Probability of Finding Terrestrial Planet Within Habitable Zone of Extrasolar Planetary System

***Ratna Satyaningsih*[1]**, *Taufiq Hidayat*[2], *Avivah Yamani*[3], *and Budi Dermawan*[2]
[1]*Badan Meteorologi, Klimatologi, dan Geofisika, Jakarta*
[2]*Bosscha Observatory and Astronomy Research Division,*
Institut Teknologi Bandung, Bandung
[3]*langitselatan.com*
e-mail: ratnasatya@bmg.go.id

Received 31 December 2009, accepted for publication 26 March 2010

Abstract

Habitable zone in a planetary system is defined as the region around a star where life-supporting planets can exist. Typically it requires the presence of liquid water on the planetary surface. Considering the formation of planetary systems, we investigate how stellar mass affects the probability of terrestrial planets formed within habitable zone. We use our Planetary System Generator code (Yamani, 2007) to generate planetary systems by investigating its sensitivity through several parameters, such as stellar mass, stellar luminosity, and effective temperature. The probability of finding terrestrial planets within the habitable zone of extrasolar planetary system has been then calculated. We selected the exoplanet systems: Gl 581, HD 128311, 55 Cnc, 47 UMa, and Ups And-like to evaluate the presence of planets within their habitable zone.

*Keywords**:** Planetary system, Habitable zone, Extrasolar planets*

Abstrak

Zona habitasi dalam suatu sistem keplanetan didefinisikan sebagai daerah di sekeliling bintang yang menjadi tempat planet dapat mendukung adanya kehidupan. Khususnya, daerah ini mensyaratkan adanya air dalam fase cair di permukaan planet. Dengan meninjau pembentukan sistem keplanetan, kami menyelidiki bagaimana massa bintang mempengaruhi probabilitas terbentuknya planet kebumian dalam zona habitasi tersebut. Kami menggunakan program Planetary System Generator (Yamani, 2007) untuk membentuk berbagai sistem keplanetan tersebut dengan menyelidiki sensitivitasnya melalui beberapa parameter, misalnya massa bintang, luminositas bintang, dan temperatur efektif. Kemudian, kami menghitung probabilitas mendapatkan planet kebumian dalam zona habitasi sistem keplanetan yang telah ditemukan. Kami memilih system: Gl 581, HD 128311, 55 Cnc, 47 UMa, dan Ups And-like, serta mengevaluasi keberadaan planet-planet dalam zona habitasi tersebut.

*Kata kunci**:** Sistem keplanetan, Zona habitasi, Planet luar-surya*

1. Introduction

Recently, more than 500 extrasolar planets have been discovered orbiting mostly main-sequence stars, including more than 40 multiple-planet systems (Schneider, 2009). The majority of extrasolar planets are hot giant planets with physical conditions that are not likely to support biosphere. Nevertheless, their existence is closely related to the fundamental question: “are we alone?” These discoveries confirm that planets are not unusual in the Universe. Improvement in planetary detection methods and strategy should make it possible to find Earth-like planets as well in the near future through future space missions as well as ground based observations.

Up to now none of such habitable planets has been detected. Note that the smallest planet detected is COROT-7b, namely a super-Earth, whose diameter is less than twice that of the Earth and this planet orbits its star once every 20 hours. Therefore, it is located very close to its parent star, and has a high surface temperature, ~2000 °C (Leger *et al.*, 2009, Queloz *et al.* 2009, Charboneau *et al.*, 2009). Two other super-Earths have been found around an M dwarf star Gl 581, i.e., Gl 581c and Gl 581d with a mass 5.1 $M_\oplus$ and 8.2 $M_\oplus$, respectively (Udry *et al.* 2007). Even if it seems that the present technology has not been feasible yet to detect directly Earth-like planets, we can simulate known exoplanetary systems using a theoretical model to investigate whether they could have Earth-like planets located within the habitable zones.

The region around a star where life-supporting planets can exist is called habitable zone (HZ). Typically it requires the presence of liquid water on the planetary surface. Kasting *et al.*, (1993) investigated habitable zone comprehensively. Using a one-dimensional climate model, they estimated the

Table 1. Basic stellar parameters of five systems selected for this work (Schneider 2009 and references therein)*.

