al.* 2014, *A&A* 561, A43

Chiang, E. I., Kite, E., Kalas, P., Graham, J. R.,& Clampin, M. 2009, *ApJ* 693, 734

Faramaz, V., Beust, H., Augereau, J.-C., *et al.* 2014, *A&A* in press, ArXiv:1409.6868

Graham, J. R., Fitzgerald, M. P., & Kalas, P., Clampin, M. 2013, *AAS* 221, 324.03

Janson, M., Carson, J. C., Lafrenière, D., *et al.* 2012, *ApJ* 747, 116

Kalas, P. & Graham, J. R., Chiang, E. *et al.* 2005, *Nature* 435, 1067

Kalas, P. & Graham, J. R., Chiang, E. *et al.* 2008, *Science* 322, 1345

Kalas, P., Graham, J. R., Fitzgerald, M. P., Clampin, M. 2013, *ApJ* 775, 56

Kennedy, G. M. & Wyatt, M. C. 2011, *MNRAS* 412, 2137

Kenyon, S. J., Currie, T., & Bromley, B. C. 2014, *ApJ* 786, 70

Mamajek, E. E. 2012, *ApJ* 754, L20

Marengo, M., Stapelfeldt, K., Werner, M. W., *et al.* 2009, *ApJ* 700, 1647

Yoshikawa, M. 1989, *A&A* 213, 436