# Dynamical effects in planetary systems and their influence on the evolution of life

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**Abstract**

I review some typical dynamical phenomena that occur in planetary systems and have a significant effect on the evolution of life. I also give a brief summary of the currently known techniques for observing exoplanet systems and the corresponding observational biases. I discuss some selection biases that may affect our conception of the probability of life (particularly in the context of dynamical effects).

## 1 Introduction

Any planetary system is absolutely packed with a zoo of dynamical phenomena ranging from macroscopic migrations and violent orbit changes to more intricate and slower wobblings around more or less stationary states and resonances (see, e.g., [1]). The spectre of chaos is always lurking behind the corner (or attacking directly). This is simply inevitable for any gravitational few- or many-body system. Most often such phenomena are presented and indexed in the framework of theoretical dynamics. Here I arrange the topics somewhat differently from an astrobiological point of view.

One classical astrobiological approach is compactly expressed via Drake's formula for the probability of (complex) life:

$$P_{\text{Life}} = \prod_i P_i, \tag{1}$$

where we zoom in on the subfactors of each factor:

$$P_i = \prod_j p_{ij}. \tag{2}$$

For example, the probability factor $P_{\text{Dyn}}$ for complex life to evolve in a dynamically suitable environment is the combination of various different aspects:

$$P_{\text{Dyn}} = p_{\text{Formation}}\, p_{\text{Stability}}\, p_{\text{Impacts}}\, p_{??}\, p_{?!} \ldots.. \tag{3}$$

This approach is more a method of bookkeeping than a practical tool. Outside (and even inside) dynamics, the number of factors and subfactors is large, and their values are poorly known. Indeed, the "determination" of these factors is not possible without interdisciplinary study. A dynamicist cannot work $P_{\text{Dyn}}$ out without a geologist, biologist, etc. I will touch here briefly on some interesting subfactors and their open questions. Before that, I first give a summary of our currently known means of getting information on exoplanetary systems. This information is usually very indirect, requiring sophisticated analysis for its extraction in the first place. This aspect not only poses some observational biases; it can also cultivate conceptual biases particularly so long as the only example we know of a life-supporting planet is the Earth. This naturally affects the weights given to probability (sub)factors, particularly the dynamical ones.

## 2 Exoplanet detection and modelling; corresponding limitations

The first exoplanets were found in 1995, and roughly one hundred systems (and planets) have been detected so far (see links [2], [3]). Below are listed the currently known major observational methods (see also link [4]). Practically all of the known systems were detected with the first technique, while there are as yet only a few sporadic cases of the use of other methods (e.g., [5]). The share of the techniques between numbers two and four is expected to increase sharply in the near future, while the rest are mostly future techniques.

1. Spectroscopy: star's changing line-of-sight velocity due to planet's mass

2. Planet transit in front of the parenting star ([6],[7], [8],[9])
3. Gravitational microlensing (brightness peak by the planet) ([10])
4. Forming systems: visible gaps and warps in protoplanetary discs
5. High-precision astrometry (e.g., the GAIA and SIM missions): wobbling star position ([11],[12])
6. Direct imaging of exoplanets (+nulling interferometry) ([13], [14])
7. Future techniques (who knows how many!)

An example of the last one is the possibility of detecting a planet's magnetosphere (see the article by S. Saar in this volume). The radial velocity methods gives, in principle, the exoplanet's primary orbit parameters (distance from the star, eccentricity) and mass. The other methods (typically combined with the first) can also provide further orbit parameters as well as the planet's size (density) and even composition (spectroscopic analysis).

Since almost all observations to date are due to velocity changes, the results have an inevitable bias for massive planets (several Jupiter masses) close to the star, causing detectable fluctuations in a short time interval. One planet is known to be so close to the star that its atmosphere is literally evaporating [15]. This of course means that these systems tend to be not at all like ours (they also include some very eccentric giant planet orbits). Our system contains mostly near-circular orbits, with rocky small planets closest to the star, and large gaseous giants further away. In the near future (<10 years), terrestrial planets can best be detected/analyzed with transits and microlensing; later also with direct imaging. Thus we still know very little, but in 5-15 years will know much more.

# 3 Some dynamical subfactors

I briefly discuss here the three main areas of dynamical effects, and mention a couple of other minor possibilities. The three areas are concerned with the birth of the planetary system, its evolution through billions of years, and the fact that objects in the system inevitably collide with each other.

