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Which exoplanetary systems could harbour habitable planets?

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Abstract: Habitable planets are likely to be broadly Earth-like in composition, mass and size. Masses are likely to be within a factor of a few Earth masses – we call such planets Earth-mass planets. It is important to find such planets. Currently, we do not have sufficiently sensitive techniques to detect planets with such small masses, except in rare circumstances. It is thus necessary to model the known exoplanetary systems to see whether Earth-mass planets could be present. In particular, we need to establish whether such planets could be present in the classical habitable zone (HZ), or whether the giant planets that we know to be present have gravitationally ejected Earth-mass planets or prevented their formation. We have answered this question by applying computer models to the 152 exoplanetary systems known as of 18 April 2006 that are sufficiently well characterized for our analysis. For systems in which there is a giant planet interior to the HZ, which must have got there by migration, there are two cases considered: first, the case when the migration of the giant planet across the HZ has not ruled out the existence of an Earth-mass planet in the HZ; second, the case where it has. In the former case we have found that 60% of the 152 systems offer safe havens to Earth-mass planets across greater than 20% of the HZ width. We regard such systems as being habitable today. We have also estimated whether habitability is possible for 1000 Myr into the past (provided that this period post-dates the heavy bombardment of planets in the HZ). Of the 143 systems that are susceptible to this second analysis, we find that about 50% offer habitability sustained over 1000 Myr. If giant planets interior to the HZ rule Earth-mass planets, then 60% and 50% fall to 7% in both cases.

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Introduction

Habitable planets in exoplanetary systems will probably be roughly Earth-like in composition, and many will orbit within the classical habitable zone (HZ), i.e. that range of distances from the star within which water on an Earth-like planet would be liquid over a substantial proportion of the surface. There could also be habitable planets outside the HZ, such as beneath the surface of tidally heated bodies, as might be the case in Jupiter's satellite Europa. However, life at a surface warmed by the star will be far easier to detect from afar, so we have focused our attention on the possibility of Earth-like planets existing in the HZ of each exoplanetary system.

Theories of planetary formation tell us that planets that form within the HZ with Earth-like composition will be within a factor of a few Earth masses. They will consequently not be very different from the Earth in size. We call such planets Earth-mass planets.

Currently, we do not have sufficiently sensitive techniques to detect Earth-mass planets, except in rare circumstances. The imaging of such small, dim planets next to bright stars is well beyond the capabilities of present telescopes. This is also true of giant planets. However, giant planets have been detected indirectly, the radial velocity (RV) technique having been by far the most fruitful. This technique relies on the motion of the star along our line of sight, induced by the orbital motion of the planets around it. The RV is detected via the periodic Doppler shifts of the star's spectral lines. We obtain the orbital period of each planet, the semi-major axis of its orbit and the orbital eccentricity. For the planet itself, we obtain only its minimum mass. A description of the RV technique, and other techniques, can be found in Jones (2004, ch. 9 and 10). Earth-mass planets do not induce enough RV amplitude to be detected at present, unless the star is considerably less massive than the Sun. However, such stars are very dim and thus difficult to observe.

It is thus necessary to model the known exoplanetary systems to see whether Earth-mass planets could be present. Of particular interest is whether such planets could be present in the HZ, or whether the giant planets that we know to be present have gravitationally ejected Earth-mass planets or prevented their formation. We have answered this question by applying computer models to the 152 exoplanetary

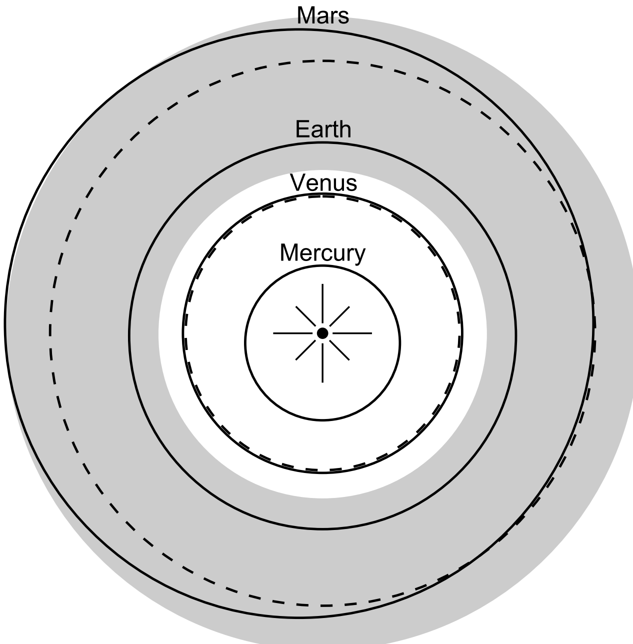

Fig. 1. The HZ of the Solar System using the boundary criteria described in the text (see classical habitable zone boundaries). The shaded annulus is the HZ location today. The dashed circles mark its location just after the birth of the Sun, 4600 Myr ago.

systems known as of 18 April 2006 that are sufficiently well characterized for our analysis (Schneider 2006). For systems in which there is a giant planet interior to the HZ, which must have got there by migration, there are two cases considered: first, the case when migration of the giant planet across the HZ has not ruled out the existence of an Earth-mass planet in the HZ; second, the case where it has.

There are two steps. First, we establish the location of the HZ around a star. Second, we obtain the critical distances interior and exterior to each of its known planets, within which an Earth-mass planet would suffer large orbital changes, ending in ejection or collision. The habitability is then evaluated on the basis of the locations of the critical distances with respect to the HZ.

Classical habitable zone boundaries

We have used boundaries for the HZ derived from the work of Kasting *et al.* (1993). The inner boundary is the maximum distance from the star where a runaway greenhouse effect would lead to the rapid evaporation of all surface water. The outer boundary is the maximum distance at which a cloud-free CO_2 atmosphere could maintain a surface temperature of 273 K. Several other criteria could be used, and the climate model of Kasting *et al.* (1993) is rather simple. However, our choice of boundary criteria gives the outcome for the Solar System shown in Fig. 1, which matches well enough what we know about Venus, the Earth and Mars. Note that the shaded annulus is for the HZ today, and the dashed circles are for the HZ 4600 Myr ago, when the Sun was very young, cooler and with only about 70% of its present luminosity. We thus use Kasting *et al.* (1993) as an empirical way of obtaining a consistent set of HZ boundaries for the various stars in the exoplanetary systems.

