Habitable planetary systems (un)like our own: Which of the known extra-solar systems could harbor Earth-like planets?

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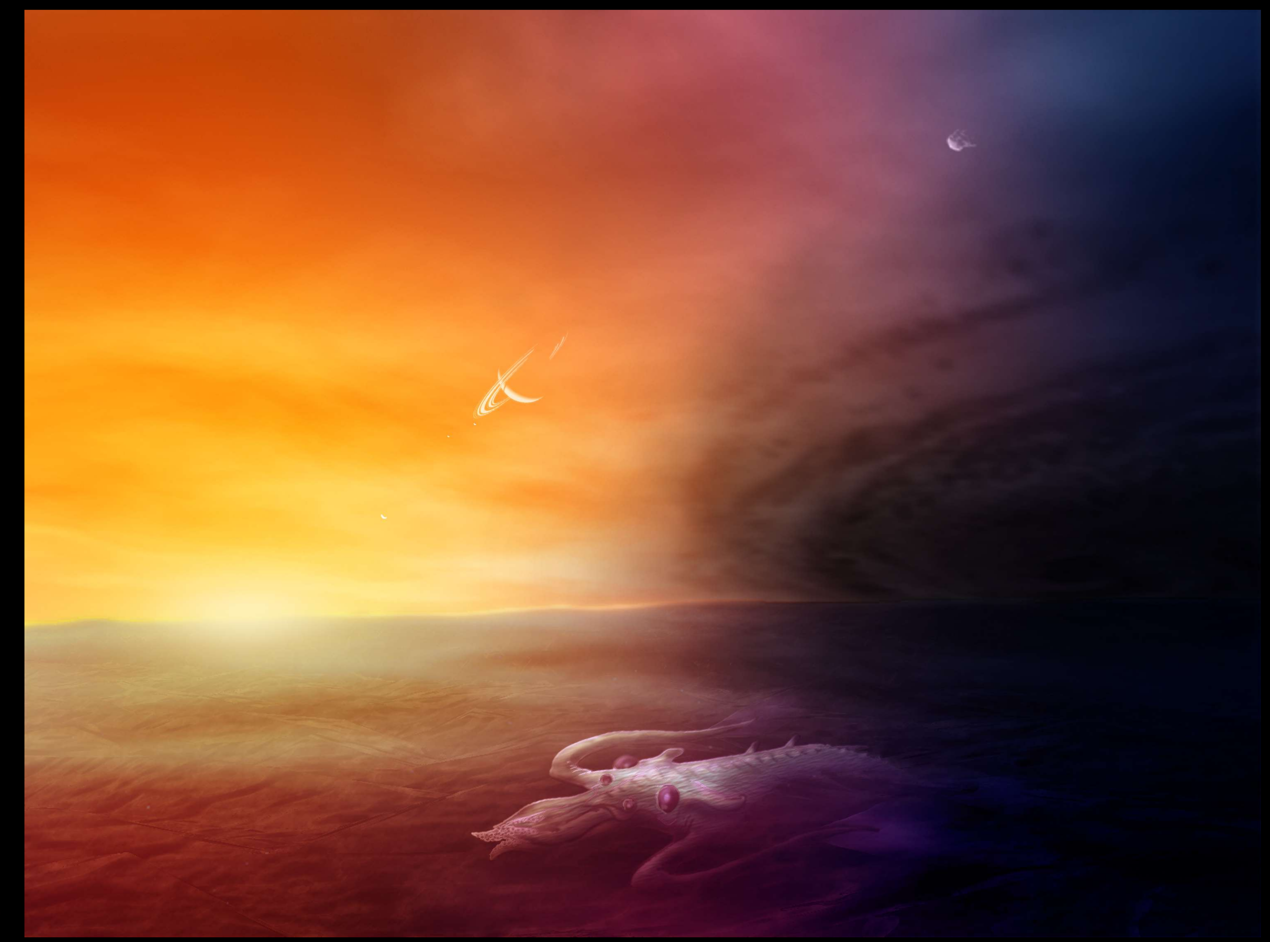
Diversity in habitable planetary systems