## 3.1 Planetary system formation

The formation stages of the system determine the sizes, masses, structures, and compositions of the planets as well as the initial values for their orbits. The most important part of this process is played by the giant Jupiter-like planets mostly composed of gas. As their accretion process evolves from dust and gas through planetesimals to early planet stages, it also largely seals the fate of the smaller planets. For example, "Earth-clone" planets should form in stable orbits in the Habitable Zone (HZ) as well as be large enough and contain suitable materials to be able to support an atmosphere, plate tectonics, and an abundance of volatiles [16]. The giants basically determine whether such a chance is given to the rocky smaller members.

Planet formation is an extremely complex dynamical process and still so insufficiently understood that it is at least as big a question mark as the processes after the primordial stage. Consequently, there are currently several incomplete hypotheses [17]. None of these quite explain why, even though the current observations are biased, the detected exoplanet systems just do not look much like our system that was thought to be something of a solar system prototype. It is not impossible that our system even turns out to be a very special one right from its beginning.

## 3.2 Stability of the system

The stability properties of a planetary system have two somewhat distinct categories: large and small scale instabilities. The large scale end comprises processes that completely alter the structure of the system, such as planet migration and violent few-body interactions. The former is usually thought to happen during the primordial stages due to the interaction between the planet and the still existing (continuously fading) protoplanetary disc, typically forcing a giant planet to move closer to the star. Dramatic few-body interactions are also thought to be more typical of the early stages, but they are in principle possible at any time due to the chaotic behaviour of the gravitational system. Such events may leave a giant planet in a very eccentric orbit (and even hurl another planet out of the system). All the above dynamical processes involve large bodies roaming around the system and are thus very probably fatal to the stability of smaller Earth-like bodies. We now know that our system is not the dynamically typical one: apparently most of the discovered systems have indeed gone through violent dynamical stages, ending up with "hot Jupiters" or Jovian planets in eccentric orbits.

So is even our solar system really stable? This brings us to small-scale instabilities. Obviously our system is not manifestly chaotic for planet-size objects: the fossil record indicates that the Earth has not suffered macroscopic orbit changes for billions of years, which implies that the other planets have been well confined to their near-circular orbits as well. This is also consistent with numerical orbit integrations. But even if there are no macroscopic changes, how likely is a system to be stable enough to support near-circular terrestrial orbits within the Habitable Zone for a long period of time? This question is the big mathematical problem that actually gave birth to modern dynamics and chaos theory via Poincaré and others at the turn of the 19th and 20th centuries when it was understood that the classical "safe" Lagrange-Laplace solution had to be extended [1]. Indeed, even our solar system is chaotic on a long enough timescale.

Chaos and dynamical instabilities are typically caused by the dynamical resonances between various orbit parameters of gravitationally interacting planets; these resonances are again mostly dictated by the giant planets. Thus each "macroscopically stable" system has its own set of resonances that may easily lead to faster and stronger small-scale chaotic fluctuations than in our solar system. So far only a few tentative stability studies have been performed on the detected systems [18], some of which may be stable enough for terrestrial planets.

Dynamical effects can also be influential in a planet-satellite system. It could be that a suitable satellite is required to keep a planet's rotation axis at a small and stable orbital plane tilt. Without the Moon, the Earth's axis tilt could vary up to 90° within tens of millions of years which would cause severe climate changes [19]. Also, a large portion of stars belong to a binary or multiple star systems, in which stable orbits are obviously much rarer than in single-star planetary systems.

### 3.3 Comet and asteroid impacts on planets

Giant planets dictate the dynamics of planetary systems in several ways. One more aspect is the "cleaning" of the system of small-body orbits that frequently reach its inner parts. For example, without Jupiter there could be extinction-level impacts on the Earth every 100 000 years instead of 100 000 000 years [20]. Jupiter's mass causes many errant comets or asteroids to collide with it, plunge to the Sun, or be hurled out of the system. Frequent fatal impacts would kill most complex lifeforms before they could reach the stage of creating civilizations.

On the other hand, impacts may have played pivotal role in rapid proliferation of life. Massive impacts may actually speed up evolution and the emergence of more complex species: after all, if dinosaurs had survived, mammals would not dominate now.

### 3.4 Other phenomena

There are probably many more minor dynamical phenomena in store, we just do not know them yet. For example, for stars less massive and thus cooler than the Sun, HZ is closer to the star. Thus the tidal forces are stronger, and consequently the planet could reach tidal locking with the star in a relatively short time. Having one half of the planet in light and the other in darkness for very long periods is perhaps not favourable to complex life. Another example is the dynamical environment for efficient transportation of amino acids and other "life-seeding" material across interplanetary distances, a potentially important mechanism for bringing life to an originally lifeless planet (due to the extreme conditions during its formation) that has become a good host for life.