Any climate model is driven externally by the stellar flux S at the distance of the planet from the Sun. At the HZ boundaries the flux is S_{bi} at the inner boundary and S_{bo} at the outer boundary. These fluxes have been established by Kasting *et al.* (1993) for various boundary criteria, including those used here. The fluxes depend mainly on the stellar luminosity L, but to some extent on the effective temperature T_e of the star. This is because the value of T_e determines the infrared fraction in L. For example, the greater this fraction, the greater the greenhouse effect for a given stellar flux. The critical fluxes, in units of the solar flux at the Earth's orbit (the solar constant), are given by

$$S_{bi}(T_e) = 4.190 \times 10^{-8}\ T_e^2 - 2.139 \times 10^{-4}\ T_e + 1.296 \qquad (1a)$$

$$S_{bo}(T_e) = 6.190 \times 10^{-9}\ T_e^2 - 1.319 \times 10^{-5}\ T_e + 0.2341 \qquad (1b)$$

where T_e is in kelvin. The boundaries are then at distances from the star in astronomical units (AU) given by

$$r_i = (L/S_{bi}(T_e))^{1/2} \qquad (2a)$$

$$r_o = (L/S_{bo}(T_e))^{1/2} \qquad (2b)$$

where L is the luminosity of the star in solar units and $S_b(T_e)$ is (still) in units of the solar constant.

We have obtained L and T_e from measured properties of stars. The value of L (in solar units) is obtained from

$$L = 0.787 d^2 \times 10^{[-0.4(V+BC)]}. \qquad (3)$$

where V is the apparent visual magnitude and BC is the bolometric correction (the apparent bolometric magnitude is $(V+BC)$). The value of BC is obtained from standard tables and depends on the observed spectral type and luminosity class. We have obtained them from Cox (2000). The distance d to the star is in parsecs (pc). The value of T_e has been obtained from the star's spectral type and luminosity class, which are tabulated by Schneider (18 April 2006), as are d and V.

In the calculation of L from Eq. (3), the uncertainty is dominated by that in d. Many of these distances come from Hipparcos, where the measured parallax has a median standard error of 0.97×10^{-3} arcsec (Perryman *et al.* 1997). At 100 pc this is $\pm 10\%$. From Eqs (2) and (3) we see that this error translates into a $\pm 10\%$ uncertainty in r. Values of T_e are perhaps subject to less uncertainty. It is also the case that the S_b are only weakly dependent on T_e (Eq. (1)). For example, for our HZ boundary criteria, at around 5700 K, a change of 300 K changes the critical flux at each boundary by only $\sim 5\%$. Also, the r values scale as the square root of L and critical flux (Eq. (2)), which reduces their sensitivity to L and S_b by a factor of ~ 2. The uncertainties in L are thus significant but not serious.

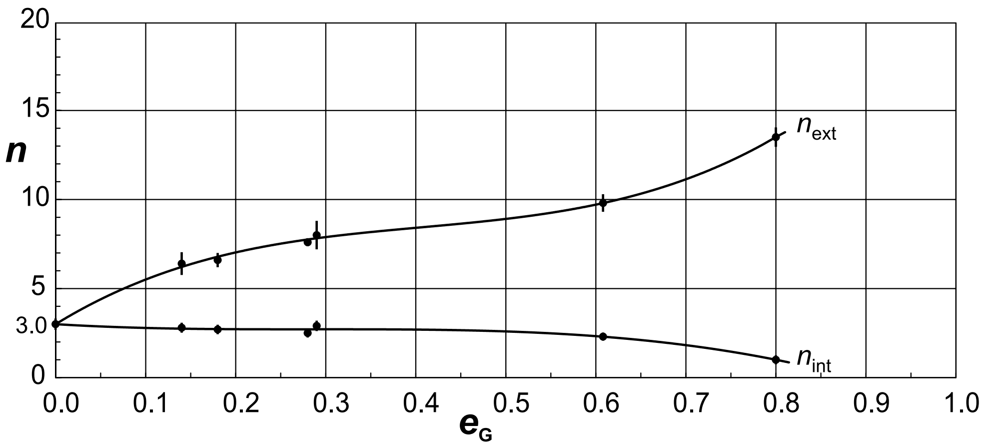

Fig. 2. A plot of $n_{\mathrm{int}}(e_{\mathrm{G}})$ and $n_{\mathrm{ext}}(e_{\mathrm{G}})$ for seven systems (points) studied in detail, and a cubic fit to these points.

A giant planet's critical distances

The critical distance is the distance from a giant planet within which an Earth-mass planet would be ejected from its orbit. On the starward side of a giant planet it is at a distance $n_{\mathrm{int}}R_{\mathrm{H}}$ closer to the sun than the periastron of the giant planet. On the other side it is at a distance $n_{\mathrm{ext}}R_{\mathrm{H}}$ exterior to the apastron. The term R_{H} is the Hill radius of a giant planet, defined by

$$R_{\mathrm{H}} = \left(\frac{m_{\mathrm{G}}}{3M_{\mathrm{star}}}\right)^{1/3} a_{\mathrm{G}} \qquad (4)$$

where m_{G} is the mass of the giant planet, a_{G} is its orbital semi-major axis and M_{star} is the mass of the star. The critical distances are thus at

$a_{\mathrm{G}}(1-e_{\mathrm{G}})-n_{\mathrm{int}}R_{\mathrm{H}}$ (interior to the semi-major axis of the giant's orbit)

$a_{\mathrm{G}}(1+e_{\mathrm{G}})+n_{\mathrm{ext}}R_{\mathrm{H}}$ (exterior to the semi-major axis of the giant's orbit)

where e_{G} is the eccentricity of the giant's orbit.

If no part of the HZ is closer to the giant than a critical distance, then the whole HZ offers *confinement*, in the *specific* sense that the semi-major axis is not caused to stray outside the HZ. If the critical distance lies within the HZ only part of the HZ offers confinement. If the whole HZ lies between a critical distance and the giant planet, then nowhere in the HZ offers confinement.

Note that even if confined to the HZ, the orbital eccentricity of an Earth-mass planet will generally increase, and might rise to the point where the planet is carried outside the HZ for a significant fraction of its orbital period. Whether a planet could be habitable in such a case depends on the response time of the atmosphere–ocean system. Williams & Pollard (2002) conclude that a planet similar to the Earth probably could. A simple calculation shows that this is reasonable. Thus, for a planet with an orbital eccentricity $e\sim0.2$, the ratio of periastron stellar flux to apastron stellar flux, $[(1+e)/(1-e)]^2$, is about the same as the ratio of summer to winter flux at mid-latitudes on Earth. They conclude that an Earth-like planet would be habitable as long as its semi-major axis a remained in the HZ, which is our confinement criterion. For an Earth-like planet, only if e exceeds ~0.6 would the excursions beyond the HZ be too large to ensure habitability. We have found from orbital integration that for confined orbits e is usually less than ~0.3, and rarely exceeds 0.4.

To obtain the n_{int} and n_{ext} values we have studied in detail seven systems with the MERCURY package of orbital integrators (Chambers 1999). An Earth-mass planet was launched into an initially circular orbit at various semi-major axes in the HZ, and its fate followed for a gigayear of simulated time. Our studies of these systems were sufficiently detailed to consume over a thousand hours of CPU time on fast PCs. Full details are given in Jones *et al.* (2005). The key discoveries are as follows.

