Chaotic Dance of Stellar Spin Caused by a Planet

• **Background:** Many hot Jupiters (extrasolar giant planets in 1-5 day orbits around their parent stars) have been found since 1990s. The origin of these hot Jupiters is still unclear – how did they get so close to their host stars? One promising idea that has been studied is that these planets migrated from an orbit at a few AU (one AU is the Earth-Sun distance), where they formed, to less than 10% of a AU from their host stars, where are now, due to the small, but cumulative gravitational force from a binary companion (a few 100 AU away from the host star) – this is the so-called Lidov-Kozai mechanism.

[Technical note: The binary companion on a highly inclined orbit pumps the planet into an eccentric orbit; tidal dissipation in the planet then circularizes and shrinks the planet's orbit.]

• **Background:** In the last few years, many hot Jupiter systems have been observed to exhibit "spin-orbit misalignment" puzzle: The orbital axis (i.e., the axis perpendicular to the orbital plane) of the planet (hot Jupiter) is misaligned with the rotation axis of their host star; sometimes the two axes are even opposite. This behavior is completely not found in our Solar system, where the rotation axis of the Sun is approximately aligned with the orbital axis of all the major planets [The Solar System alignment is consistent with the long-standing notion (dating back to 18th century philosophers/scientists Immanuel Kant and Pierre-Simon Laplace) that our solar system formed a few billions years ago out of a rotating nebulous cloud — everything rotated in the same direction.]

The above is the results of other researchers' work in recent years.

How to explain this spin-orbit misalignment puzzle? That is where our work comes in.

• **A bit of technical note/background:** A lot of recent theoretical works (by other researchers) have focused on how the planet's orbital axis changes due to the small-force effect from the binary companion [the Lidov-Kozai mechanism noted above] or another planet (gravitational scattering, "secular chaos"). This change of the planet's orbital axis can indeed explain some of the observed spin-orbit misalignments.

• **OUR WORK:** We show that as the planet comes close their host star, it can make the star' spin axis precess (like a spinning top; see the ppt or pdf slides) and more importantly, can make the stellar spin axis change direction in a rather complex – even chaotic, way. For example (see the animations): In some cases, the stellar spin axis follows the planet's orbital axis closely — like a kid closely follows a slowly walking adult; in some other cases, the stellar spin axis does not follow the orbital axis at all, and gets separated (corresponding to a large misalignment angle) — like a kid gets completely separated from the adult if the latter runs too fast. We elucidate in our paper how these different spin evolutions may come about under different conditions (e.g., different planet masses and stellar rotation rates). We show that this complex change/variation of the stellar spin axis plays an extremely important (and starring) role in explaining the observed spin-orbit misalignment. Thus, our work provides a theory (more technical details will be published in a follow-up paper) for understanding of how the stellar spin axis changes under different conditions. This will be helpful for interpreting observations of spin-orbit misalignment of hot Jupiter systems, and will ultimately be helpful for understanding the origin of these enigmatic planets.

[Technical note: While some previous works included stellar spin evolution in the calculations, our paper is the first to quantify different regimes of spin evolution (for different planet mass and stellar spin) and to demonstrate the complex/chaotic behavior of the spin dynamics and its consequence for spin-orbit misalignments.]

• **Another Important Point of Our Paper** (Beyond the interests of Astronomy and Planetary Science): The chaotic change of the stellar spin discovered in our work is similar to other chaotic phenomena found in nature (such as weather and climate, where the outcome may depend sensitively on the initial conditions – the so-called "butterfly effect"). Our finding of "periodic islands in ocean of chaos" is reminiscent of some well-known chaotic systems (e.g. logistic map).

• **An amusing fact:** A star's spin axis can exhibits such a rich and complex variation even though its binary stellar companion is 100's of AU away – this is possible all because of a tiny planet (about 1/1000 of the stellar mass) in the system, which "mediates" the communication between the two stars!