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INSIGHTS ON COMPLEX EXOPLANETARY SYSTEMS AND THEIR DYNAMICAL HISTORY WITH HERSCHEL

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Abstract. Resolved images of debris disks often reveal spatial asymmetries which can be interpreted as the dynamical signatures of hidden massive perturbers, potentially planets. The capabilities of *Herschel*[*] have lead for instance to the resolution of an eccentric debris disk around ζ^2 Reticuli, and confirmed the existence of an eccentric dust belt around Fomalhaut. These indicate the presence of massive and eccentric belt-shaping perturbers.

We present here how dynamical modeling using N-body numerical simulations allows us to explain the structure of the debris disk of ζ^2 Reticuli and set constraints on a potential planetary perturber. We also show how such numerical simulations allows us to get insights the dynamical history of the Fomalhaut planetary system. Indeed, the orbit of the planet Fom b, which was thought to shape the belt, and detected near its inner edge, is highly eccentric and incompatible with the present dynamical status of the belt. This gives clues for the presence of another more massive perturber in the system, that is, the belt-shaping planet of the Fomalhaut system is yet undetected. Investigation of the dynamics of this two-planets system has revealed a robust three-step process by which an eccentric massive perturber such as the belt-shaping unseen Fom c sets less massive bodies on orbits similar to that of Fom b. This process provides a plausible dynamical scenario for the Fomalhaut system history. In addition, it may be at the origin of inner belts in the Fomalhaut system, and provide a solution to the presence of unusual high levels of dust in the vicinity of a significant number of stars with age $> 100\,$Myr.

Keywords: Circumstellar matter – Planetary systems – Methods: N-body Simulations – Celestial mechanics – Stars: Fomalhaut – ζ^2 Reticuli.

1 Introduction

At least $\sim 20\%$ of the planetary systems are known to harbor debris disks (Marshall et al. 2014). Spatially resolved structures in debris disks can provide clues to the invisible planetary component of those systems. Such planets may be responsible for sculpting these disks and may leave their signature through various asymmetries such as wing asymmetries, resonant clumpy structures, warps, spirals, gaps, or eccentric ring structures (see, e.g., Wyatt 1999).

The diversity of these asymmetries is to be compared with the variety of exoplanetary systems discovered around main sequence stars since 1995 (51 Peg b, Mayor & Queloz 1995). In particular, the common discovery of significantly eccentric planets is in complete contrast with the circular planetary orbits of our solar system (median eccentricity of 0.29 for planets with orbital period greater than 6 days Udry & Santos 2007). This has revealed that our own Solar System is far from being a reference, and that our current planetary systems formation and evolution models, which were naturally built from its study, require refinements. Therefore, the study of systems containing eccentric perturbers and their dynamical history is crucial to achieve these refinements.

We focus here on two systems which eccentric debris disks were observed with *Hershel*, surrounding ζ^2 Reticuli and Fomalhaut. Results of dynamical modeling and investigation of the dynamical history of the ζ^2 Reticuli and Fomalhaut systems thanks to N-body simulations are presented in Sect. 2 and Sect. 3, respectively.

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[*] *Herschel* Space Observatory is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

2 The ζ^2 Ret system: Can eccentric debris disks be long-lived?

Recent *Herschel*/PACS observations of the debris disk surrounding the 2-3 Gyr old star ζ^2 Reticuli, obtained as part of the DUNES key program (Eiroa et al. 2013), reveal an asymmetric double-lobed circumstellar feature (Fig. 1, left panel), interpreted as a ring like structure seen almost edge-on with an elliptical shape and minimum eccentricity of 0.3, at ~ 100 AU (Eiroa et al. 2010). This provides evidence for the presence of a massive eccentric perturber in this system. The case of ζ^2 Ret is particularly interesting since the system is Gyr-old and thus gives a picture of what mature systems containing an eccentric perturber can look like. These systems are rarely accessible to observations and represent less than 5% of the total resolved circumstellar emissions. It is indeed because debris disks tend to lose luminosity on long-term periods: the dust grains emitting at infrared wavelengths are continuously blown away by radiation pressure (see e.g. Thébault & Augereau 2007) while replenished via collisional processes among the km-sized parent bodies (Backman & Paresce 1993). Since the parent bodies population is not replenished, the amounts of dust, and thus the disk luminosity in mid-far IR decreases adiabatically (Krivov 2010), until instrument sensitivity does not allow us to detect them anymore. In the ζ^2 Ret system, one might question whether the disk asymmetry can be sustained on Gyr timescales, or whether the dynamical history of this system would rather involve a recent setting of the belt-shaping massive perturber on its eccentric orbit.