Gas giant planets are far easier than terrestrial planets to detect around other stars, and are thought to form much more quickly than terrestrial planets. Thus, in systems with giant planets, the final stages of terrestrial planet formation are strongly affected by the giant planets' dynamical presence. Observations of giant planet orbits may therefore constrain the systems that can harbor potentially habitable, Earth-like planets. We combine two recent studies and establish rough inner and outer limits for the giant planet orbits that allow terrestrial planets of at least 0.3 Earth masses to form in the habitable zone (HZ). For a star like the Sun, potentially habitable planets can form in systems with relatively low-eccentricity giant planets inside 0.5 Astronomical Units (AU) or outside 2.5 AU. More than one third of the currently known giant planet systems could harbor a habitable planet.



The view from a "water world" planet with a close-in giant planet. Credit: Nahks Tr'Ehnl.

1. Outer giant planet limits: planetary systems like our own Solar System (giant planets exterior to Hab. Zone)

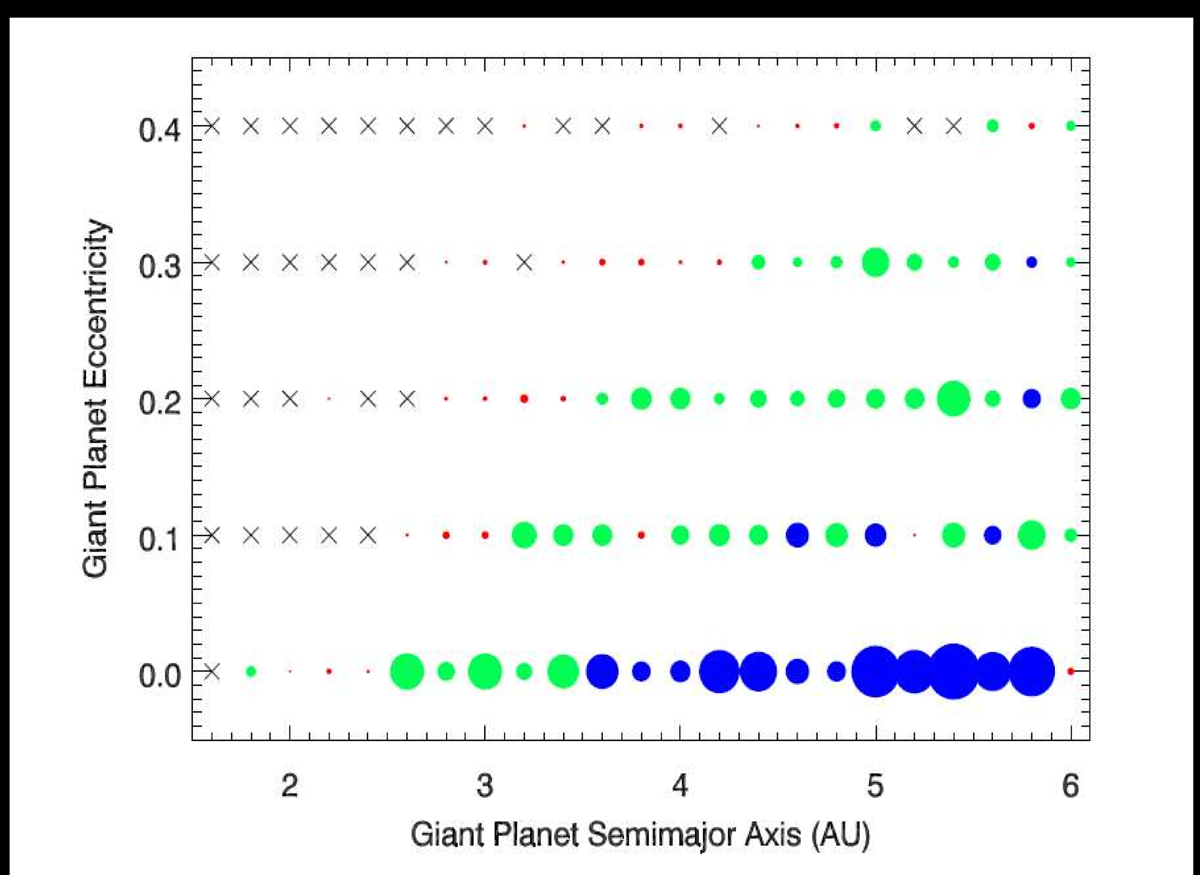


Fig 1 – Giant planet orbital parameter space that allows potentially habitable terrestrial planets to form. Each symbol represents the orbit of a single giant planet, for which we performed 4 simulations of terrestrial planet formation. X's mark regions where no terrestrial material survived in the HZ. Red dots mark regions where the average HZ planet mass was <0.3 M_{Earth}. Green dots formed >0.3 M_{Earth} planets in