- The values of n_{int} and n_{ext} are sensitive only to the eccentricity, e_{G}, of the giant planet's orbit (and not, e.g., to $m_{\mathrm{G}}/M_{\mathrm{star}}$ and a_{G}).
- It is an increase in the eccentricity of the orbit of an Earth-mass planet that leads to its ejection or collision. A giant planet can increase this eccentricity to large values with an associated change no greater than a few percent in the semi-major axis of the Earth-mass planet. (Mean-motion and secular resonances can enhance the increase.)

The values of $n_{\mathrm{int}}(e_{\mathrm{G}})$ and $n_{\mathrm{ext}}(e_{\mathrm{G}})$ are shown in Fig. 2, where the data points are connected by cubic fits. These fits to the n_{int} and n_{ext} data are excellent, with correlation coefficients ρ such that $\rho^2=0.970$ for n_{int} and 0.998 for n_{ext}.

The values of $n_{\mathrm{int}}=n_{\mathrm{ext}}=3$ at low eccentricity are in accord with analytical values obtained by Gladman (1993) and others for e_{G} close to zero. Analytical solutions are not possible at higher eccentricity. See Jones *et al.* (2005) for a brief discussion of why there is a relationship between n_{int}, n_{ext} and e_{G}.

Habitability of the known exoplanetary systems

Armed with the critical distances from a giant planet we can now see whether this reduces the extent to which the HZ

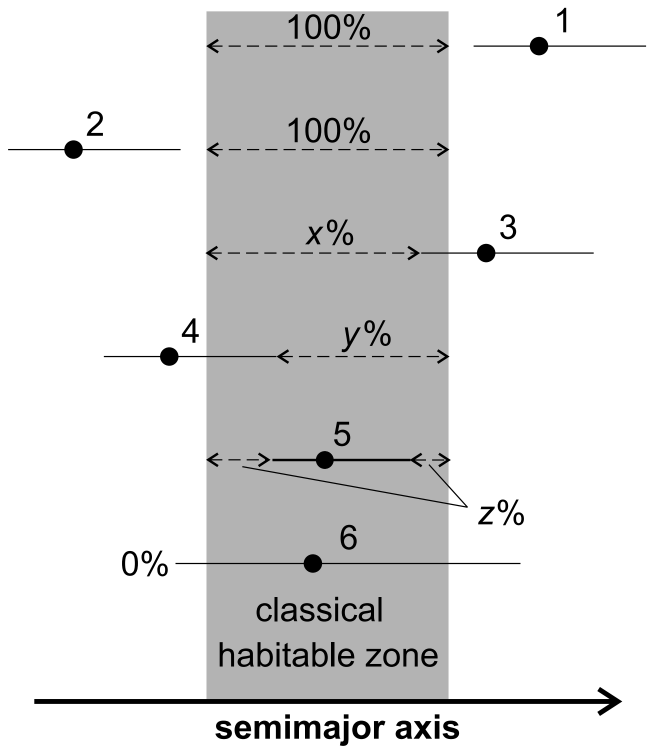

Fig. 3. Six configurations of the critical distances of a giant planet with respect to the position of the HZ.

would offer confinement for an Earth-mass planet. There are six distinct configurations, labelled 1–6 in Fig. 3, where the lines represent the critical distances from the semi-major axis of the giant. As the HZ migrates outwards as the star goes through its main-sequence lifetime, these are instantaneous configurations and will change with stellar age. The confinement outcome relates to the configuration as given in Table 1.

We initially assume that a giant planet interior to the HZ will *not* have ruled out the presence of Earth-mass planets beyond the giant, even though the giant will probably have got there by traversing the HZ. We then examine the result when the formation of Earth-mass planets *is* ruled out by such traversals.

We are interested in two types of outcome.

(1) The system habitability *today*, which is determined by the confinement outcome today. The possible system habitabilities today are defined in Table 1 as 'Yes', a percentage or 'No'.

(2) *Sustained* habitability, which requires the star to be at least 1700 Myr old. The first 700 Myr covers a presumed heavy bombardment phase as on Earth and elsewhere in the inner Solar System, followed by at least 1000 Myr for life to emerge, which for the Earth is about the most pessimistic delay (Jones 2004, Section 3.2.1). The possible results are as follows.

- If the system habitability today is 'Yes' then the *sustained* habitability of the system will be included in one of the following groups:
  - 'Yes' if the star's age is greater than or equal to 1700 Myr and it is on the main sequence, as indicated by luminosity class V (this extends from the star's birth to when it starts evolving rapidly – it is a relatively long phase);
  - 'Too young' if the star's age is less than 1700 Myr;
  - 'No age' if a plausible age is unavailable (see next paragraph);
  - 'Post m-s' if the star has left the main sequence, thus entering its comparatively rapidly evolving, relatively short luminous lifetime, as indicated by a luminosity class IV, III or (rarely) II.
- If the system habitability today is a percentage then the *sustained* habitability of the system will included in one of the following groups:
  - 'Yes' if greater than 20 %, if the star's age is greater than or equal to 1700 Myr and if it is on the main sequence as indicated by luminosity class V;
  - 'No' if less than or equal to 20 % – the case is too marginal, so we take the pessimistic view;
  - 'Too young', 'No age', 'Post m-s' as defined above.
- If the system habitability *today* is 'No' then the *sustained* habitability outcome is 'No'.

Table 1. *Configuration*, *confinement*, *habitability*

Configuration	Confinement outcome	System habitability today
1, 2	Confinement throughout the HZ	Yes
3, 4, 5	x%, y%, z%, fraction of HZ width offering confinement	<value> %
6	Confinement nowhere in the HZ	No

Stellar ages in the literature have been used. Most ages are based on spectroscopic data, such as, for example, from chromospheric activity (Donahue 1998). For some of the stars no age has been found in the literature. For most of these cases we have obtained plausible estimates by calculating how the star's luminosity evolves during the main sequence, and determining the age at which the present luminosity (using Eq. (5)) occurs. The evolutionary model is that of Mazzitelli (1989).

Note that to establish sustained habitability we require an estimate of how much the HZ has moved outwards in the past 1000 Myr. Except in very marginal cases this can be performed well enough for class V and IV stars from the star's mass. Marginal cases are excluded by the less than or equal to 20 % criterion given above.

Table 2 summarizes the results of this kind of analysis applied to the 152 exoplanetary systems known as of 18 April 2006 and listed in Schneider (2006). Note the following points.

- The systems are ordered by increasing period of the planet closest to each star.
- Under luminosity class, values in brackets ( ) have been inferred by the authors on the basis of age and mass, and occasionally by spectral class also; all are V. In five cases the spectral type sub-divisions (numerical) have been estimated – also shown in brackets.