System	Stellar mass (in $M_\odot$)	Radius (in $R_\odot$)	Surface gravity (× 10^4 cm s^{-2})	Age (in Gyr)	Distance (in pc)	Metallicity (Fe/H)	T_{eff} (in K)	Luminosity (in $L_\odot$)	Spectral type
Gl 581	0.31	0.38	5.88	8	6.26	-0.33	3200	0.02	M3V
HD 128311	0.80	0.73	4.11	0.39	16.6	0.08	4965	0.29	K0V
55 Cnc	1.03	1.15	2.13	5.5	13.02	0.29	5243	0.85	G8V
47 UMa-	1.03	1.24	1.83	7.3	13.97	0 ± 0.07	5892	1.34	G0V
Ups And	1.27	1.63	1.31	3.8	13.47	0.09	6212	3.83	F8V

*Note: Uncertainties of each value are not shown in the table, except for the metallicity of 47 UMa

width of the HZ. The inner boundary of the HZ is determined in their model by the loss of water via photolysis and hydrogen escape. The outer boundary of the HZ is determined by the formation of CO_2 clouds. They calculated the HZ boundaries of our Sun as 0.84 AU and 1.67 AU for inner and outer boundary, respectively. Furthermore, the stellar mass plays an important role in the habitability of the planets. Kasting *et al.*, (1993) also calculated the HZ around other main sequence stars and suggested that mid-to-early K stars along with G main sequence stars are the promising candidates to find extraterrestrial life.

Considering the formation of planetary systems, in this paper we present a Monte Carlo simulation using Planetary System Generator (Yamani, 2007, Yamani *et al.*, 2010) to estimate probability of finding terrestrial planet within the habitable zone of extrasolar planetary systems.

We have chosen five multiple-planet systems that represent various mass and spectral type in stars detected harboring planets. The five systems selected are Gl 581, HD 128311, 55 Cnc, 47 UMa, and Ups And, with their basic parameters shown in Table 1. Input parameters of these systems are taken from observational data (Schneider, 2009 and references therein) and then we generate 100 planetary systems for each corresponding system.

2. Habitability in Planetary System Generator

We use a simple Monte Carlo planetary formation model based on ACRETE-Stargen (Dole, 1970, Isaacman and Sagan, 1977, Burrows, 2003, Yamani, 2007), called Planetary System Generator. This code generates planetary system by injecting planetary nuclei randomly through accretion processes of particles within clouds of gas and dust surrounding a newly-formed star. The initial mechanism of the planetary nuclei formation is not specified. However, once a planetary nucleus formed, it can continue to grow by capturing particles (dust) which have low relative velocity. This process will increase its mass and subsequently increase its ability to capture particles with higher relative velocity continuously. Gas can also be accreted once a planet reaches a critical mass. A complete planetary system generation is accomplished after all planets formed. For more detailed explanation about the planetary system formation in the Planetary System Generator as well as its limitation, see Yamani (2007) and Yamani *et al.*, (2010) and references therein.

The Planetary System Generator adopts the criterions suggested by Dole (1964) and Fogg (1992) to determine habitability of the planets generated (Burrows, 2003). There are three aspects that determine the habitability of a planet, i.e., ecosphere, atmosphere, and breathability. The ecosphere represents the stellar habitable zone around the host star. Instead of using approximated ecosphere boundaries provided by the original generator, we calculated the HZ boundary using formulas given by Jones *et al.*, (2006) who adopted previous results from Kasting *et al.*, (1993). The inner and outer boundaries are at distances from the star in AU respectively given by

$$r_{inner} = \left[\frac{L}{S_i(T)}\right]^{1/2} \tag{1}$$

$$r_{outer} = \left[\frac{L}{S_o(T)}\right]^{1/2}, \tag{2}$$

where L is the stellar luminosity in solar units whereas S is critical flux in units of solar constant given by

$$S_i = (4.190 \times 10^{-8}\, T^2) - (2.139 \times 10^{-4}\, T) + 1.296 \tag{3}$$

at the inner boundary, and

$$S_o = (6.190 \times 10^{-9}\, T^2) - (1.319 \times 10^{-5}\, T) + 0.2341 \tag{4}$$

at the outer boundary. T is the effective temperature of the star in Kelvin. Moreover, L and T are obtained from measured properties of stars. In solar units L is calculated by using the relation