the HZ. Blue dots formed >0.3 M_{Earth}, water-rich planets in the HZ. Average planet mass is proportional to the dot size. For solar-mass stars, systems with giant planets outside 2.5 AU can form >0.3 M_{Earth} planets in the habitable zone (0.3 M_{Earth} is a rough lower limit for habitability – Williams et al 1997). Systems with giant planets outside 3.5 AU can form water-rich planets in the HZ (Fig 1). These limits are sensitive to the giant planet's orbital eccentricity.

$M_\star$ ($M_\odot$)	Sp. Type[1]	Hab Zone (AU)[2]	Inner Limit (AU)	Outer Limit (AU)
0.1	M6	0.024-0.045	0.015	0.075
0.4	M3	0.10-0.19	0.06	0.32
0.7	K6	0.28-0.52	0.17	0.87
1.0	G2	0.8-1.5	0.5	2.5
1.3	F8	2.3-4.3	1.45	7.2
1.6	F0	6.5-12.3	4.1	20.5
2.0	A5	25-47	15.7	78.3

Table 1 – Giant planet limits for potentially habitable planetary systems. Systems with giant planets inside the inner limit or outside the outer limit, with relatively low eccentricities, are good candidates for life.

2. Inner giant planet limits: planetary systems unlike our Solar System (giant planets interior to Hab. Zone)

We simulated terrestrial planet growth with close-in giant planets, in a realistic scenario including giant planet migration. Potentially habitable planets form, and are likely to be covered in global oceans. The spacing between the close-in giant and the innermost >0.3 M_{Earth} planet was variable, with a mean orbital period ratio of about 10 (Fig 2). So, on average, systems with giant planets inside 0.5 AU can form terrestrial planets inside the outer edge of the HZ (assumed to be 1.5 AU).