A detailed modeling of the structure of this debris disk consists in performing N-body simulations with trial eccentric perturbers, exploring their dynamical influence on massless planetesimals on Gyr timescales, and determine which of these perturbers can create a 0.3 eccentric parent debris ring. The dust production resulting from the collisional activity of these parent planetesimals, along with their emission can then be computed to produce synthetic images fully comparable to *Herschel*/PACS observations (see Fig. 1, right panel).

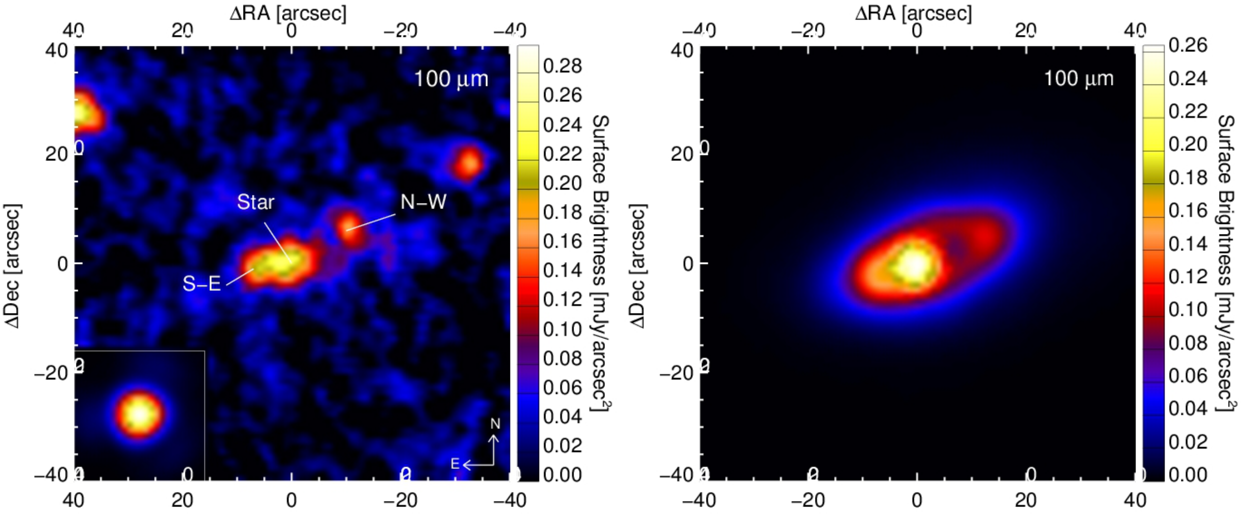

Fig. 1. Left: Herschel/PACS image at 100 microns. **Right:** Synthetic image of a resulting disk in one of our simulations with $e > 0.3$ as seen with Herchel/PACS at 100 microns.

This leads to constraints on the mass and orbital characteristics of the putative perturber: ζ^2 Ret hosts a planetary companion with minimum orbital eccentricity 0.3 at several tens of AU from the host star (Faramaz et al. 2014). In addition, Faramaz et al. (2014) showed that eccentric debris disks can be sustained on Gyr timescales, which involves that the dynamical history of this system does ot necessarily involves a recent access of the massive shepherding planet to its current eccentric orbit.

3 The Fomalhaut system: a dynamical history involving an unseen Fom c?

Fomalhaut (α Psa) is a 440 Myr old (Mamajek 2012) A3V star, located at 7.7 pc (van Leeuwen 2007; Mamajek 2012). Fomalhaut is surrounded by an eccentric dust ring ($e = 0.11 \pm 0.01$) (Kalas et al. 2005). This eccentric shape hinted at the presence of a massive body orbiting inside the belt on an eccentric orbit, dynamically shaping the belt (Quillen 2006; Deller & Maddison 2005). This hypothesis was apparently confirmed by the direct detection of a companion near the inner edge of the belt, Fomalhaut b (hereafter Fom b) (Kalas et al. 2008). However, orbital fitting for this perturber has revealed a highly eccentric and crossing-belt orbit, near with apsidal alignement with the belt, which cannot be responsible for the disk shaping (Graham et al. 2013; Beust et al. 2014). The most straightforward solution to this apparent paradox is to suppose the presence of a second more massive and yet undetected body in the system (hereafter named Fom c), which is responsible for the disk shaping because of a predominant dynamical influence. This implies that Fom b is rather a low-mass body compared to the putative Fom c, as confirmed by recent dynamical or photometric studies which suggest that it is no more than Earth- or Super-Earth sized (Beust et al. 2014; Janson et al. 2012; Galicher et al. 2013).

However, in this configuration, which is illustrated in the bottom panel of Fig. 2, the orbit of the belt-shaping putative planet Fom c would be crossed by that of Fom b, which would make this two-planet system highly unstable and require Fom b to have been set recently on its current orbit. It could have been put there by a more or less recent scattering event, potentially with Fom c (Beust et al. 2014).

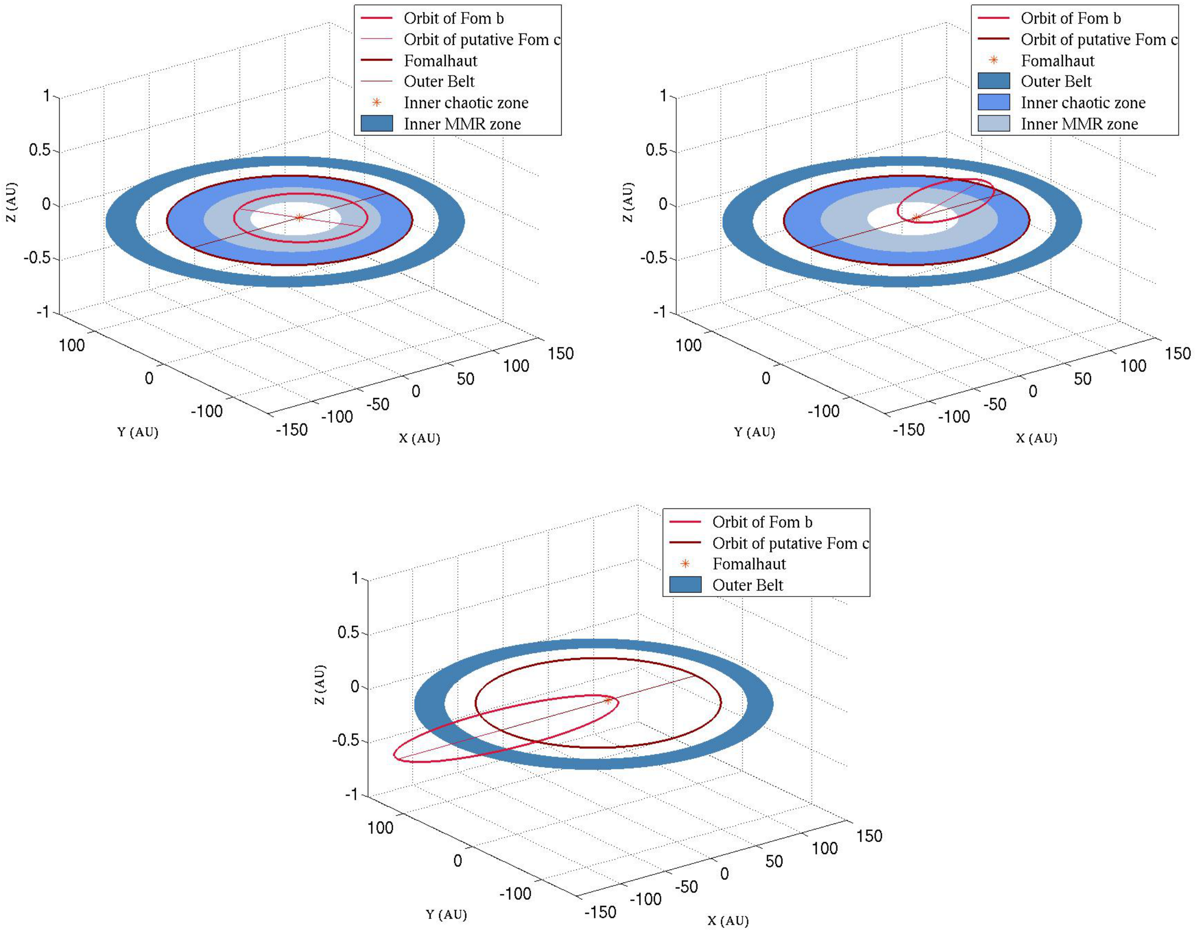

Fig. 2. Top-left: Probable initial configuration of the Fomalhaut system. Fom b is in MMR with the belt shaping eccentric Fom c. **Top-right:** Probable intermediary configuration of the Fomalhaut system. MMRs with an eccentric perturber generate very eccentric orbits, which leads Fom b to cross the chaotic zone of Fom c and be scattered by it on its current orbit. **Bottom:** Probable current configuration of the Fomalhaut system.