Table 2. Gas inventory adopted in the Planetary System Generator

Gas	Atomic weight	Melting point (K)	Boiling point (K)	Density (g cm^{-3})	Terrestrial abundance	Solar abundance	Reac-tivity
H_2	1.0079	14.06	20.40	8.99×10^{-5}	0.001255893	27925.4	1
He	4.0026	3.46	4.20	0.0001787	7.94328×10^{-9}	2722.7	0
N_2	14.0067	63.34	77.40	0.0012506	1.99526×10^{-5}	3.13329	0
O_2	15.9994	54.80	90.20	0.001429	0.501187	23.8232	10
Ne	20.1700	24.53	27.10	0.0009	5.01187×10^{-9}	3.4435×10^{-5}	0
Ar	39.9480	84.00	87.30	0.0017824	3.16228×10^{-6}	0.100925	0
Kr	83.8000	116.60	119.70	0.003708	1×10^{-10}	4.4978×10^{-5}	0
Xe	131.3000	161.30	165.00	0.00588	3.16228×10^{-11}	4.69894×10^{-6}	0
NH_3	17.0000	195.46	239.66	0.001	0.002	0.0001	1
H_2O	18.0000	273.16	373.16	1.000	0.03	0.001	0
CO_2	44.0000	194.66	194.66	0.001	0.01	0.0005	0
O_3	48.0000	80.16	161.16	0.001	0.001	0.000001	2
CH_4	16.0000	90.16	109.16	0.010	0.005	0.0001	1

$$L = (0.787d^2) \times 10^{[-0.4(V+BC)]}, \qquad (5)$$

where V is the apparent visual magnitude, BC is bolometric correction, and d is the distance to the star in parsecs. The spectral type and luminosity class of stars from which we can calculate T are tabulated by Schneider (2009) and references therein. The distance d and apparent visual magnitude V are tabulated as well, whereas BCs can be obtained from Cox (2000).

The Planetary System Generator takes into account the greenhouse effect, surface temperature, and fraction of the planet's surface covered by water, ice, and clouds, and the planet's albedo following Burrows (2003). The greenhouse effect calculations are based on initial surface temperature and the state of water on the surface. If it is too hot, the water will never condense out of the atmosphere, rain down, and form an ocean. The generator also adapts minimum/maximum temperatures and simple atmosphere simulation from Starform (Croughton, 2006). Starform also uses a standard model to determine the state of elements for the temperature and pressure of each planet. Then it calculates abundances of each material. The Planetary System Generator only covers the major atmospheric gases (see Table 2).

In order to determine planetary habitability, the generator evaluated breathability of the atmosphere. It applied the formulas from Dole (1964) to calculate the inspired partial pressure for a gas. Then the generator used it to compare each of the gases from Starform model to the maxima and minima from Dole (1964) (see also Table 3 and 4). Hence, a planet's atmosphere can be categoryzed as breathable, unbreathable (too little oxygen), or poisonous.