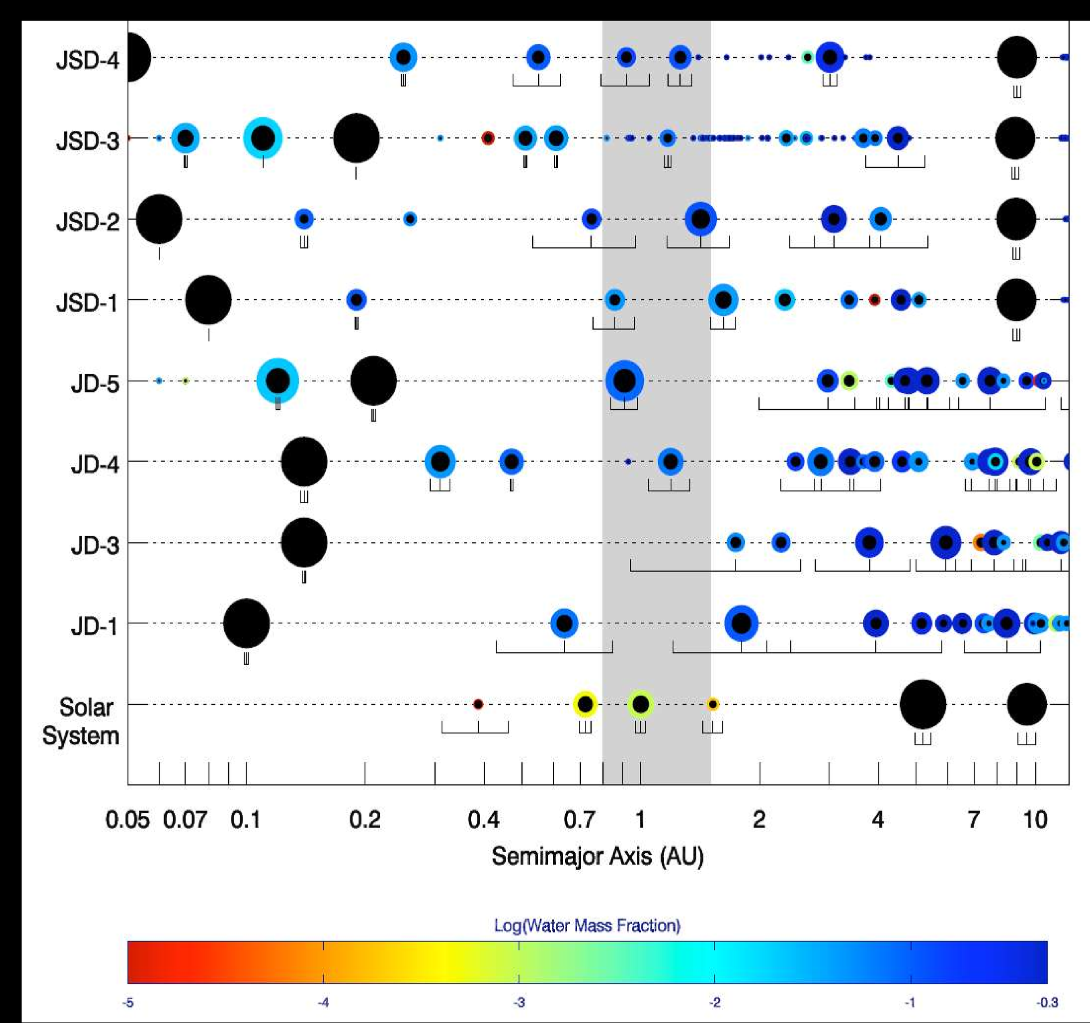


Fig 2 Final Outcomes of 8 simulations including giant planet migration, with the Solar System shown for scale. Dot size indicates relative mass, the inner dark region is the iron core, and the color represents water content. Orbital eccentricity is shown below each planet by the radial excursion over an orbit. The HZ is shaded.

3. Application to Known Exosystems

We scale our limits to other stellar masses by assuming that the ratio of orbital periods between the HZ and our giant planet orbital limits does not change with the stellar mass (Table 1). Out of 178 systems in our sample, 65 (37%) meet our criteria (Fig 4, Table 2).

