THE NUMBER OF HABITABLE PLANETS IN THE MILKY WAY OVER COSMOLOGICAL TIME SCALES

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ABSTRACT

A general modeling scheme for assessing the suitability for life on any Earth-like extrasolar planet is presented. This approach is based on an integrated Earth system analysis in order to calculate the habitable zone in main-sequence-star planetary systems. A new attempt by Lineweaver [1] to estimate the formation rate of Earth-like planets over cosmological time scales is applied to calculate the average number of habitable planets in the Milky Way as a function of time. The combination of this results with our estimations of extrasolar habitable zones yields the average number of habitable planets over cosmological time scales. We find that there was a maximum number of habitable planets at the time of Earth's origin.

1. METHODOLOGY

To estimate the planet formation rate of Earth-like planets in the Milky Way an approach by Lineweaver [1] has been followed. The PFR is derived from the star formation rate and star metallicity as an ingredient for the formation of Earth-like planets. The number of Earth-like planets, *P(t)*, can be calculated from the PFR with the help of the convolution integral

$$P(t) = \int_0^t PFR(t') \times p_{hab}(t - t')\, dt' \qquad (1)$$

where p_{hab} is the probability that an Earth-like planet is habitable:

$$p_{hab}(\Delta t) = \frac{1}{C} N_p \int_{0.8 M_s}^{1.2 M_s} M^{-2.5} \int_{R_{inner}}^{R_{outer}} R^{-1} dR\, dM\,. \qquad (2)$$

C is a normalisation factor resulting from solving Eq.1 between the central-star-mass-dependent minimum and maximum HZ boundaries $0.1 \cdot M/M_s$ AU and $4 \cdot M/M_s$ AU, respectively. In order to estimate p_{hab}, the following assumptions are made:

1. The stellar masses, *M*, are distributed according to a power law [2] $\propto M^{-2.5}$;
2. the distribution of planets can be parameterised by $p(R) \propto R^{-1}$, i.e. their distribution is uniform on a logarithmic scale in the distance, *R*, from the central star [3];
3. R_{inner} and R_{outer} are the inner and outer boundaries of the HZ, respectively. They are explicit functions of the central star mass and the age of the corresponding planetary system [4];
4. the average number of Earth-like planets per stellar system, N_p, is set to 4.

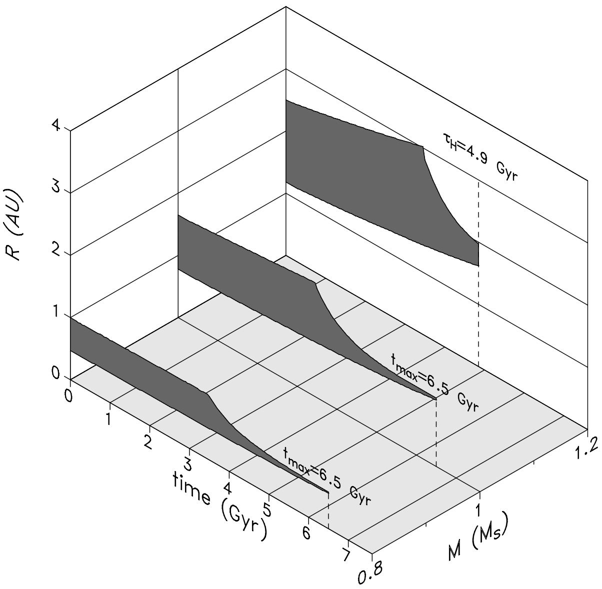

Fig. 1. Width and position of the HZ (grey shaded) as a function of time for three different central-star masses (M = 0.8, 1.0, 1.2 M_s) for an Earth-like planet. t_{max} is the maximum life span of the biosphere limited by geodynamic effects. τ_H indicates the hydrogen burning time on the main sequence limiting the life span of more massive stars.

The time-dependent HZ is derived from an Earth-system model [4]. Previous studies use climatic constraints, e.g. the presence of liquid water at the planetary surface, to assess habitability of planets. Our method defines additional constraints: habitability is linked to photosynthetic activity and strongly influenced by the "geodynamics" of the Earth-like planet.

Photosynthesis-based life with productivity Π is possible if the global temperature is in the tolerance window of [0°C…60°C] and the CO_2 atmospheric partial pressure is greater than 10^{-5} bar. In this way the HZ is the habitable R corridor in time

$$HZ := \{R \,|\, \Pi(P_{atm}(R,\Delta t), T(R,\Delta t)) \succ 0\} \\ = [R_{inner}(\Delta t), R_{outer}(\Delta t)] \quad . \qquad (3)$$

2. RESULTS AND DISCUSSION

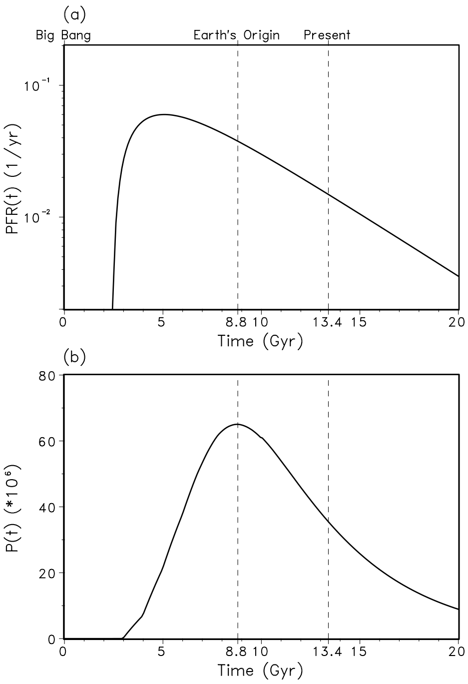

Fig. 2. (a) Earth-like planet formation rate, *PFR*, [1], and (b) number of habitable planets, *P(t)*, as a function of cosmological time for the Milky Way. The vertical dashed lines denote the time of Earth's origin and the present time, respectively.

The HZs for three different central star masses are shown in Fig.1. The HZ is ultimately limited to a time of 6.5 Gyr caused by the decline of volcanic activity and increase of continental area. The results for the calculation of the number of habitable planets in the Milky Way are shown in Fig.2. *P(t)* has a distinct maximum at 8.5 Gyr after Big Bang. This is just before the time of Earth's origin (t=8.8 Gyr). This supports the idea that panspermia might have caused a kick-start to the processes by which life originated on Earth [5]: there is palaeogeochemical evidence of an early appearance of life leaving not more than 1 Gyr for the emergence of life.

3. ACKNOWLEDGEMENTS

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4. REFERENCES

1. Lineweaver C. H., An estimate of the age distribution of terrestrial planets in the universe: quantifying metallicity as a selection effect, *ICARUS*, Vol. 151, 307-313, 2001.

2. Scheffler H. and Elsässer H., *Physics of the Galaxy and Interstellar Matter*, Springer-Verlag, Berlin, 1988.

3. Whitmire D. P. and Reynolds R. T., Circumstellar habitable zones: astronomical considerations, In *Circumstellar habitable zones* (Doyle L. R. Ed.), 117-143, Travis House Publications, Menlo Park, 1996.

4. Franck S. et al., Determination of habitable zones in extrasolar planetary systems: where are Gaia's sisters?, *J. GEOPHYS. RES.*, Vol. 105E, 1651-1658, 2000.

5. von Bloh W. et al., Maximum number of habitable planets at the time of Earth's origin: new hints for panspermia? *ORIG. LIFE EVOL. BIOSPH.*, accepted, 2002.