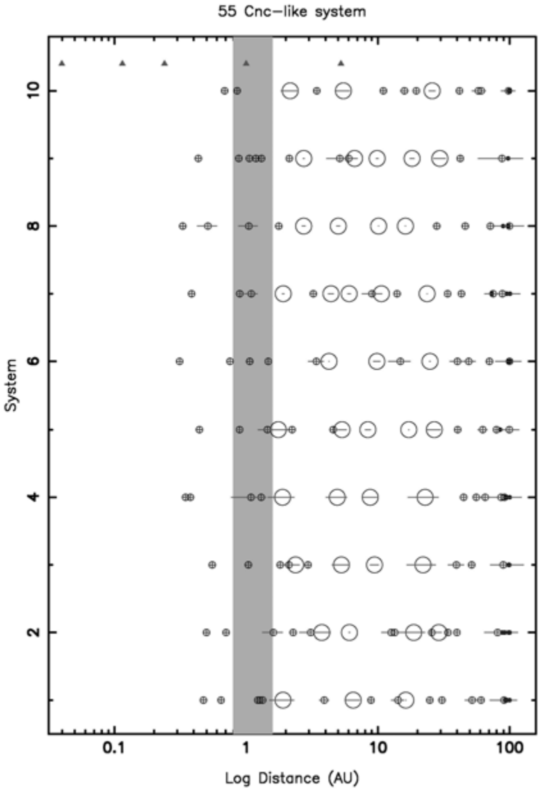

Figure 1. The diagram shows ten out of 100 systems of the 55 Cnc-like system generated by the Planetary System Generator. The gray shaded area indicates the habitable zone of the system. Open circles, crossed circles, and filled circles represent Jovian planets, terrestrial planets, and small bodies, respectively. Locations of the five planets detected orbiting 55 Cnc (represented by filled triangles) are presented here as comparison. Horizontal lines mark the range of orbital distances for planets in eccentric orbits.

3. Results and Discussion

Subsequently, our code simulated 5 different planetary systems: Gl 581-like, HD 128311-like, 55 Cnc-like, 47 Uma-like, and Ups And-like. We generated 100 samples for each system, so the total sample is 500 systems. Actually, a greater number of the sample is better since our code is basically a Monte Carlo method (Yamani *et al.*, 2010).

By using the HZ defined in (1) and (2), the generated systems have been then plotted for each system as a function of the position of the planets. An example of result is shown in Figure 1. The shaded area is the corresponding HZ and one may easily identify the presence of planets within this HZ and then determine the number of the planets in this region. We also show the distance in a logarithmic scale in order to be able to cover a distance up to 120 AU.

Note also that we use symbols open circles, crossed circles, and filled circles (Figure 1) to represent Jovian planets, terrestrial planets, and small bodies, respectively. Locations of the five planets detected orbiting 55 Cnc are also shown, represented by filled triangles (Fischer *et al.*, 2008) for comparison. The horizontal lines mark the range of orbital distances for planets in eccentric orbits. We see that bodies with a relatively high eccentric orbit are mostly found at far distance from the parent star.

In our previous work (Satyaningsih, 2007), by using the stellar mass, luminosity, and spectral type of the stars as parameters, we obtained that, among the selected five stars, a 55 Cnc-like (1.03 $M_\odot$, G8V) with luminosity of 0.85 $L_\odot$ has the highest probability (93%) of finding venusian or rocky planets within the HZ.

A 47 UMa-like (G0V) with the same mass but higher luminosity (1.34 $L_\odot$) has a lower probability (76%). The simulation results show that there is no Earth-like planet within the HZ for both cases. Even if there were any, it would lie far outside the HZ and has an atmosphere that does not support life.

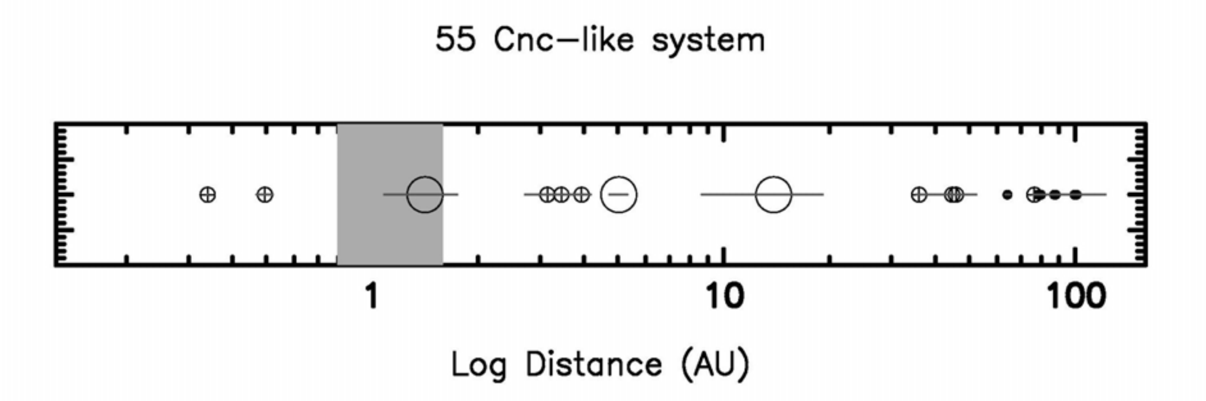

Figure 2. An interesting system of the generated 55 Cnc-like systems where a Jovian planet with Uranus mass resides in the HZ. Although this planet type is unlikely to harbor life, there is a possibility for habitable conditions at the surface of the moons orbiting the planet. Further study in the moons formation is necessary. Symbols used here are the same as in Figure 1.

