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GALACTIC HABITABILITY AND STELLAR MOTION

B. VUKOTIĆ
Astronomical Observatory, Volgina 7, 11060 Belgrade, Serbia
E–mail: bvukotic@aob.rs

Abstract. One of the key factors of both, galactic and Galactic habitability, is the movement of stars. Stellar flybys can influence the stability of planetary systems and possible matter exchange between the individual stellar systems. The recent detection of interstellar objects, Oumuamua asteroid and comet 2I/Borisov, leads to estimates that about ten such objects are present in the Solar system at any instant. In addition, the indications of stellar migrations within the Galactic disk imply that individual stellar systems may experience different Galactic environments during their lifetimes. Advanced models of Galactic habitability should appreciate these factors. We consider the potential for capturing the interstellar objects and stellar migrations, given the overall distribution of stars in the Galactic disk and re-assess the recent findings on Galactic habitability.

1. INTRODUCTION

Planet Earth and the Solar system are an integral part of the Milky Way galaxy. It is a well established notion that galaxies interact with each other and evolve and change over time. Even isolated galaxies are subjected to evolutionary changes being the aggregates of evolving stellar populations and gaseous and dust content , together with the evolution of Cold Dark Matter Halo (CDMH) as well. Even in the case of isolated galaxies where most of the CDMH evolution was finished in the very early epochs, some of them could unfold slow enough to have some impact in the later epochs, when the galaxy under consideration is already habitable.

Habitability of a particular planet can not be considered as an isolated phenomena, particularly on timescales that are relevant for galactic processes. On the other end of the scale, the galaxies are the most pronounced constituents (visual) of the Universe and their evolution is conditioned with cosmological parameters.

A life on Earth, or on any other planet, can not be fully comprehend if studied as an isolated phenomena against the rather “empty” vastness of interstellar space and cosmological galaxy-less voids. The traces of microbial activity date back to > 3.7 Gyr ago (Dodd et al. 2017). This establishes biological evolution at time scales of billions of years, similar as the timescales of galactic evolution.

We are yet to find out what life is. So far we know what it is not and we are very good in perceiving the material manifestations of life, its matter dwelling. Because of the constant interaction with its physical environment, manifesting through multiple feedback cycles and influences, life could then be viewed as a part of the overall evolution of matter in the Universe.

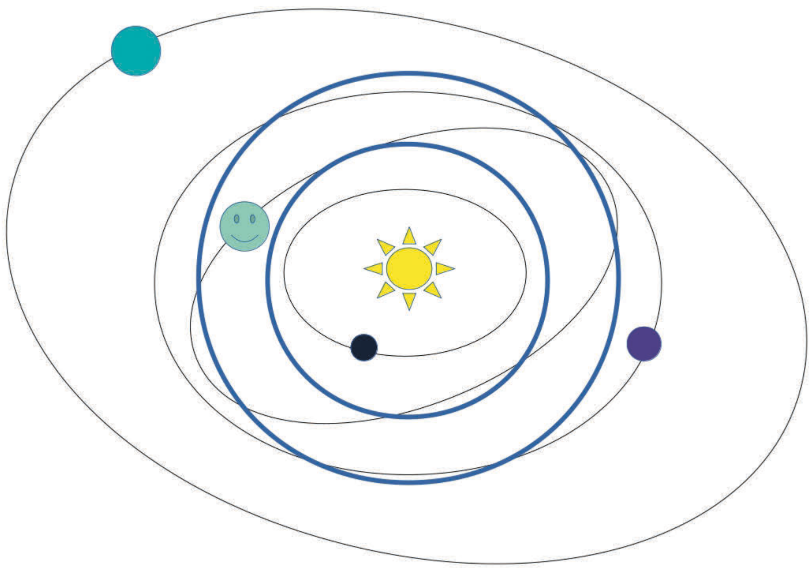

Figure 1: Schematic representation of the Circumstellar Habitable Zone.

The material part, or material foundation of a biosphere dwells in the planetary host. Earlier considerations of life being wide-spread in the Galaxy were significantly boosted by the discovery of exoplanet(s) (Mayor & Queloz 1995) – surely worth the Nobel Prize in physics for 2019. With the increasing number of newly discovered exoplanets, especially thanks to the Kepler space mission, people started to wonder which one of them might be habitable. Because of the importance of Sun for life on Earth creating a lush biosphere, it was a logical step to consider the habitability of exoplanets with a model that highlights the importance of the host star for defining the habitable parts of the planetary system.