Table 2. *The habitability of the known exoplanetary systems, with HZs based on observed stellar properties*

Star name	M_{star} (M_{Sun})	Spectral type, class	*BC*	*d* (pc)	*V*	HZ Inner (AU)	HZ outer (AU)	Planet	Minimum mass (m_J)	*a* (AU)	*e*	Confi-guration	System habitability today	Sustained habitability?
OGLE-TR-56	1.04	G(5)V	−0.18	1500	16.6	0.565	1.12423	b	1.45	0.0225	0	2	Yes	Yes
OGLE-TR-113	0.77	K(5)V	−0.36	1500	14.42	1.832	3.600	b	1.35	0.0228	0	2	Yes	No age
OGLE-TR-132	1.35	F(5)V	−0.09	1500	15.72	0.713	1.452	b	1.19	0.0306	0	2	Yes	Too young
Gliese 876	0.32	M4V	−2.41	4.72	10.17	0.117	0.232	d	0.023	0.0208	0	6	No	No
								c	0.56	0.13	0.27			
								b	1.935	0.208	0.0249			
HD 86081	1.21	F8V	−0.17	91	8.73	1.251	2.497	b	1.5	0.039	0.008	2	Yes	No age
HD 189733	0.83	K1-2(V)	−0.41	19.3	7.67	0.552	1.085	b	1.15	0.0313	0	2	Yes	Yes
HD 212301	1.03	F8V	−0.17	52.7	7.77	1.127	2.250	b	0.45	0.036	0	2	Yes	Too young
HD 73256	1.05	G8(V)	−0.30	36.5	8.08	0.787	1.549	b	1.87	0.037	0.03	2	Yes	Too young
GJ 436	0.41	M3(V)	−1.98	10.2	10.68	0.162	0.321	b	0.067	0.0278	0.12	2	Yes	Yes
55 Cancri	1.03	G8V	−0.30	13.4	5.95	0.770	1.517	e	0.045	0.038	0.174	2	Yes	Yes
								b	0.784	0.115	0.0197			
								c	0.217	0.24	0.44			
								d	3.92	5.257	0.327			
HD 63454	0.8	K4V	−0.60	35.8	9.37	0.518	1.016	b	0.38	0.036	0	2	Yes	Yes
HD 149026	1.3	G0IV	−0.18	78.9	8.15	1.456	2.896	b	0.36	0.042	0	2	Yes	Post m-s
HD 83443	0.79	K0V	−0.36	43.54	8.23	0.920	1.808	b	0.41	0.04	0.08	2	Yes	Yes
HD 46375	1.00	K1IV	−0.48	33.4	7.94	0.858	1.685	b	0.249	0.041	0.04	2	Yes	Post m-s
TrES-1	0.87	K0V	−0.36	157	11.79	0.644	1.265	–	0.61	0.0393	0.135	2	Yes	Yes
HD 179949	1.24	F8V	−0.17	27	6.25	1.163	2.322	b	0.98	0.04	0.05	2	Yes	Yes
HD 187123	1.06	G5(V)	−0.24	50	7.86	1.129	2.231	b	0.52	0.042	0.03	2	Yes	Yes
OGLE-TR-10	1.22	G(9)(V)	−0.24	1500	14.93	1.306	2.580	b	0.54	0.04162	0	2	Yes	Yes
τ Bootis	1.3	F7V	−0.16	15	4.5	1.426	2.851	b	3.9	0.046	0.01	2	Yes	Yes
HD 188753A	1.06	K0(V)	−0.36	44.82	7.43	1.369	2.690	b	1.14	0.0446	0	2	Yes	Yes
HD 330075	0.95	G5(V)	−0.24	50.2	9.36	0.568	1.123	b	0.76	0.043	0	2	Yes	Yes
HD 88133	1.2	G5IV	−0.29	74.5	8.01	1.647	3.244	b	0.22	0.047	0	2	Yes	Post m-s
HD 2638	0.93	G5(V)	−0.24	53.71	9.44	0.586	1.158	b	0.48	0.044	0	2	Yes	Yes
BD-10 3166	1.1	G4V	−0.22	<200	10.08	<1.601	<3.166	b	0.48	0.046	0	2	Yes	No age
HD 75289	1.05	G0V	−0.18	28.94	6.35	1.224	2.434	b	0.42	0.046	0.054	2	Yes	Yes
HD 209458	1.05	G0V	−0.18	47	7.65	1.092	2.172	b	0.69	0.045	0	2	Yes	Yes
HD 76700	1.00	G6V	−0.25	59.7	8.13	1.210	2.388	b	0.197	0.049	0	2	Yes	Yes
OGLE-TR-111	0.82	G(9)(V)	−0.24	1500	15.55	1.004	1.984	b	0.53	0.047	0	2	Yes	No age
HD 149143	1.21	G0IV	−0.18	63	7.9	1.305	2.595	b	1.33	0.053	0.016	2	Yes	Too young
HD 102195	0.928	K0V	−0.36	28.98	8.05	0.688	1.35	b	0.48	0.049	0.06	2	Yes	Yes
51 Pegasi	1.0	G2IV	−0.20	14.7	5.49	0.948	1.880	b	0.468	0.052	0	2	Yes	Post m-s
υ Andromedae	1.3	F8V	−0.17	13.47	4.09	1.569	3.132	b	0.69	0.059	0.012	6	No	No
								c	1.89	0.829	0.28			
								d	3.75	2.53	0.27			
HD 49674	1.00	G5V	−0.24	40.7	8.10	0.823	1.626	b	0.12	0.0568	0	2	Yes	Yes
HD 109749	1.2	G3IV	−0.21	59	8.1	1.159	2.296	b	0.28	0.0635	0.01	2	Yes	Post m-s
Gliese 581	0.31	M3(V)	−2.11	6.26	10.55	0.113	0.224	b	0.056	0.041	0	2	Yes	Yes
HD 118203	1.23	K0(V)	−0.36	88.6	8.05	2.034	3.997	b	2.13	0.07	0.309	2	Yes	Pos m-s
HD 68988	1.2	G0(V)	−0.18	58	8.21	1.041	2.071	b	1.9	0.071	0.14	2	Yes	Yes
HD 168746	0.92	G5(V)	−0.24	43.12	7.95	0.934	1.846	b	0.23	0.065	0.081	2	Yes	Yes
HD 217107	0.98	G8IV	−0.36	37	6.16	2.024	3.977	b	1.37	0.074	0.13	6	No	No
								c	2.1	4.3	0.55			
HD 162020	0.7	K2V	−0.46	31.26	9.18	0.455	0.892	b	13.75	0.072	0.277	2	Yes	Yes
HD 160691	1.08	G3IV/V	−0.21	15.3	5.15	1.169	2.316	d	0.044	0.09	0	6	No	No
								b	1.67	1.5	0.31			
								c	3.1	4.17	0.57			
HD 130322	0.79	K0V	−0.36	30	8.05	0.689	1.353	b	1.08	0.088	0.048	2	Yes	Too young
HD 108147	1.27	F9V	−0.09	38.57	6.99	1.021	2.080	b	0.4	0.104	0.498	2	Yes	Yes
HD 38529	1.39	G4IV	−0.28	42.43	5.94	2.413	4.757	b	0.78	0.129	0.29	6	No	No
								c	12.7	3.68	0.36			
HD 4308	0.83	G5V	−0.24	21.9	6.54	0.908	1.794	b	0.047	0.114	0	2	Yes	Yes
Gliese 86	0.79	K1V	−0.41	11	6.17	0.618	1.214	b	4.01	0.11	0.046	2	Yes	Too young
HD 99492	0.78	K2V	−0.46	18	7.57	0.549	1.078	b	0.122	0.119	0.05	2	Yes	Yes
HD 190360	0.96	G6IV	−0.30	15.89	5.71	1.027	2.022	c	0.057	0.128	0.01	3	64%	Yes
								b	1.502	3.92	0.36			
HD 27894	0.75	K2V	−0.46	42.37	9.36	0.567	1.113	b	0.62	0.122	0.049	2	Yes	Yes
HD 33283	1.24	G3V	−0.21	86	8.05	1.729	3.424	b	0.33	0.122	0.049	2	Yes	No age