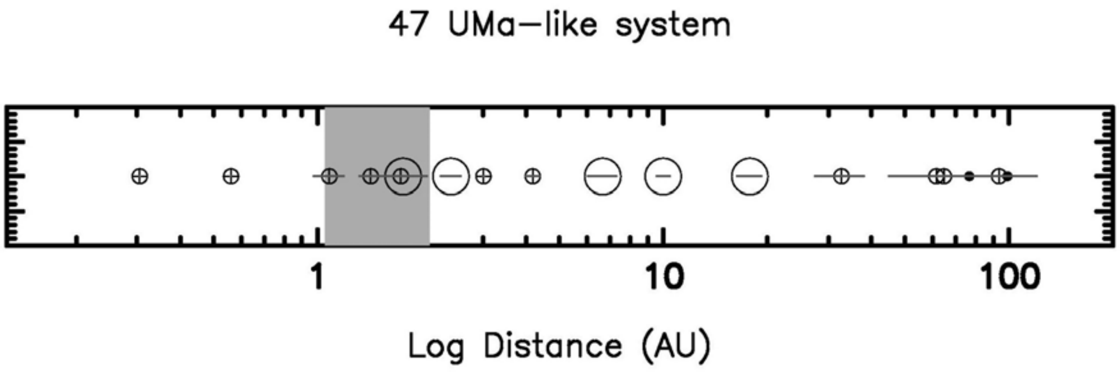

Figure 3. An interesting system of the generated 47 Uma-like systems where a terrestrial planet lies as close as 0.002 AU to a Jovian planet. Both planet reside in the system's HZ along with two other terrestrial planets. It is presumed that the terrestrial planet is either satellite candidate or in resonance to the jovian one.

Table 3. Approximate upper limits for permitted inert gases in a breathable atmosphere, adopted from Dole (1964)

Gases	Approximate maximum permissible inspired partial pressure (mmHg)
Oxygen	60 - 400
Hydrogen	0
Helium	0 - 61000
Neon	0 - 3900
Nitrogen	10 - 2330
Argon	0 - 1220
Krypton	0 - 350
Xenon	0 - 160
Carbon dioxide	0.05 - 7

Table 4. Tolerable concentration of selected gases

Gases	Threshold limits (in parts of milion at 1 atm)
Amonia, NH_3	100
Metana, CH_4	50000
Ozone, O_3	0.1

We found an Ups And-like (1.27 $M_{\odot}$, F8V, 3.83 $L_{\odot}$) that has relative a high probability of finding venusian or rocky planets within the HZ, i.e., ~42%. However, we did not find any Earth-like planet in this system.

For the late spectral type we simulated Gl 581-like system with stellar mass of 0.31 $M_{\odot}$, luminosity 0.02 $L_{\odot}$, and spectral type M3V. The probability of finding venusian or rocky planets within its HZ is 8%. Among 100 systems generated we did not find any gas planet but 52 systems of them have planets which are rich in water. Planets falls in this category in the Planetary System Generator will turn into Earth-like planets if only they have higher temperature. However, the simulation results show that these planets lay outside the HZ of the planetary system.

In the present work, we made a different approach regarding the planet types. We divided planets into three types, i.e., small body, terrestrial, and Jovian, based on planetary masses instead of using ten specific types provided by the generator. Planets with masses less than or equal to 2.1×10^{-3} $M_{\oplus}$ (Pluto mass) are categorized as small body. Those that have masses between the Pluto mass and 9 $M_{\oplus}$ are categorized as terrestrial planets, otherwise they will be called Jovian.

Each system generated has approximately 17 objects in average. Figure 1 shows a typical planetary system formed in our simulations. Here we only show 10 of the 55 Cnc-like systems generated by the Planetary System Generator. A general feature which can be seen clearly is a clump of small bodies in the outer edge of each system. Most of them have high eccentricity. They may correspond to Kuiper Belt Objects (KBOs) in our Solar System. Furthermore, we barely find such objects in the inner part of the systems. It seems that KBOs-like are a common feature in a planetary system as predicted by the theory of the Solar System formation. Another remarkable feature is that planets in the inner part of the systems orbit their host stars in circular or nearly circular orbits.