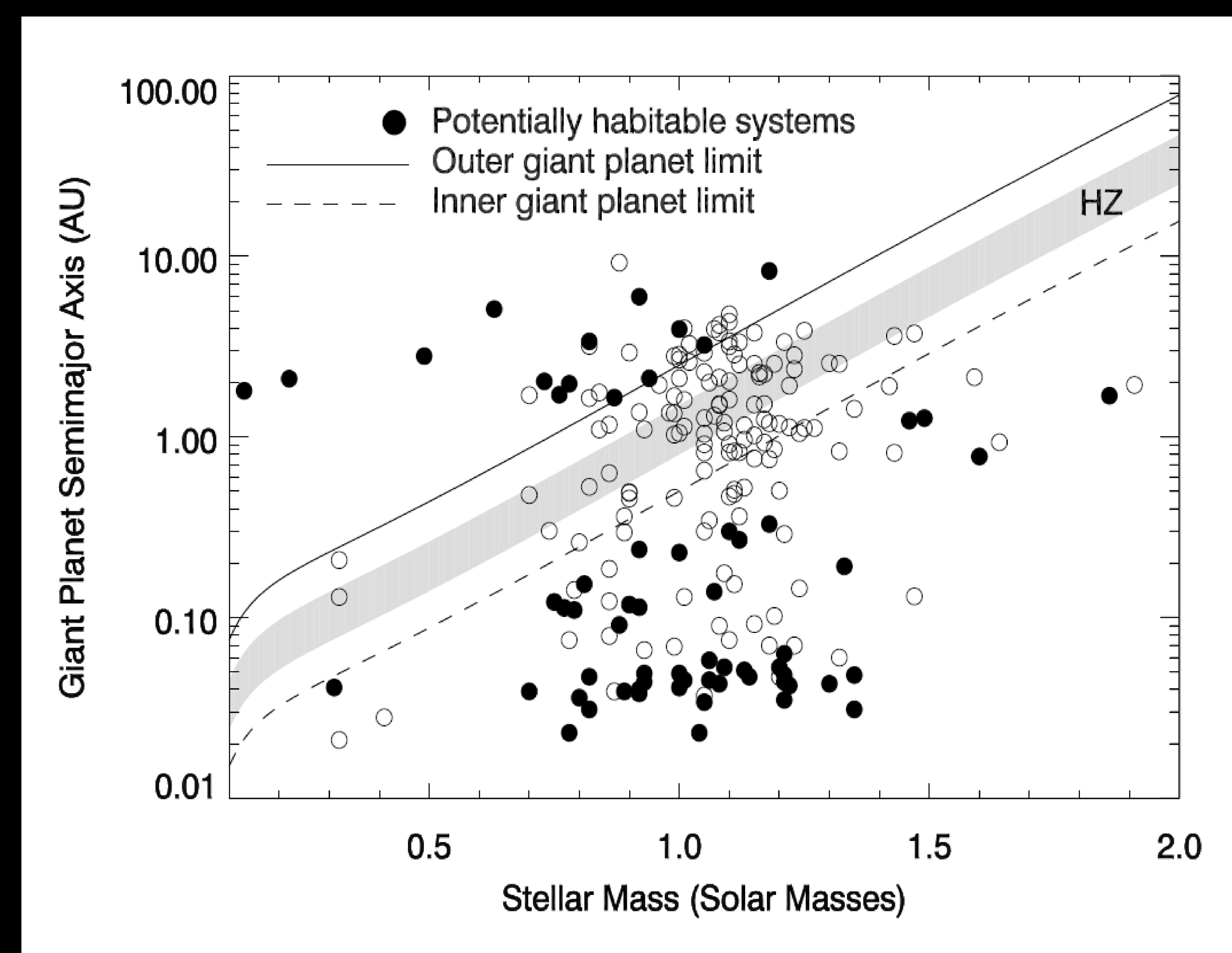


Fig 3 – Giant planet orbital limits vs. stellar mass. The solid and dashed lines mark the outer and inner giant planet limits. Circles represent known exoplanets: filled circles satisfy either the inner or outer giant planet limit. The Habitable Zone (HZ) is shaded.

Table 2. Potentially Habitable Exoplanet Systems[1]