Investigation of the dynamics of this two-planet system in Faramaz et al., in prep., where Fom c is a massive belt-shaping body and Fom b a much less massive body originating from the inner parts of the system, has revealed a three-step dynamical scenario involving interactions with the putative eccentric Fom c, which can both explain why Fomalhaut b is on such an eccentric orbit and why it was set on it recently:

1. *Mean-Motion Resonances between Fom b and the suspected Fom c :* Fom b is likely to have formerly resided in an inner mean-motion resonance (MMR) with the additional planet, as illustrated in the top-

right panel of Fig. 2. MMRs with an eccentric perturber such as the belt-shaping putiative Fom c induce a gradual eccentricity increase, which can lead Fom b to cross the chaotic zone of Fom c, where it can then be scattered by Fom c on its current orbit (top-left panel of Fig. 2). The dynamical timescale involved in this process, that is, the typical time necessary for Fom b to reach a sufficient orbital eccentricity from its MMR position and be scattered on its current orbit, strongly depends on the mass of the putative Fom c. In particular, the scattering event can be delayed on timescales comparable to the age of the system with a Neptune or Saturn-sized Fom c, which would explain why Fom b was recently set on its orbit.

2. *Close encounter with the suspected Fom c:* inspection of the close-encounters between Fom b and the putative Fom c reveals that these can set Fom b on an orbit with semi-major axis compatible with this of Fom b, but that they also preferentially produce orbits which are not eccentric enough to be compatible with that of the observed one ($a = 81 - 415\,\mathrm{AU}$ and $e = 0.69 - 0.98$, in the 95% level of confidence Beust et al. 2014).
3. *Secular evolution with the suspected Fom c:* an additional eccentricity increase can be provided by the mean of secular evolution of Fom b under the influence of the putative eccentric Fom c, which is indeed mainly expected at semi-major axes with $a = 81 - 415\,\mathrm{AU}$. However, this eccentricity increase is accompanied by an apsidal alignement with the belt-shaping Fom c, and thus with the belt, which may explain the tendency for the observed orbit to be apsidally aligned with the belt.

The whole process is summarized and illustrated in Fig. 3.

In addition, in the case an eccentric planet such as the putative Fom c coexists with km-sized solid planetesimals, interactions that generates orbits such as that of Fom b can be expected to apply in a very general manner (Faramaz et al., in prep.). Therefore, one should probably expect the Fomalhaut system to contain a broad population of solid bodies on highly eccentric orbits, which can lead them to approach their host star extremely closely when being at periastron. Then, if these solids endure any collisional activity, they may feed the inner parts of the system with dust, which results in hot or warm inner belts. This is extremely interesting in the context of the Fomalhaut system, since both a warm and a hot inner belts were detected (Lebreton et al. 2013). A straightforward question to address then is whether the dynamical scenario constrained in Faramaz et al. (in prep) also explains the presence of these inner belts.

4 Conclusions

Searching for gravitational signatures in debris disks is a particularly helpful indirect detection technique when orbital separations prevent us from detecting these planets via classical detection techniques such as radial-velocities or transits, which are biased to catch short-period objects. This is indeed the case for the Gyr-old system of ζ^2 Ret, which eccentric debris disk was unraveled by *Herschel.* A subsequent dynamical study has revealed that this type of pattern could be sustained over Gyr timescales, and allowed to set first contraints on the belt-shaping perturber at work in this system. However, Faramaz et al. (2014) suggest the eccentric structure of the debris disk of this system could be produced either by an inner or an outer companion. Since the ring limiting radii and its global eccentricity are not well constrained, the parameter space explored is large, that is, there is solution degeneracy. The large orbital separation of this planetary companion, along with its age, makes it very challenging to observe. The only possible way to detect it is to characterize it through its gravitational print on the disk, and thus, to obtain better and more detailed constraints on the geometry of this debris disk, which are hoped to be obtained with facilities such as ALMA.