We found similar results in probability of finding terrestrial planets within the HZ around the stars with a slightly higher mass than the solar mass. The highest probability is given by 55 Cnc-like system with 95 out of 100 systems have terrestrial planets within their HZ. About 35% of these planets have mass ≥ 2 $M_{\oplus}$. We name it as super terrestrial planets. The corresponding results of the probability of findings terrestrial planets within the HZ are shown in Table 5.

Table 5. Probability of findings terrestrial planets within the HZ.

System	Probability (%)
Gl 581-like	8
HD 128311-like	< 2
55 Cnc-like	95
47 UMa-like	83
Ups And-like	62

We found an interresting case where a Jovian planet with Uranus mass resides in the HZ as displayed in Figure 2. Although this planet type is unlikely to harbor life, there is a possibility for habitable conditions at the surface of moons orbiting the planet. Further study in the moons formation included in the code is accordingly necessary. This will be considered in the future work.

Subsequently, following the formation and orbital evolution of 47 UMa-like system discussed in Yamani *et al.*, (2010), we also generate these systems and found a probability of 83% to obtain terrestrial planets within its HZ. We also found an interesting system generated where a terrestrial planet lies as close as 0.002 AU to a Jovian planet. Both planets reside in the HZ of the system along with two other terrestrial planets (Figure 3). We presume that the terrestrial planet could be either satellite candidate or in orbital resonance to the Jovian one.

For a higher mass star, Ups And-like system has a better probability than our previous work, i.e., 55% (Satyaningsih, 2007). We found that out of 100 systems generated there are 62 systems having Jovian planet in their HZs either along with terrestrial planet or Jovian itself.

For a low mass star, the results of simulation for Gl 581-like system show the same probability with our previous result (Satyaningsih, 2007) of finding terrestrial planets, i.e., ~8%. With our new definition for the planet types, we found that there are Jovian planets formed in this system.

The case for HD 128311 is different from GL 581. The former has a mass of 0.81 $M_\odot$, higher than that of GL 581. However, neither Jovian planets nor super terrestrial planets are formed in the HZ. We estimated that the probability to find terrestrial planets is not greater than 2%. This suggests that we need to take more samples for various low mass and spectral type stars for a future work.

4. Concluding Remarks

With a Monte Carlo computer simulation we can generate planetary systems that possibly have common features as our Solar System. The corresponding code was used to study the probability of finding rocky planets within its habitable zone. The results are approximately realistic within the limitation of the method used, especially if the sampled system is large. This may also provide us with an insight of any possible planetary systems formed.

Our present simulation results suggest that the best candidates for searching terrestrial planets are main sequence stars with ~1 $M_\odot$ and late G spectral type. A system of 55 Cnc-like has a higher probability to have terrestrial planets within its HZ. The probability seems decreasing for higher mass stars. However, the result for low mass stars is still not conclusive and needs to be studied further.

Our model did not form any hot Jupiter as expected. It is because we did not include migration mechanism in our model and this will be devoted to one of our future works. It is necessary as well to investigate satellite and moon formation. In separate model we can study atmospheric evolution to study planetary habitability.

Acknowledgements

This research was supported by *Hibah Penelitian Tim Pascasarjana – Dikti, Batch IV*, 2006-2007, to which the authors gratefully appreciated.

References

Burrows, J., 2003, *STARGEN – Solar System Generator*. http://www.eldacur.com/~brons/NerdCorner/StarGen/StarGen.html.

Charbonneau, D., *et al.*, 2009, A super-Earth transiting a nearby low-mass star, *Nature*, **462**, 891-894.

Cox, A.N., 2000, *Allen's Astrophysical Quantities* 4th Edition, Springer, New York.

Croughton, C., 2007, http://www.keris.net/stars/readme.txt

Dole, S.H,, 1964, *Habitable Planets for Man*, Blaisdell, New York.

Dole, S.H., 1970, Computer Simulation of the Formation of Planetary Systems, *Icarus*, **13**, 494-508.

Fischer, D. A., G. W. Marcy, R. P. Butler, S. S. Vogt, G. Laughlin, G. W. Henry, D. Abouav, K. M. G. Peek, J. T. Wright, J. A. