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DYNAMIC HABITABILITY OF EXTRASOLAR PLANETARY SYSTEMS

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Abstract. In this paper, we estimate the likelihood to find habitable Earth-like planets on stable orbits for the extrasolar planetary systems ε Eridani, 55 Cancri, 47 Ursae Majoris, and ρ Coronae Borealis and provide a new tool to assess habitability of extrasolar planetary systems. For determining the habitable zone in these systems an integrated system approach is used taking into account a variety of climatological, biogeochemical, and geodynamical processes. Habitability is linked to the photosynthetic activity on the planetary surface. We find that habitability strongly depends on the age of the stellar system and the characteristics of the Earth-like planet. In particular the portion of land/ocean coverages plays an important role. In general, a high percentage of ocean area significantly increases the probability for habitability of planets on stable orbits in extrasolar planetary systems. We show that the systems ε Eridani and 55 Cancri are most promising to find dynamic habitable Earth-like planets, while the system ρ Coronae Borealis is most unpromising.

Key words: extrasolar planets, geodynamics, habitable zone, orbital stability, planetary climate.

1. Introduction

The search for extrasolar Earth-like planets is one of the main goals of present research. More than 150 extrasolar giant planets are known to orbit around Sun-like stars including several multiple-planet systems. These giant planets, with hydrogen and helium as the main constituents, have atmospheres too turbulent to permit the emergence of life and have no underlying solid surfaces or oceans that could support a biosphere. The distribution of masses of all known exoplanets lets scientists suppose that there must be a multitude of planets with lower masses (Marcy et al., 2003). The existence of Earth-type planets around stars other than the Sun is strongly implied by various observational findings including (1) the steep rise of the mass distribution of planets with decreasing mass, which implies that more small planets form than giant ones; (2) the detection of protoplanetary disks (with masses between 10 and 100 times that of Jupiter)

around many solar-type stars younger than ~3 Myr; and (3) the discovery of "debris disks" around middle-aged stars, the presumed analogs of the Kuiper Belt and zodiacal dust (Marcy and Butler, 2000 and references therein).

Even if it seems today beyond the technical feasibility to detect Earth-mass planets we can apply computer models to investigate known exoplanetary systems to determine whether they could host Earth-like planets with surface conditions sufficient for the emergence and maintenance of life on a stable orbit. Such a configuration is described as dynamically habitable. Jones et al. (2001) have investigated the dynamical habitability of known exoplanetary systems. They used the boundaries of the habitable zone (HZ) originating from Kasting et al. (1993). The inner boundary is defined as the maximum distance from the star where a runaway greenhouse effect would lead to the evaporation of all the surface water, and the outer boundary as the maximum distance at which a cloud-free CO_2 atmosphere could maintain a surface temperature above 0°C. To test the intersection of stable orbits and the HZ, putative Earth-mass planets were launched into various orbits in the HZ and a symplectic integrator was used to calculate the celestial evolution of the extrasolar planetary system. In this paper, we adopt a somewhat different definition of HZ already used by Franck et al. (1999, 2000a, b). Here habitability (i.e., presence of liquid water at all times) does not just depend on the parameters of the central star, but also on the properties of the planet itself. In particular, habitability is linked to the photosynthetic activity of the planet, which in turn depends on the planetary atmospheric CO_2 concentration, and is thus strongly influenced by planetary geodynamics. This leads to additional spatial and temporal limitations of habitability, as the stellar HZ (defined for a specific type of planet) becomes narrower with time due to the persistent decrease of the planetary atmospheric CO_2 concentration.

2. Habitability of Extrasolar Planetary Systems

Hart (1978,1979) calculated the evolution of the atmosphere of a terrestrial planet over geologic time by varying its distance from the Sun. In his approach, the HZ is the region within which an Earth-like planet might enjoy moderate surface temperatures needed for advanced life forms. He found that the HZ ($[R_{inner}, R_{outer}]$) between runaway greenhouse and runaway glaciation is surprisingly narrow for G2 stars like our Sun: $R_{inner} = 0.958\,AU$, $R_{outer} = 1.004\,AU$. A main drawback of these calculations is the neglect of the negative feedback between atmospheric CO_2 content and mean global surface temperature discovered later by Walker et al. (1981).