## 4 Anthropocentric bias?

Terrestrial planets were mentioned several times above, but can (complex/intelligent) life develop in non-terrestrial conditions? The fact that we find the Earth to be such a perfectly tuned blue-green planet may be explained simply by the fact that if we did not live in a solar system like ours, there would not be such a planet to be observed by such creatures. In this sense the beautiful stability and order of our solar system may be a manifestation of the anthropic principle (usually connected with physical laws and the universe at large). However, we do not know anything about other possible types of life on planets other than stable blue-green ones, so we should not introduce a planetary anthropocentric bias.

For example, the completely unterrestial moons of giant planets may well harbour life. In a Jovian-like system, tidal forces can produce heat for billions of years, so global solar system stability or circular "HZ orbits" are perhaps not essential for the existence of life. To borrow terms from dynamical terminology, perhaps the terrestrial requirements represent just a very small and special "island of stability" in the biological parameter space. There may well be larger islands in completely different parts of that space. The main question is whether complex/intelligent life is unique to this special island and thus vulnerable to dynamical effects.

## 5 Discussion

As noted earlier, the "Drake approach" is all but useless in the quantitative sense. For $P_{\rm Dyn}$ alone, we easily have, say, 5-15 dynamical subfactors. Even $50\%^{10}$ only gives 0.1%, while $70\%^{10}$ already yields 3% – but $20\%^{10}$ only the meagre 0.00001%. Reliable probability estimates are thus probably never possible. All we can say is that the more factors we come up with, the tougher the case for Life Everywhere becomes at least for one galaxy.

It is perhaps best to avoid speculation. Rather than guess at *a priori* probabilities, we should estimate *a posteriori* probabilities: which detected systems might be capable of supporting (complex) life? We will soon know hundreds or even thousands planetary systems, and the various detection techniques will make sure that the sample is less biasd than it is now. Taking this set as a representative one, we should be able to evaluate the probability of terrestrial conditions and perhaps think of other potential life-supporting scenarios.

# References

[1] Murray C.D., Dermott S.F., 2001, *Solar system dynamics*, Cambridge University Press.

[2] `www.obspm.fr/encycl/encycl.html`

[3] `www.astro.helsinki.fi/seminars/exo/lisasivu.shtml`

[4] `http://astro.estec.esa.nl/SA-general/Projects/Staff/perryman/planet-paper.pdf`

[5] Konacki M. et al., 2003, *Nature* **421**, 507

[6] `http://bigcat.ifa.au.dk/Roemer/en/nush0.html`

[7] `www.kepler.arc.nasa.gov/`

[8] `http://smsc.cnes.fr/COROT/`

[9] `http://spdext.estec.esa.nl/home/eddington/`

[10] `www.nd.edu/~srhie/MPS/`

[11] `http://sci.esa.int/home/gaia/`

[12] `http://planetquest.jpl.nasa.gov/SIM/sim_index.html`

[13] `http://ast.star.rl.ac.uk/darwin/Welcome.html`

[14] `http://planetquest.jpl.nasa.gov/TPF/tpf_index.html`

[15] Vidal-Madjar A. et al., 2003, *Nature* **422**, 143

[16] Levison H.F., Agnor C., 2003, *Astron. J.* **125**, 2692

[17] Falk D., 2003, *Nature* **422**, 659

[18] Jones B.W., Sleep P.N., 2002, *Astron. Astrophys.* **393**, 1015

[19] Laskar J., Robutel P., 1993, *Nature* **361**, 608

[20] Wetherill G.W., 1995, *Nature* **373**, 470

# 6 The most important concepts

- Line-of-sight or radial velocity = the speed component of an object away from or towards us, usually measured using the Doppler phenomenon
- Transit = passage of a planet across the disc of a star
- Microlensing = a relativistic effect that focuses the ligt rays from on object due to the gravity of a body between us and the object
- Protoplanetary disc = the primordial disc around a star from which planets are formed
- Astrometry = the accurate determination of a target's position on the sky (celestial sphere)
- Interferometry = the use of the physical phenomenon of light interference for gathering indirect information on scales smaller than direct image resolution
- Eccentricity = the size of the deviation of an elliptic orbit from a circular one
- Planetesimal = an ever-increasing lump of matter formed by accretion inside the protoplanetary disc; planets are formed as such lumps gradually collide with each other and form larger masses
- Habitable Zone (HZ) = usually associated with the orbital zone in which water on a planet can remain liquid (neither too close to nor too far away from the star); more refined definitions take other terrestrial conditions into account
- Tidal force = close enough to a massive body, different parts of an orbiting body experience different gravitational pulls, resulting in a net stretching force across the body
- Tidal lock = when the stretching tidal forces operate long enough, they produce a state in which the rotation period of a body around its axis equals its orbital period