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Obliquity variations of terrestrial planets in habitable zones

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We have investigated obliquity variations of possible terrestrial planets in habitable zones in extrasolar planetary systems, by deriving analytical formulae of obliquity variations in spin-orbit resonant regions as well as in non-resonant regions and statistically studying obliquity variations of a hypothetical terrestrial planet in a habitable zone (HZ) perturbed by a giant planet(s) with these formulae.

Extrasolar planets so far discovered are inferred to be Jovian-type gas giants, however, terrestrial planets could also exist in the extrasolar planetary systems. In order for life, in particular for land-based life, to progress and survive on a possible terrestrial planet in a HZ, small obliquity variations of the planet could be required in addition to orbital stability, because large obliquity variations may cause significant climate change. In general, large obliquity variations are caused by spin-orbit resonance where the precession frequency of the planet's spin nearly coincides with one of the precession frequencies of ascending node of the planet's orbit (Ward 1973,1974, Laskar et al. 1993).

Considering a system that consists of a host star, a hypothetical giant planet(s), and a hypothetical mass-less terrestrial planet, we have derived the analytical formula of obliquity variation amplitude in resonant regions, as well as that in non-resonant regions. In some cases, we compared the analytical formula with numerical integration of the precession equation and found excellent agreement.

Using these expressions, we evaluate the probability for the terrestrial planet to have obliquity variation amplitude larger than given critical values, averaged over the HZ and likely prograde spin periods (the spin-orbit resonance does not occur for retrograde spin). We find that the obliquity of terrestrial planets in a habitable zone is most largely affected by giant planets as far from the habitable zone as the orbits of the terrestrial planets are stable, but not too far from that zone. The obliquity variations are rather small when giant planets are so close that they destabilize the orbits of the terrestrial planets. Small obliquity variations of a terrestrial planet is not necessarily accompanied by its orbital stability.

We applied these statistical arguments to known extrasolar planetary systems. We found about half of the known extrasolar planetary systems show small obliquity variations (smaller than 10 degrees) over the entire HZ. However, the systems with both small obliquity variations and stable orbits in their HZs are only 1/5 of the known systems. Most of them are systems with short-period giant planets. If additional planets are found, they generally tend to enhance obliquity variations. On the other hand, such a large and/or close satellite that significantly enhances precession rate of the spin is likely to reduce obliquity variations of a terrestrial planet on a stable orbit near 1AU. Retrograde spin or large and/or close satellites might be essential for land-based life to survive on a terrestrial planet in a HZ.