First such models of planetary habitability were models of Circumstellar Habitable Zone (CHZ). Simply viewed as the distance from the host star where the radiation field of the star enables the black body approximated planet to attain temperatures indicative of liquid water:

$$\sigma T_{\mathrm{p}}^4 = L_*/(4\pi d^2), \tag{1}$$

where the planet's temperature T_{p}, depends on stellar luminosity L_* and distance d from the star. A simple schematic representation of the CHZ is depicted in Figure 1. In the planar-like shape, that characterizes the planetary systems, such a constraint appear like an annular ring centered on the host star, with the inner edge characteristic of T_{p} values that can efficiently evaporate planetary water content, while at the outer boundary T_{p} drops to water freezing point. We note here that sufficiently small eccentricities (circularized orbits) are assumed. Close stellar passages and major planetary migrations are likely to lead to strong build-ups of eccentricity, which subsequently might take quite a long time to circularize. The later improvements of such concept added the effect of the planetary atmosphere and radiogenic heating.

While this surely moved the position of the boundaries, it did not change the overall shape of the CHZ. It is also evident that even the evolution of stellar luminosity would only also change just the extent but not the shape. In the next section, we describe how the galactic habitability in general and also the habitability of the Milky Way in particular, were introduced starting from similar principles used in CHZ models.

2. GALACTIC HABITABILITY MODELING

In the case of abiogenesis the galactic conditions should be critical for the formation of habitable planets and their respective stellar hosts, in addition to required subsequent continuity in habitable conditions. This might give more weight to galactic "climate"[1] at the immediate environment of the biosphere, but could also be misleading in comprehending abiogenesis and life development in other parts of the galaxy which is very relevant for modern SETI studies. In addition, the panspermia hypothesis assumes slow wide spreading of life which also requires the global consideration of galactic conditions.

The galaxies, as the main constitutional units of matter in the Universe, are focal points for life evolution studies in cosmological context. The evolution of galaxies and related phenomena are thus the key to understand the overall evolution of life. The evolution of galaxies considered in habitability context include the evolution of galaxies in general but also the evolution of Milky Way. This follows essentially from the Copernican principle suggesting that we should treat our Galaxy as a typical kind of habitat for life, unless we have some evidence to the contrary. Of course, such evidence can only be found, in the first place, by looking into what particular properties of galaxies are indeed relevant to life and intelligence, so the problem is not trivially simple as sometimes looks (and is, rather carelessly, dismissed). For instance, it may be the case that star-formation in the Milky Way is somewhat more quiescent than in an average large spiral galaxy (Hammer et al., 2007), although this was before the discovery of Fermi superbubbles, so should be taken with a grain of salt. In any case, we should be on constant watch for anything atypical or "special" as far the Galaxy is concerned.

A robust CHZ model presented in the previous section, greatly influenced the first models of the galactic habitability. By replacing the role of host star radiation gradient with the gradient of galactic metallicity, as the primary parameter that describes the availability of material for the formation of planets (Gonzalez et al., 2001), the Galactic Habitable Zone (GHZ) appeared also as an annular ring-shaped area in the plane of the Milky Way disk that encompass Sun's Galactic orbit.

However, very soon, it became clear that other factors might interfere with such a simplistic initial view of galactic habitability. While certain amount of metals makes the available material for the formation of planets, the metallic content also enables efficient cooling of the proto-planetary disc and hence more gas is available for accretion onto planetary cores and giant planet formation. Migrations of such planets can interfere with the habitability of Earth-like worlds (Lineweaver, 2001).

Another habitability constraint might come from stellar fly-buys, that can disrupt the orbits of planets with life and disable habitable conditions on their surfaces, along

[1] As with the case of the Earth system and our everyday experience, climate both consists of local and short-term (weather) conditions, and is not entirely reducible to such conditions.

the lines of the CHZ modeling approach. In addition, an intense radiation from a nearby stellar explosion could significantly erode atmospheres of planets within distances of up to $\sim 10^3$ pc affecting their potential to accommodate surface life.

Depending on the implementation way of relevant Galactic parameters, their adopted values and habitability relevance, the GHZ models gave diverse predictions. Early conservative approach by Lineweaver, Fenner and Gibson (2004) positioned the GHZ ring between 7 and 9 kpc. According to Gowanlock et al. (2011), central parts of the Galactic disk were hosting the higher numbers of habitable planets and GHZ was more pronounced in the inner parts of the Galactic disk. Prantzos (2008) made a re-assessment of GHZ modeling and the resulting Galactic habitability constraints indicating that it might be likely that the whole Galactic disk might be hospitable to life. For more studies that also include GHZ habitability modeling see also Peña-Cabrera & Durand-Manterola (2004), Spitoni et al. (2014) or Legassick (2015).

Unlike in the case of CHZ models, large number of parameters that are relevant for galactic habitability made no census on the GHZ constraints, which was particularly relevant for SETI studies and possible Fermi Paradox solutions. The main goal of probabilistic based approaches (Đošović et al., 2019; Vukotić & Ćirković 2012) was to examine the available space of astrobiological parameters within a single modeling platform. While the work of Đošović et al. (2019) was focused on the rectifying the values of relevant timescales that fit into our current perception of Galactic life, a Probabilistic Cellular Automata (PCA) approach from Vukotić & Ćirković (2012) included a spatial spreading aspect of possible advanced civilizations in our galaxy.