The study of the Fomalhaut system has revealed a robust process by which orbits such as this of Fom b naturally result from interactions between low-mass solid bodies and an eccentric massive perturber such as this which shapes the outer belt of this system. In addition, this process involves a delay in the production of Fom b-like orbits, which can be greater than 100 Myr if the eccentric massive perturber is Saturn-Neptune sized. This can provide an explanation both for the shape of the outer belt and the current dynamical status of Fom b, and may also explain the presence of inner belts in this system. This also indicates that warm and hot inner belts potentially resulting from this process may start to be produced very late in the history of a system. This may indeed give a solution to the yet unexplained detection of numerous hot belts in systems older than 100 Myr, and which contain levels of dust too large to be sustained over a system's age (Absil et al. 2013; Ertel et al. 2014; Bonsor et al. 2012, 2014). Indeed, such a process involves that one should not necessarily assume that hot belts in systems older than 100 Myr have been sustained over the system's age (Faramaz et al., in prep).

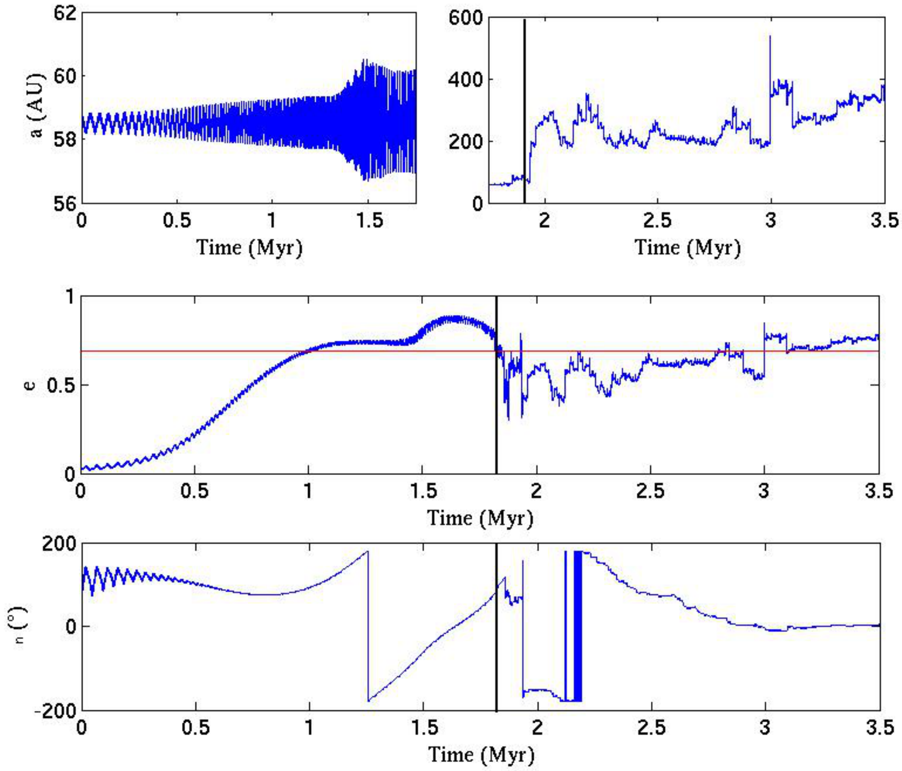

Fig. 3. Example of the three-step process that may have led Fom b on its current orbit. We display the evolutions in time of the semi-major axis a, eccentricity e, and longitude of periastron ν of a massless test-particle initially in 5:2 MMR with a $3\mathrm{M_{Jup}}$ Fom c, with semi-major axis 108.6 AU and orbital eccentricity 0.1. Note that this process can be generated via several other MMRs. The test-particle endures a three-step dynamical evolution, starting with a resonant evolution, where its semi-major axis suffers small oscillations around the exact resonant location, and its eccentricity largely increases, while co-evolving with the longitude of periastron. The vertical black line at $\sim 2Myr$ indicates the second step of the process, that is, a close encounter with Fom c when the highly eccentric orbit of the test-particle leads its orbit to cross the chaotic zone of Fom c. Note that this delay of several Myr with a Jupiter sized Fom c increases up to several 100 Myr with a Saturn-Neptune sized Fom c. The semi-major axis of the test-particle is compatible with this of Fom b after the close encounter, but its eccentricity remains smaller than 0.69 *(horizontal red line)*, and thus is incompatible with that of Fom b. The third step consists mainly in a secular evolution of the test-particle with the eccentric Fom c, although its orbit endures small chaotic variations. This secular evolution allows the eccentricity to increase and become greater than 0.69, which occurs when there is an apsidal alignement between the perturber and the test-particle, that is, when the longitude of periastron of the test-particle is close to zero.

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