Table 2 (*cont.*)

Star name	M_{star} (M_{Sun})	Spectral type, class	*BC*	*d* (pc)	*V*	HZ Inner (AU)	HZ outer (AU)	Planet	Minimum mass (m_J)	*a* (AU)	*e*	Configuration	System habitability today	Sustained habitability?
HD 195019	1.02	G3IV/V	−0.36	20	6.91	0.773	1.520	b	3.43	0.14	0.05	2	Yes	Yes
HD 102117	0.95	G6V	−0.25	42	7.47	1.154	2.277	b	0.14	0.149	0	2	Yes	Yes
HD 6434	1.00	G3IV	−0.21	40.32	7.72	0.944	1.869	b	0.48	0.15	0.3	2	Yes	Post m-s
HD 192263	0.79	K2V	−0.46	19.9	7.79	0.549	1.077	b	0.72	0.15	0	2	Yes	Too young
HD 224693	1.33	G2IV	−0.30	94	8.23	1.872	3.711	b	0.71	0.233	0.05	2	Yes	Post m-s
HD 11964	1.125	G5(V)	−0.29	33.98	6.42	1.562	3.077	b	0.11	0.229	0.15	2	Yes	Yes
ρ Coronae Borealis	0.95	G0V	−0.18	16.7	5.4	1.094	2.175	b	1.04	0.22	0.04	2	Yes	Yes
HD 74156	1.05	G0(V)	−0.18	64.56	7.62	1.521	3.025	b	1.86	0.294	0.636	6	No	No
								c	6.17	3.4	0.583			
HD 117618	1.05	G2V	−0.20	38	7.18	1.125	2.232	b	0.19	0.28	0.39	2	Yes	Yes
HD 37605	0.8	K0V	−0.36	42.9	8.69	0.733	1.441	b	2.3	0.25	0.677	2	Yes	No age
HD 168443	1.01	G5(V)	−0.24	33	6.92	1.149	2.270	b	7.2	0.29	0.529	6	No	No
								c	17.1	2.87	0.228			
HD 3651	0.79	K0V	−0.36	11	5.8	0.712	1.398	b	0.2	0.284	0.63	2	Yes	No age
HD 121504	1.00	G2V	−0.20	44.37	7.54	1.113	2.208	b	0.89	0.32	0.13	2	Yes	Yes
HD 101930	0.74	K1V	−0.41	30.49	8.21	0.670	1.315	b	0.3	0.302	0.11	2	Yes	No age
HD 178911 B	0.87	G5(V)	−0.24	46.73	7.98	0.999	1.973	b	6.292	0.32	0.1243	2	Yes	Yes
HD 16141	1.00	G5IV	−0.29	35.9	6.78	1.398	2.755	b	0.23	0.35	0.21	2	Yes	Post m-s
HD 114762	0.82	F9V	−0.17	28	7.30	0.744	1.484	b	11.02	0.3	0.34	4	89%	Yes
HD 80606	0.9	G5(V)	−0.24	58.38	8.93	0.806	1.591	b	3.41	0.439	0.927	6	No	No
70 Virginis	1.1	G4V	−0.22	22	5.00	1.827	3.614	b	7.44	0.48	0.4	2	Yes	Yes
HD 216770	0.9	K1V	−0.41	38	8.10	0.878	1.724	b	0.65	0.46	0.37	2	Yes	Yes
HD 52265	1.13	G0V	−0.18	28	6.30	1.211	2.409	b	1.13	0.49	0.29	2	Yes	Yes
HD 208487	0.95	G2V	−0.20	45	7.48	1.161	2.302	b	0.45	0.49	0.32	2	Yes	Yes
HD 34445	1.11	G0(V)	−0.18	48	7.32	1.298	2.582	b	0.58	0.51	0.4	2	Yes	Yes
GJ 3021	0.9	G6V	−0.24	17.62	6.59	0.714	1.411	b	3.32	0.49	0.505	4	24%	Too young
HD 93083	0.7	K3V	−0.53	28.9	8.3	0.655	1.285	b	0.37	0.477	0.14	4	90%	No age
HD 37124	0.91	G4V	−0.22	33	7.68	0.798	1.578	b	0.61	0.53	0.055	3	44%	Yes
								c	0.6	1.64	0.14			
								d	0.66	3.19	0.2			
HD 219449	1.7	K0III	−0.50	45	4.21	6.679	13.098	b	2.9	0.3	0	2	Yes	Post m-s
HD 73526	1.02	G6V	−0.25	99	9.00	1.344	2.653	b	2.9	0.66	0.19	4	63%	Yes
								c	2.5	1.05	0.14			
HD 104985	1.5	G9III	−0.46	102	5.79	7.105	13.938	b	6.3	0.78	0.03	2	Yes	Post m-s
HD 82943	1.05	G0(V)	−0.18	27.46	6.54	1.064	2.116	c	0.88	0.73	0.54	6	No	No
								b	1.63	1.16	0.41			
HD 169830	1.4	F8V	−0.17	36.32	5.90	1.839	3.669	b	2.88	0.81	0.31	6	No	No
								c	4.04	3.6	0.33			
HD 8574	1.15	F8(V)	−0.17	44.15	7.12	1.274	2.543	b	2.23	0.76	0.4	4	72%	Yes
HD 202206	1.15	G6V	−0.25	46.34	8.08	0.961	1.897	b	17.4	0.83	0.435	6	No	No
								c	2.44	2.55	0.267			
HD 89744	1.4	F7V	−0.16	40	5.74	2.148	4.295	b	7.99	0.89	0.67	4	70%	Yes
HD 134987	1.05	G5V	−0.24	25	6.45	1.081	2.135	b	1.58	0.78	0.24	4	67%	Yes
HD 12661	1.07	G6V	−0.25	37.16	7.44	1.035	2.042	b	2.3	0.83	0.35	6	No	No
								c	1.57	2.56	0.2			
HD 150706	1.06	G0(V)	−0.18	27.2	7.03	0.841	1.672	b	1	0.82	0.38	4	7%	No
HD 40979	1.08	F8V	−0.17	33.3	6.74	1.145	2.285	b	3.32	0.811	0.23	4	50%	Yes
HD 59686	1.7	K2III	−0.60	92	5.45	8.197	16.076	b	5.25	0.911	0	2	Yes	Post m-s
HR 810	1.2	G0V	−0.18	15.5	5.4	1.015	2.019	b	1.94	0.91	0.24	4	33%	Too young
HD 142	1.1	G1IV	−0.19	20.6	5.70	1.190	2.364	b	1	0.98	0.38	4	38%	Post m-s
HD 92788	1.06	G5(V)	−0.24	32.82	7.31	0.955	1.886	b	3.86	0.97	0.27	6	No	No
HD 28185	0.99	G5(V)	−0.24	39.4	7.81	0.911	1.799	b	5.7	1.03	0.07	4	1%	No
HD 196885	1.27	F8IV	−0.17	33	6.39	1.333	2.660	b	1.84	1.12	0.3	4	34%	Post m-s
HD 142415	1.03	G1V	−0.19	34.2	7.34	0.929	1.844	b	1.62	1.05	0.5	6	No	No
HD 33564	1.25	F6V	−0.15	20.98	5.08	1.508	3.012	b	9.1	1.1	0.34	4	18%	No
HD 177830	1.17	K0(V)	−0.35	59	7.17	2.031	3.991	b	1.28	1	0.43	4	95%	Yes
HD 108874	1.00	G5(V)	−0.24	68.5	8.76	1.022	2.019	b	1.36	1.051	0.07	6	No	No
								c	1.018	2.68	0.25			
HD 154857	1.17	G5V	−0.24	68.5	7.25	2.049	4.048	b	1.8	1.11	0.51	4	76%	Yes
HD 4203	1.06	G5(V)	−0.24	77.5	8.68	1.200	2.370	b	1.65	1.09	0.46	6	No	No
HD 27442	1.2	K2IV	−0.53	18.1	4.44	2.451	4.809	b	1.28	1.18	0.07	2	Yes	Post m-s