The PCA was evolved on a 2D grid, with grid cells having one of the four states indicating the astrobiological complexity from 0 – no life to 3 – a civilization with colonization capacity (Figure 2, left). The intrinsic evolution of cells towards the states of higher complexity was constrained by the beamed radiative explosion events (indicative of gamma-ray bursts) and also with omni-directional radiation from events of smaller magnitude (supernovae or even magnetar burst events). Apart from the grid parts with no presence of advanced civilizations, the results also showed a percolated clusters of civilizations spreading which both fits into our current perception of Fermi Paradox (Figure 2, right).

3. STELLAR MOTION AND GALACTIC HABITABILITY

All of the galactic habitability models presented above lack the direct implementation of stellar motion, i.e. stellar dynamics. The mounting evidence of stellar migrations (e.g., Roškar et al. 2012) highlighted that stars can make significant radial migrations during their lifetimes, i.e. change the galactocentric distance of their orbits. Together with the vertical motions of the planetary systems in respect to the plane of the galactic disk, this significantly changes the galactic environment imposed onto the habitable planets. All this clearly puts the question of life into cosmological context and pronounce the need to conduct modern habitability studies including evolution of galaxies and their interactions within the cosmological framework.

One of the best tools to implement stellar dynamics in habitability studies are N-body simulations of individual galaxies and also cosmological simulations of structure evolution on a larger scale. The use of this tool for habitability studies of isolated Milky Way like galaxy was presented in Vukotić et al. (2016). The results indicated that the outward motion of galactic stellar component makes the outer parts of the

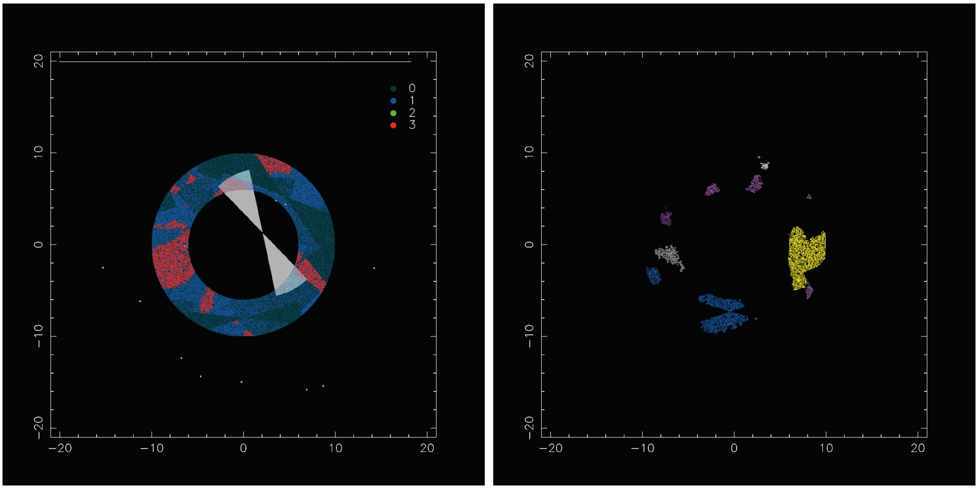

Figure 2: Axis designate the galactic distance in kpc. Left: A late epoch (a white line just below the top axis represent time from the beginning of the run) PCA snapshot from the model described in Vukotić & Ćirković (2012). White areas present radiation events that constrain the evolution of astrobiological sites towards higher complexity. The cell states are coded as 0-no life, 1-simple life, 2-complex life and 3-advanced life. Right: The clusters of advanced civilizations (state 3 of PCA grid cells) at the end of the simulation run. Color coding represents different clusters of state 3.

galactic disk $\sim 10 - 15$ kpc populated with stars that have the highest probability of being habitable. A similar result was reached by Forgan et al. (2017), performing the analysis of cosmological simulation of the Local Group. They also find a significant habitability of dwarf satellite galaxies.

These were much different habitability landscapes when compared with the ones from the first studies of galactic habitability. Also, other prominent works that inspect galactic habitability in the cosmological context were by Dayal et al. (2015), Gobat & Hong (2016), Stanway et al. (2018) and also Stojković et al. (2019ab). This further changed our notions of habitability distribution, e.g. Zackrisson et al. (2016) reported that a typical earth-like planet in a local universe is located in a galaxy that is dominated by a spheroid shape a with a stellar mass comparable to the stellar mass of our Galaxy. Clearly, the introduction of dynamical aspect of galactic evolution and a wider, cosmological perspective, have significantly change our views of galactic habitability than the ones that have emerged from the pioneering studies.