System	$M_\star$ ($M_\odot$)	[Fe/H]	M_{pl} (M_J)	a (AU)	e	HZ
OGLE-05-071L	0.13	—	0.9	1.800	—	0.03-0.06
OGLE-05-390L	0.22	—	0.02	2.100	—	0.06-0.10
GJ 581	0.31	-0.25	0.052	0.041	0.00	0.08-0.14
OGLE235-MOA53	0.36	—	1.5	3.000	—	0.09-0.17
HD 41004 A	0.40	0.16	17.892	0.018	0.08	0.10-0.19
OGLE-05-169L	0.49	—	0.04	2.800	—	0.14-0.25
HD 330075	0.70	0.08	0.623	0.039	0.00	0.28-0.52
HD 27894	0.75	0.3	0.618	0.122	0.05	0.33-0.62
HD 114386	0.76	0.004	1.343	1.714	0.23	0.34-0.64
HD 13445	0.77	-0.27	3.9	0.113	0.04	0.35-0.66
OGLE-TR-113	0.77	0.14	1.35	0.023	0.00	0.35-0.66
HD 111232	0.78	-0.36	6.803	1.975	0.20	0.37-0.69
HD 63454	0.80	0.11	0.385	0.036	0.00	0.39-0.74
HD 192263	0.81	0.05	0.641	0.153	0.05	0.41-0.76
OGLE-TR-111	0.81	0.12	0.52	0.047	0.00	0.41-0.76
Eps Eri	0.82	-0.03	1.058	3.377	0.25	0.42-0.79
HD 189733	0.82	-0.03	1.152	0.031	0.00	0.42-0.79
HD 130322	0.88	0.006	1.088	0.091	0.02	0.52-0.98
TrES-1	0.89	0.001	0.759	0.039	0.00	0.54-1.01
HD 4308	0.90	-0.31	0.047	0.118	0.00	0.56-1.05
55 Cnc e	0.91	0.31	0.038	0.038	0.09	0.58-1.09
55 Cnc b			0.833	0.114	0.01	0.58-1.09
55 Cnc c			0.157	0.238	0.07	0.58-1.09
55 Cnc d			3.887	5.964	0.09	0.58-1.09
HD 46375	0.92	0.24	0.226	0.040	0.06	0.60-1.13
HD 2638	0.93	0.16	0.477	0.044	0.00	0.62-1.17
HD 102195	0.93	-0.09	0.492	0.049	0.06	0.62-1.17
HD 164922	0.94	0.17	0.36	2.110	0.05	0.65-1.21
HD 89307	1.00	-0.16	2.601	3.945	0.01	0.80-1.50
HD 83443	1.00	0.36	0.398	0.041	0.01	0.80-1.50
Rho Cnc B	1.00	-0.20	1.092	0.229	0.06	0.80-1.50
BD -10 3166	1.01	0.38	0.458	0.045	0.02	0.83-1.55
HD 70642	1.05	0.16	1.97	3.230	0.03	0.96-1.79
HD 73256	1.05	0.26	1.867	0.037	0.03	0.96-1.79
HD 212301	1.05	-0.18	0.396	0.034	0.00	0.96-1.79
HD 49674	1.06	0.31	0.105	0.058	0.09	0.99-1.86
HD 195019	1.07	0.07	3.681	0.139	0.01	1.03-1.92
HD 187123	1.08	0.12	0.527	0.043	0.02	1.06-1.99
51 Peg	1.09	0.20	0.472	0.053	0.01	1.10-2.07
HD 107148	1.12	0.31	0.21	0.269	0.05	1.23-2.30
HD 76700	1.13	0.35	0.232	0.051	0.09	1.27-2.38
HD 209458	1.14	0.014	0.689	0.047	0.00	1.31-2.47
OGLE-TR-10	1.17	0.12	0.63	0.042	0.00	1.46-2.74
OGLE-TR-56	1.17	—	1.24	0.023	—	1.46-2.74
HD 121504	1.18	0.16	1.221	0.329	0.03	1.51-2.84
HD 149143	1.20	0.25	1.327	0.053	0.00	1.63-3.05
HD 75289	1.21	0.22	0.466	0.048	0.03	1.68-3.16
HD 109749	1.21	0.26	0.277	0.063	0.00	1.68-3.16
HD 179949	1.21	0.14	0.916	0.044	0.02	1.68-3.16
HD 86081	1.21	0.26	1.49	0.035	0.01	1.68-3.16
HD 149026	1.30	0.36	0.337	0.043	0.00	2.31-4.34
HD 224693	1.33	0.34	0.718	0.192	0.04	2.57-4.82
Tau Boo	1.35	0.23	4.126	0.048	0.02	2.76-5.17
OGLE-TR-132	1.35	0.43	1.19	0.031	0.00	2.76-5.17
HD 177830	1.46	0.54	1.531	1.227	0.10	4.04-7.58
Eps Ret	1.49	0.42	1.556	1.270	0.06	4.48-8.41
HD 104985	1.60	-0.35	6.315	0.779	0.03	6.55-12.27

Table 2 – Known, potentially habitable exoplanet systems. These include one multi-planet system, 55 Cancri. Orbits from www.exoplanets.org and www.exoplanet.eu.

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