Table 2 (*cont.*)

Star name	M_{star} (M_{Sun})	Spectral type, class	*BC*	*d* (pc)	*V*	HZ Inner (AU)	HZ outer (AU)	Planet	Minimum mass (m_J)	*a* (AU)	*e*	Configuration	System habitability today	Sustained habitability?
HD 210277	0.99	G0(V)	−0.18	22	6.63	0.818	1.626	b	1.24	1.097	0.45	6	No	No
HD 128311	0.8	K0(V)	−0.36	16.6	7.51	0.489	0.960	b	2.18	1.1	0.25	3	11%	No
								c	3.21	1.76	0.17			
HD 19994	1.35	F8V	−0.17	22.38	5.07	1.660	3.313	b	2	1.3	0.2	4	59%	Yes
HD 188015	1.09	G5IV	−0.29	52.6	8.22	1.006	1.988	b	1.26	1.19	0.15	4	6%	No
HD 13189	4.5	K2II	−0.60	185	7.57	6.210	12.178	b	14	1.85	0.28	2	Yes	Post m-s
HD 20367	1.04	G0(V)	−0.18	27	6.41	1.110	2.209	b	1.07	1.25	0.23	4	1%	No
HD 114783	0.92	K0(V)	−0.36	22	7.57	0.630	1.238	b	0.99	1.2	0.1	3	29%	Yes
HD 147513	0.92	G3V	−0.21	12.9	5.37	0.891	1.765	b	1	1.26	0.52	6	No	No
HIP 75458	1.05	K2III	−0.60	31.5	3.31	7.520	14.747	b	8.64	1.34	0.71	2	Yes	Post m-s
HD 222582	1.00	G5(V)	−0.24	42	7.70	1.021	2.017	b	5.11	1.35	0.76	6	No	No
HD 20782	1.00	G2V	−0.20	36.02	7.38	0.973	1.929	b	1.8	1.36	0.92	6	No	No
HD 65216	0.92	G5V	−0.24	34.3	7.98	0.733	1.448	b	1.21	1.37	0.41	6	No	No
HD 183263	1.17	G2IV	−0.20	53	7.86	1.147	2.276	b	3.69	1.52	0.38	6	No	No
HD 141937	1.00	G2V	−0.20	33.46	7.25	0.959	1.903	b	9.7	1.52	0.41	6	No	No
HD 41004 A	0.7	K1V	−0.41	42.5	8.65	0.762	1.497	b	2.3	1.31	0.39	6	No	No
HD 11977	1.91	G8.5III	−0.44	66.5	4.7	7.548	14.810	b	6.54	1.93	0.4	2	Yes	Post m-s
HD 47536	1.1	K0II	−0.50	123	5.26	11.256	22.074	b	4.96	1.61	0.2	2	Yes	Post m-s
HD 23079	1.1	F9V	−0.17	34.8	7.1	1.028	2.048	b	2.61	1.65	0.1	6	No	No
16 Cygni B	1.01	G2.5V	−0.20	21.4	6.20	1.002	1.985	b	1.69	1.67	0.67	6	No	No
HD 4208	0.93	G5V	−0.24	33.9	7.79	0.791	1.562	b	0.8	1.67	0.05	3	57%	Yes
HD 114386	0.75	K3V	−0.53	28	8.73	0.521	1.021	b	0.99	1.62	0.28	3	63%	Yes
HD 45350	1.02	G5IV	−0.29	49	7.88	1.150	2.265	b	0.98	1.77	0.78	6	No	No
γ Cephei A	1.59	K0III	−0.60	11.8	3.22	2.936	5.758	b	1.59	2.03	0.2	4	80%	Post m-s
HD 213240	1.22	G4IV	−0.28	40.75	6.80	1.477	2.922	b	4.5	2.03	0.45	6	No	No
HD 187085	1.22	G0V	−0.18	44.98	7.22	1.274	2.534	b	0.75	2.05	0.47	6	No	No
HD 81040	0.96	G2-3(V)	−0.20	32.56	7.72	0.757	1.500	b	6.86	1.94	0.526	6	No	No
HD 10647	1.07	F8V	−0.17	17.3	5.52	1.043	2.082	b	0.91	2.1	0.18	3	30%	Yes
HD 10697	1.1	G5IV	−0.29	30	6.29	1.464	2.885	b	6.12	2.13	0.11	6	No	No
47 Ursae Majoris	1.03	G0V	−0.18	13.3	5.10	1.000	1.989	b	2.54	2.09	0.061	3	34%	Yes
								c	0.76	3.73	0.1			
HD 190228	1.3	G5IV	−0.29	66.11	7.3	2.027	3.992	b	4.99	2.31	0.43	6	No	No
HD 114729	0.93	G3V	−0.21	35	6.69	1.316	2.607	b	0.82	2.08	0.31	6	No	No
HD 111232	0.78	G8V	−0.30	29	7.61	0.776	1.528	b	6.8	1.97	0.2	3	6%	No
HD 2039	0.98	G2V	−0.20	89.8	9.01	1.145	2.270	b	4.85	2.19	0.68	6	No	No
HD 136118	1.24	F9V	−0.17	52.3	6.94	1.663	3.313	b	11.9	2.3	0.37	6	No	No
HD 50554	1.1	F8(V)	−0.17	31.03	6.86	1.010	2.015	b	4.9	2.38	0.42	6	No	No
HD 196050	1.1	G3V	−0.21	46.9	7.50	1.215	2.406	b	3	2.5	0.28	6	No	No
HD 216437	1.07	G4V	−0.22	26.5	6.06	1.351	2.672	b	2.1	2.7	0.34	6	No	No
HD 216435	1.25	G0V	−0.18	33.3	6.03	1.631	3.245	b	1.49	2.7	0.34	6	No	No
HD 106252	1.05	G0(V)	−0.18	37.44	7.36	0.994	1.977	b	6.81	2.61	0.54	6	No	No
HD 23596	1.3	F8(V)	−0.17	52	7.24	1.420	2.834	b	7.19	2.72	0.314	6	No	No
14 Herculis	1.00	K0V	−0.36	18.1	6.67	0.784	1.541	b	4.74	2.8	0.338	3	26%	Yes
HD 142022 A	0.99	K0V	−0.36	35.87	7.70	0.967	1.901	b	4.4	2.8	0.57	6	No	No
HD 39091	1.1	G1IV	−0.19	20.55	5.67	1.204	2.391	b	10.35	3.29	0.62	6	No	No
HD 70642	1.00	G5V	−0.24	29	7.18	0.896	1.770	b	2	3.3	0.1	1	Yes	Yes
HD 33636	0.99	G0V	−0.18	28.7	7.06	0.875	1.740	b	9.28	3.56	0.53	6	No	No
ε Eridani	0.8	K2V	−0.46	3.2	3.73	0.572	1.123	b	0.86	3.3	0.608	3	17%	No
HD 50499	1.27	G1V	−0.19	47.26	7.22	1.356	2.693	b	1.71	3.86	0.23	3	61%	Yes
HD 117207	1.04	G8V	−0.30	33	7.26	1.038	2.043	b	2.06	3.78	0.16	1	Yes	Yes
HD 30177	0.95	G8V	−0.30	55	8.41	1.018	2.005	b	9.17	3.86	0.3	3	16%	No
HD 89307	1.27	G0V	−0.18	33	7.06	1.006	2.001	b	2.73	4.15	0.27	1	Yes	Too young
HD 72659	0.95	G0V	−0.18	51.4	7.48	1.292	2.569	b	2.96	4.16	0.2	3	71%	Yes

