

Habitable zones and the number of Gaia's sisters

Abstract

We present a general modelling scheme for assessing the suitability for life on any Earth-like extrasolar planet by calculating the habitable zone (HZ) in main-sequence-star planetary systems. Our approach is based on an integrated Earth system analysis that relates the boundaries of the HZ to the limits of C4-photosynthesis processes. Within this model, the evolution of the HZ for any main-sequence-star planetary system can be calculated straightforwardly, and a convenient filter can be constructed that picks the candidates for photosynthesis-based life from all the extrasolar planets discovered by novel observational methods. These results can be used to determine the average number of planets per planetary system that are within the HZ. With the help of a segment of the Drake equation, the number of "Gaia's" (i.e., extrasolar terrestrial planets with a globally acting biosphere) can be estimated. Our calculation gives about two million Gaia's in the Milky Way.

wardly, and a convenient filter can be constructed that picks the candidates for photosynthesis-based life from all the extrasolar planets discovered by novel observational methods. These results can be used to determine the average number of planets per planetary system that are within the HZ. With the help of a segment of the Drake equation, the number of "Gaia's" (i.e., extrasolar terrestrial planets with a globally acting biosphere) can be estimated. Our calculation gives about two million Gaia's in the Milky Way.

Integrated systems approach for an extrasolar Earth-like planet

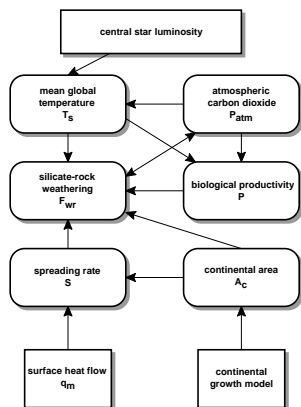


Fig. 1: Integrated system box model. The arrows indicate the different forcings and feedback mechanisms (Franck et al., 2001).

Results for the HZ

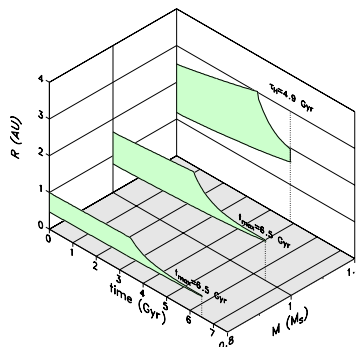


Fig. 3: Graphs of the width and position of the HZ derived from the geodynamic model for three different stellar masses M (0.8, 1.0, 1.2 M_{\odot}). t_{max} is the maximum life span of the biosphere limited by geodynamic effects. τ_H indicates the hydrogen burning time on the main-sequence limiting the lifespan of more massive stars (Franck et al. 2001).

Drake estimation

The Drake equation was first presented by Drake in 1961 to estimate the number of technological civilisations that might exist among the stars. From our view of Earth system analysis we will focus on an estimation for the contemporary sisters of Gaia in the Milky Way on the base of a subset of the Drake equation. These are habitable planets with a biosphere interacting with its environment on a global scale, denoted by N_{Gaia} :

$$N_{Gaia} = N_{MW} \cdot f_p \cdot n_{CHZ} \cdot f_L \quad (1)$$

where N_{MW} denotes the number of stars in the Milky Way. We use the value $N_{MW} = 4 \cdot 10^{11}$. The fraction of stars with planets is f_p . According to Marcy et al. (2000) we use $f_p = 0.05$. The average number of planets per planetary system which are suitable for the development of life is n_{CHZ} . This number can be calculated directly from our results about the HZ (Franck et al., 2001). We find $n_{CHZ} = 0.012$ which means that only about 1% of all the extrasolar planets are habitable.

Central star luminosity

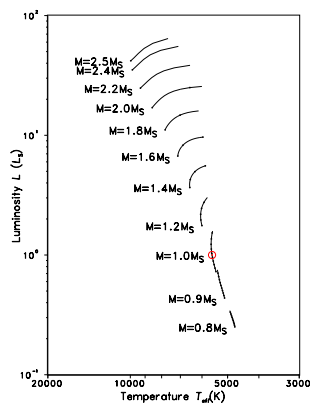


Fig. 2: Hertzsprung-Russell diagram for central stars in the mass range between 0.8 and 2.5 M_{\odot} . Only the main sequence evolution is considered. Successive dots on the mass-specific branches are separated in time by 1 Gyr (Franck et al., 2000).

General results

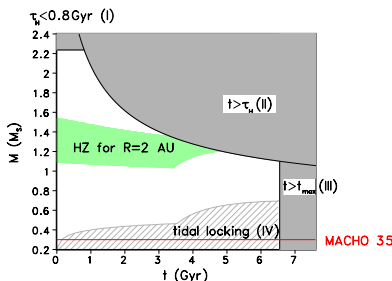


Fig. 4: Shape of the GDM HZ (green shading) in the mass-time plane for an Earth-like planet at distance $R = 2$ AU from the central star. The potential overall domain for accommodating the HZ for planets at some arbitrary distance is limited by a number of factors that are independent of R : (I) minimum time for biosphere development, (II) central star life time on the main sequence, (III) geodynamics of the Earth-like planet, and (IV) tidal locking of the planet (nontrivial sub-domain excluded). The excluded realms are marked by grey shading in the case of the first three factors and by grey hatching for the tidal-locking effect. The horizontal red line represents the hypothetical MACHO-98-BLG-35 planet, which is assumed to orbit a 0.3 M_{\odot} star (Franck et al. 2000).

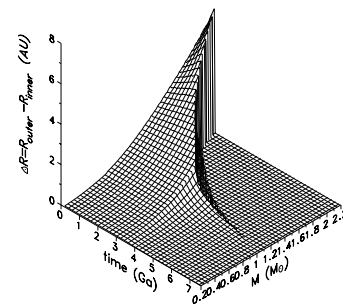


Fig. 5: The width of the HZ, ΔR , given by the geodynamic approach. ΔR is measured in astronomical units (AU).

The fraction of habitable planets where life emerges and a full biosphere develops (f_L) is a topic of controversial discussion. We use $f_L = 10^{-2}$ as a guesswork and as a conservative approximation in comparison to the predominant optimistic view. With the help of the numbers given above we arrive at

$$N_{Gaia} \approx 2.4 \cdot 10^6 \quad (2)$$

which is indeed a rather large number.

References

- Franck, S., von Bloh, W., Bounama, C., Steffen, M., Schönberner, D., Schellnhuber, H.-J. 2000. Determination of habitable zones in extrasolar planetary systems: Where are Gaia's sisters? *J. Geophys. Res.* **105** no. E1, 1651-1658.
 Franck, S., Block, A., von Bloh, W., Bounama, C., Garrido, I., Schellnhuber, H.-J. 2001. Planetary habitability: Is Earth commonplace in the Milky Way? *Naturwissenschaften*, submitted.
 Marcy, G. W., Cochran, W. D., Mayor, M. 2000. Extrasolar planets around main-sequence stars. In: *Protostars and Planets IV*, eds. V. Mannings, A. Boss, and S. Russell, University of Arizona Press, Tucson, pp. 1285-1311.

S. Franck¹, W. von Bloh¹, C. Bounama¹, M. Steffen², D. Schönberner², and H.-J. Schellnhuber¹



¹POTSDAM INSTITUTE FOR CLIMATE IMPACT RESEARCH • P.O. BOX 601203 • 14412 POTSDAM • GERMANY
²ASTROPHYSICAL INSTITUTE POTSDAM • AN DER STRENNWART 16 • 14482 POTSDAM • GERMANY