The habitability concerns from nearby stellar encounters were discussed in Jiménez-Torres et al. (2013). Apart from a possibility to disrupt planetary orbits they could also lead to matter exchange between the planetary systems and hazardous small body encounters.

The recent discovery of extrasolar visitors in the Solar system, an asteroid like object Oumuamua (Meech et al. 2017) and a comet 2I/Borisov (Guzik et al. 2019, Guzik et al. 2020), demonstrate that evolution of the habitability of individual planetary systems should account for their galactic environment. A study by Bailer-Jones et al. (2020) integrated the orbits of stellar neighborhood stars from GAIA DR2 data to argue that 2I/Borisov might have been picked up in the Solar interstellar encounter occurring 910 kyr ago. A similar analysis was performed earlier for Oumuamua (Bailer-Jones et al. 2018a). This approach was also used to predict the 20 stellar nearby passages within 1 pc from the Sun per Myr (Bailer-Jones at el. 2018b).

The possibilities for the exchange of matter during stellar encounters, described above, except their direct relevance for galactic habitability, also raise another aspect that is important for galactic habitability concerning the question of origin of life. The panspermia hypothesis (as reviewed in Vukotić et al. 2021) heavily depends on the possibility of matter exchange. On the other hand, even the abiogenesis might depend on the disturbance of asteroidal belts and volatiles delivery on the rocky planets (for water delivery by asteroids on the planets in TRAPPIST-1 system see Đošović et al. 2020 and references therein). A hypothesis that cycles of hydration and dehydration are crucial for synthesis or encapsulated organic material, possibly occurring near hot springs is presented in Damer & Deamer (2020). It should be also noted here that, in contrast to pure matter transport, panspermia is inherently nonlinear phenomenon: a small cause can cause large consequences. Even the directed panspermia (in the most general sense, which includes colonization of other planetary systems by evolved civilizations) could be included in the wider picture. A very small initial shift in abiogenesis could lead to transformation of the large parts of the Milky Way!

4. A HYBRID APPROACH

The extent of exploiting the dynamical aspect of the habitability modeling clearly depends on the stellar mass resolution that is achieved in the models (simulations). The simulations with mass resolution on a single star level are still not achieved, even for isolated galaxies. The reported masses of stellar component in such N-body simulations are usually at 10^4 $M_\odot$, which is a mass indicative of a stellar cluster.

However, a conceptual aspect, readily found in meteorology, would still be at stake. Even at unrealistically high resolution in mass and time, there would still remain a random component that would make a difference between actual and simulated values. This highlights the need for statistical approach that uses multiple simulation runs which raise the computing requirements even higher. A possibility to achieve higher mass resolutions, with multiple run allowance, might be to make models that use analytic potential in the cosmological framework of numerically generated potential. An analytical approximation might then be used to generate galactic trajectories of individual stars for a given epoch in order to obtain the galactic habitability landscape of higher resolution. As argued in Stojanović (2015), the data from a GAIA mission, on components of stellar motion, can be used to calculate realistic stellar orbits in a given Galactic potential.

There is a significantly more stars in the Milky Way ($\sim 10^{11}$) then the typical number of particles used in an N-body simulation of an isolated galaxy ($\sim 10^7$). Calculation of stellar orbits in an analytic potential might offer the means to bridge this gap in terms of required computation times. According to Stojanović (2015), a highly efficient calculation can be achieved for stars with regular galactic orbits, e.g. nearly circular orbits of thin disk stars from the Solar neighborhood. Another important aspect is that the ambition for GAIA is to ultimately have about 10^9 objects, which is far more representative than the Solar vicinity. Therefore, on its basis one could precisely calculate how typical our immediate environment is in terms of particular parameters of interest for astrobiology, e.g., the distribution of stellar metallicities, multiplicity, etc.

5. SUMMARY

The studies of galactic and Milky Way habitability have significantly matured in the past two decades. It is now clear that the robust results can be achieved relying on a cosmological framework of evolution of galaxies and not just on a simple circumstellar-like habitability model that was extensively used in the pioneering studies of galactic habitability.

The emerging picture of galactic habitability turn out to be much more complex than previously thought. The motion of stars within a galaxy at timescales of several Gyr is one of the key factors that should be studied to a greater extent in the context of habitability and galactic environments that these stellar systems are subjected to. Also, individual planetary systems should not be considered as an isolated chunks of habitable matter within the rather empty interstellar space. The recent discovery of extrasolar bodies that are passing through our Solar system shows that habitability concerns clearly reach beyond the confinement of Sun's influence.

This lecture proposed that a detailed models of stellar motion that include cosmological effects of galactic evolution and interaction might be computationally realized with the use of hybrid models that mix analytical and numerical approaches. The future studies of galactic habitability should consider this kind of modeling.

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