The observed magnitudes of the OGLEs are I not V, except for OGLE-TR-56, where it is V. The appropriate magnitude has been used to calculate *L*. A multiplier of 1.3 has been used to obtain the final three columns, except for cases (*italicized*) where *i* is known, always $>81°$, so the minimum mass is used.

- The great majority of systems have been observed *only* by the RV method. This gives $m_G \sin(i_0)$, where i_0 is the inclination of the planetary orbit with respect to the plane of the sky. The minimum actual mass is for $i_0 = 90°$ corresponding to an edge-on presentation of the orbit, and it is these values that are tabulated. However, i_0, with a few exceptions (see next point), is unknown. Therefore, to obtain R_H for the i_0-unknown systems the minimum mass has been multiplied by 1.3, this being the reciprocal of the mean value of the function $\sin(i_0)$. However, R_H varies slowly with m_G, as $m_G^{1/3}$ (see Eq. (4)), and consequently the 1.3 multiplier increases R_H by only 9% over the minimum mass value. This will make little or no difference to the great majority of habitability results.

- Minimum masses have been used for the 10 systems shown in *italics*. Of these, nine have planets that have been observed with sufficient precision in transit in front of their stars that we know i_0 to be greater than 81° in all cases, and thus the multiplier is greater than or equal to 0.99. Gliese 876b has been observed astrometrically, and $i_0 \approx 90°$, again giving a multiplier very close to 1.
- For systems with more than one giant planet the nR_H for each giant planet is obtained, and the confinement outcome is based on the combined gravitational reaches. The configuration in Table 2 is for the giant with the worst (highest numbered) configuration.
- A few of the stars are components of binary stellar systems. In the closest binaries the stellar separations are ~20 AU, specifically HD 41044A, Gliese 86 and γ Cephei A (Eggenberger *et al.* 2004). We have not included the gravitational effect of these companion stars, so further study is needed and the results in Table 2 are preliminary, although γ Cephei A is already uninhabitable and will remain so. Studies by David *et al.* (2003) indicate that binary stars with separations much greater than 20 AU are very unlikely to have their habitability disturbed by the stellar companion, which thus applies to the other presently known binary systems, where the next closest separation is 100 AU.

From Table 2 we have established that 60% of the 152 exoplanetary systems listed offer habitability today – they have 'today' outcomes of 'Yes' or '>20%'. If, however, giant planets interior to the HZ have got there by migrating through the HZ, and if this ruled out the survival of Earth-mass planets in the HZ or their subsequent formation, then the proportion falls to only 7%.

To determine *sustained* habitability we need to establish whether the star has an age greater than 1700 Myr. It is fortunate that this is all we need to know, because estimates of stellar ages are fraught with uncertainty. Even so, for nine of the systems we have not been able to obtain plausible ages, indicated by 'No age' in Table 2. Of the remaining 143 systems, the 'Yes' proportions for sustained habitability are as follows:

- 41% if all 'Post m-s' stars are excluded (luminosity classes other than V);
- 50% if class IV stars (sub-giants) are included (provided that the only reason for exclusion was that they had left the main sequence);
- 7% if giant planets interior to the HZ have got there by migration through the HZ, and if this ruled out the survival of Earth-mass planets in the HZ or their subsequent formation.

The inclusion of class IV stars is justifiable because most of them will still be evolving fairly sedately, whereas the luminosities of class III and II stars are changing rapidly.

Comparisons with other work

In an earlier work by the authors (Jones *et al.* 2005) the Mazzitelli (1989) stellar evolution model was used, rather than measured stellar properties, to obtain the confinement outcomes across the whole main sequence for the then 110 known exoplanetary systems with class V and IV stars. For the population common to this work, the agreement for what we refer to here as sustained habitability is striking. We can thus conclude that the results of our work regarding sustained habitability in the current exoplanetary system population are not sensitive to the stellar properties as determined variously by stellar models and observations. This is not unexpected, but it was important be certain. For two such different approaches, this agreement gives us confidence in each set of results.

