Planetary Systems in the Universe - Observation, Formation and Evolution
Proceedings IAU Symposium No. 202, ©2004 IAU
Alan Penny, Pawel Artymowicz, Anne-Marie Lagrange, & Sara Russell, eds.

Terrestrial planet orbits in the habitable zones of exoplanetary system

B. W. Jones and P. N. Sleep

Astronomy Group, The Open University, Milton Keynes MK7 6AA, UK

Abstract. We have investigated whether terrestrial planets can exist in orbits in known exoplanetary systems such that life could have emerged on those planets. We have shown that Rho CrB and 47 UMa could have terrestrial planets in orbits that remain confined to their habitable zones for biologically significant lengths of time. We have also shown that the Gliese 876 and Ups And systems are very unlikely to have such orbits.

1. Introduction

The question we have addressed is: 'can terrestrial planets exist in orbits in known exoplanetary systems such that life could have emerged on those planets?'.

The detection of terrestrial planets is beyond present capabilities, and so one can only theorise about their existence. We assume that terrestrial planets could be present in at least some of the exosystems, and we have concentrated on four contrasting systems — Gliese 876, Ups And, and particularly Rho CrB and 47 UMa. Whether life could have emerged on terrestrial planets in any of these systems depends on whether the terrestrial orbits remain confined long enough to the habitable zone of each system.

2. The habitable zone

All life on Earth requires liquid water during at least part of its life cycle. Consequently, it is usual to define the habitable zone (HZ) as the range of distances from a star within which any water at the surface of a terrestrial planet would be in the liquid phase (Kasting, Whitmire, & Reynolds 1993). A variety of criteria have been used to define the boundaries of the HZ. For the inner boundary we use the maximum distance from the star where a runaway greenhouse effect occurs leading to the evaporation of all surface water. For the outer boundary we use the maximum distance at which a cloud-free CO_2 atmosphere can maintain a surface temperature of 273 K. Kasting et al. (1993) have used these criteria in conjunction with climate models to obtain values for the boundary distances for various stars, and we have used these values. The values are conservative because of simplifying features in the models.

For zero-age main-sequence stars (ZAMS stars) the boundaries of the HZ lie closer to the star the later its spectral type. This is because of the combined

https://doi.org/10.1017/S0074180900217841 Published online by Cambridge University Press

effects of the star's lower luminosity and the shift in its spectrum to longer wavelengths.

3. The method of orbital investigation

To establish whether terrestrial orbits could remain confined to the HZ of a system we must investigate the stability of orbits launched in the HZ. We use the second-order mixed-variable symplectic (MVS) integrator contained within the Mercury integrator package (Chambers 1999).

MVS integrators cannot handle close encounters between planets accurately. The smallest distance at which it is safe to use the integrator is about three times the Hill radius of the planet in the encounter with the larger Hill radius. The Hill radius $R_{\rm H}$ is defined as

$$R_{\rm H} = \left(\frac{m}{3M_*}\right)^{1/3} a \tag{1}$$

where m is the mass of the planet, a is its orbital semimajor axis, and M_* is the mass of the star. When the two planets are separated by $R_{\rm H}$ their gravitational interaction is of the same order as the gravitational interaction of each planet with the star, and so considerable orbital modification will occur, particularly for the terrestrial planet in a giant-terrestrial encounter. We halt integration at $3R_{\rm H}$. This not only avoids using the MVS integrator in an inaccurate domain, it is also a conservative definition of the point at which orbits become unstable.

For there to be a stable orbit we require that the $> 3R_{\rm H}$ criterion be met, but this alone is not sufficient. We also require that the orbit remains confined to the HZ, otherwise it is unlikely that life could evolve. We take confinement to mean that the semimajor axis remains in the HZ at all times in an integration that is not halted by a close encounter. An even tighter criterion would additionally restrict the orbits in the HZ to some upper limit of eccentricity, but we have not adopted such a criterion.

We integrate for simulated times between 10^8 and 10^9 years, unless the integration is halted automatically by a close encounter ($3R_{\rm H}$). Ideally we would have liked to integrate all systems for 10^9 years, because for the Earth the biosphere was well established at this age (Chyba 1993). However, in order to avoid integration instabilities, we have shown that the integration time-step needs to be less than one-twelfth of the orbital period of the planet with the shortest period, and so for some systems an integration for 10^9 years would then consume several thousand hours of CPU time on the Compaq Alpha-based workstations used.

4. Results

Details of the four contrasting exosystems selected for study are given in Table 1, where m is the mass of the giant (in Jupiter masses $m_{\rm J}$), $i_{\rm o}$ is the (unknown) orbital inclination, a is the semimajor axis (sma) of the orbit, and e is its orbital eccentricity.

We have found that, up to several times the minimum giant mass, Rho CrB and 47 UMa could have terrestrial planets in orbits that remain confined to their habitable zones for biologically significant lengths of time — for at least a few hundred million years. We also conclude that the Gliese 876 and Ups And systems are very unlikely to have such orbits. To a first order the masses and initial orbital inclinations of the terrestrial planets have little effect on the outcome; it is the mass of the giant, and the initial semimajor axes of all the planetary orbits that matter. When a second terrestrial planet is present, close encounters between the two terrestrial bodies reduce the range of initial semimajor axes for which the orbits are stable.

In 47 UMa mean motion resonances cut strips of instability in the habitable zone. Away from resonances and boundaries between stable and unstable zones there is a tendency for instability in terms of the $3R_{\mathrm{H}}$ criterion to show itself within 10^8 years.

Star			Planet(s)		
name	type	mass/$M_{\odot}$	$m \sin (i_{\mathrm{o}})/m_{\mathrm{J}}$	a/AU	e
Gliese 876	M4V	0.336	2.1±0.2	0.21±0.1	0.27±0.03
Rho CrB	G0Va	1.00	1.1	0.23	0.028±0.04
Ups And	F8V	1.3	0.71	0.059	0.034±0.15
			2.11	0.83	0.18±0.11
			4.61	2.50	0.41±0.11
47 UMa	G1V	1.03	2.41	2.10	0.096±0.03

Table 1. The exosystems selected for study. Comments: Gliese 876 – low mass star ; Rho CrB – small a and e ; Ups And – a family of giants, one with high e ; 47 UMa – most like Solar System

References

Chambers, J.E. 1999, MNRAS, 304, 793

Chyba, C.F. 1993, Geochim. Cosmochim. Acta 57, 3351

Kasting, J.F., Whitmire, D.P., & Reynolds, R.T. 1993, Icarus 101, 108