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Kozai resonance and tidal friction as a way to explain the dynamical evolution of Gliese 436b

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Abstract

The M-dwarf GJ 436 is known to host a close-in Neptune-mass planet (GJ 436b,[4]) that was furthermore observed to be transiting [8, 1]. GJ 436b's orbit appears to have a significant non-zero eccentricity (~ 0.15; [11, 5]). This eccentricity is abnormally high for such a small period (2.64 days) planet. With this orbital period, tidal forces are expected to circularize the orbit within much less than the present age of the system (1–10 Gyr,[13]).

Many theories were proposed in recent years to account for the residual eccentricity of GJ 436b. The most straightforward one is that its is not circularized *yet*, given the age of the system [10]. This assumption requires nevetherless the tides to be much weaker than in comparable Solar System planets.

Alternatively, many authors proposed that the eccentricity of GJ 436b is sustained by secular perturbations by an outer massive planet, despite strong tides. The long term radial velocity data of GJ 436 reveal indeed a possible drift in addition to the orbital signal of GJ 436b [11] that could be due to a more distant, probably Jovian sized planet, with still unconstrained characteristics. Could such a planet efficiently sustain the high eccentricity of GJ 436b? [12] suggested a mean-motion resonance configuration with GJ 436b, but dynamical calculations by [10] showed that GJ 436b's eccentricity cannot be sustained this way. Incorporating the tides leads inevitably to damp all the eccentricity modulation and to circularize the orbit. [2] found that this effect can be considerably delayed if the two planet system lies initially in a specific configuration where the eccentricities of the two planets are locked at stationary points in the secular dynamics diagram. This requires both planets to assume very specific eccentricity values.

We present here an alternate model based on Kozai resonance (or Kozai mechanism), assuming again a distant perturber. Kozai mechanism is a major dynamical effects in non-coplanar systems that can trigger eccentricity modulations up to very high values [9, 7]. Basically, we suggest the presence of a distant giant planet perturber to GJ 436b, but we assume that both planets are not coplanar. If the initial inclination is high enough, then in a pure 3-body dynamics, GJ 436b's orbit is subject to drastic secular evolution that drives its eccentricity to very high values while its inclination is subject to large amplitude modulation.

We first present calculations starting from the present day orbit of GJ 436b and a giant inclined pertuber. We show that in any case, the Kozai mechanism cannot overcome the damping effect of tidal friction. With such a small orbital period, Kozai resonance appears to be overriden by both General Relativity precession and tides. As a result, the circularization time of the planet appears almost unaffected with respect to a situation without any perturber.

We suggest then that GJ 436b's orbit used to be much wider initially, and that it was furthermore subject to major evolution in the past. We show that if we assume an initial orbit 5–10 times wider than today, then the Kozai dynamics is now strong enough to initiate eccentricity/inclination Kozai cycles, despite the presence of tides and General Relativity. The orbital evolution of GJ 436b is then the following: We have a first phase characterized by Kozai cycles with a slow gradual evolution. Indeed, in high eccentricity phases of the cycles (and thus small periastron) the tides are now strong enough to play a role and slighly modify the orbit of the planet. Basically, the semi-major axis gradually decreases in a kind of stroboscopic manner, with tides acting only in high eccentricity phases of the Kozai cycles. Meanwhile the bottom eccentricity of the Kozai cycles slightly increases. At some point this phase ends and the planet gets out of the Kozai resonance with a high eccentricity. Then begins a second phase characterized by a steeper tidal orbital decrease that drives GJ 436b it to its present day location.

Dynamically speaking, this two-phase mechanism

was already described by [14] and [6]. We apply it here to the GJ 436 case, incorporating it into a symplectic N-body code [3]. For the first time we are able to quantify the duration of this process. We show that depending on the characteristics of the assumed perturber, the duration of the first phase (Kozai cycles with tidal friction) can vary by several orders of magnitude. With a $\sim$ Saturn-like perturber located at a few AU from the star, this first phase can last up to several Gyrs. And even in this context, the subsequent orbital decrease phase lasts at least 1 Gyr. We show that this mechanism can explain the present day orbital configuration (semi-major axis + eccentricity) of GJ 436b despite an age of several Gyrs. According to this scenario, GJ 436b would be currently in the middle of the second phase (orbital decrease phase) with an already reduced semi-major axis and a still noticeable eccentricity. The final circularization will still take up to 1 Gyr more.

We then try to explore the parameter space of our model to derive the conditions of its application. Basically, if the perturber is too close or too massive, the mechanism is extremely efficient and the circularization occurs too quickly. If the perturber is either too far away or too small, then the first phase never ends. In some cases there is even no Kozai cycles. In that case the planet remains at its initial location and the orbit does not shrink towards its present day location. There is thus an optimal regime for the mass and the orbital distance of the perturber where the Kozai cycles actually end after a few Gyrs, and when GJ 436b can actually come to its present day configuration despite a system age of several Gyrs.

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