Few others have examined the habitabilities of a large proportion of the known systems. Menou & Tabachnik (2003) studied 85 known exoplanetary systems by scattering particles across the HZ at zero stellar age and examining the number still present in the HZ after 1 Myr. They require that the particle remains in the HZ in the whole of its orbit, and not just that the semi-major axis does so. In spite of the substantial differences between their approach and ours, and their use of zero-age HZs, there is remarkable correspondence between the results at comparable giant planet masses. For example, their cases where a large proportion of the particles were retained correspond nearly always to 'Yes' in 'sustained habitability?' in Table 2, and where a small proportion were retained this corresponds to 'No'.

In a different type of study, Turnbull & Tarter (2003) examined 55 known exoplanetary systems using a technique similar to that used in this paper for 'sustained habitability?' They assumed minimum giant masses and used 3 for n_{int} and n_{ext} as the R_H multiplier. The use of $n_{ext} = 3$ will overestimate the confinement possible when the giant planet is in an eccentric orbit interior to the HZ. Making an allowance for this, and for significant differences in stellar parameters in several systems, there is reasonable agreement between their work and ours.

Conclusions and future work

Of the 152 exoplanetary systems known as of 18 April 2006 and listed by Schneider (2006), 143 have ages estimated well enough for us to establish whether they have offered sustained habitability, i.e. over the past 1000 Myr, providing that this post-dates 700 Myr allowed for a heavy bombardment. Of these 143, we have obtained the following results:

- 41% are 'Yes', and thus have had sustained habitability;
- this increases to 50% if class IV stars are included (provided that the only reason for exclusion was the stars being post m-s);

- this decreases to 7% if giant planets interior to the HZ have got there by migration through the HZ, and if this ruled out the survival of Earth-mass planets in the HZ or their subsequent formation there.

Comparison with our earlier work reveals that these results are not sensitive to stellar properties as determined variously by stellar models and observations.

The decrease to 7% demonstrates the importance of understanding how readily or rarely at least one Earth-mass planet can form in the HZ after a giant planet has migrated through it. This urgent question has received some attention. Formation in 47 Ursae Majoris has been examined by Laughlin *et al*. (2002). They have shown that Earth-mass planets could form within about 0.7 AU of the star, which is interior to the HZ and possibly a bit further out in the inner HZ. It is the proximity of the inner giant planet to the HZs that hinders formation, by stirring up the orbits of the planetesimals and planetary embryos. The most comprehensive treatment to date is by Fogg & Nelson (2005), who have shown that post-migration formation of Earth-mass planets from planetesimals and planetary embryos is fairly likely. This gives cause for optimism. However, this problem needs further study.

Future discoveries are likely to reveal hot Jupiters by the transit method and systems more akin to ours by the RV method. This is because of observational biases – the closer the planet is to the star the more likely it will be seen in transit, and the longer we observe systems the more likely we are to observe the periodic effects of a giant planet in an orbit at several AU. If Earth-mass planets can form after the migration of a giant through the HZ, then with the giant lying well interior to the HZ, the HZ should have had sustained habitability. Likewise, in systems similar to ours, with the giant planets situated well beyond the HZ, sustained habitability is again likely. So, the proportion of systems with HZs that have had sustained habitability should rise. Countering this trend would be the discovery of additional planets in the known systems, where at least one is close to the HZ. Habitability would then be reduced or eliminated. Overall, the proportion of giant planets well beyond the HZ, and as yet undiscovered by the RV method, is likely to increase.

An area that needs more investigation is the orbital stability of putative large satellites of giant planets in the HZ, where tidal heating is not necessary to produce liquid water. Work so far (Barnes & O'Brien 2002) indicates that Earth-mass satellites could survive in a wide variety of cases, in agreement with our work in progress.

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References

Barnes, J.W. & O'Brien, D.P. (2002). Stability of satellites around close-in extrasolar giant planets. *Astrophys. J.* **575**, 1087–1093.

Chambers, J.E. (1999). A hybrid symplectic integrator that permits close encounters between massive bodies. *Mon. Not. R. Astron. Soc.* **304**, 793–799.

Cox, A.N. (2000). *Allen's Astrophysical Quantities*. AIP Press/Springer, New York.

David, E.-M., Quintana, E.V., Fatuzzo, M. & Adams, F.C. (2003). Dynamical stability of Earth-like planetary orbits in binary systems. *Pub. Astron. Soc. Pacific* **115**, 825–836.

Donahue, R.A. (1998). Stellar ages using the chromospheric activity of field binary stars. *Proc. Astronomical Society of the Pacific Conf. Series* **154**, CD-1235–CD-1242.

Eggenberger, A., Udry, S. & Mayor, M. (2004). Statistical properties of exoplanets. III Planet properties and stellar multiplicity. *Astron. Astrophys.* **417**, 353–360.

Fogg, M.J. & Nelson, R.P. (2005). Oligarchic and giant impact growth of terrestrial planets in the presence of gas giant planet migration. *Astron. Astrophys.* **441**, 791–806.

Gladman, B. (1993). Dynamics of systems of two close planets. *Icarus* **106**, 247–263.

Jones, B.W. (2004). *Life in the Solar System and Beyond*. Springer/Praxis, London.

Jones, B.W., Underwood, D.R. & Sleep, P.N. (2005). Prospects for habitable 'Earths' in known exoplanetary systems. *Astrophys. J.* **622**, 1091–1101.

Kasting, J.F., Whitmire, D.P. & Reynolds, R.T. (1993). Habitable zones around main sequence stars. *Icarus* **101**, 108–128.

Laughlin, G., Chambers, J.E. & Fischer, D.A. (2002). A dynamical analysis of the 47 UMa planetary system. *Astrophys. J.* **579**, 455–467.

Mazzitelli, I. (1989). The core mass at the helium flash: influence of numerical and physical inputs. *Astrophys. J.* **340**, 249–255.

Menou, K. & Tabachnik, S. (2003). Dynamical habitability of known extrasolar planetary systems. *Astrophys. J.* **583**, 473–488.

Perryman, M.A.C. *et al.* (1997). The Hipparcos catalogue. *Astron. Astrophys.* **323**, L49–L52.

Schneider, J. (2006). The extrasolar planets encyclopaedia. http://www.exoplanet.eu/ [18 April 2006].

Turnbull, M.C. & Tarter, J.C. (2003). Target selection for SETI. I A catalog of nearby habitable stellar systems. *Astrophys. J.* (Supplement Series) **145**, 181–198.

Williams, D.M. & Pollard, D. (2002). Earth-like worlds on eccentric orbits: excursions beyond the habitable zone. *Int. J. Astrobiol.* **1**, 61–69.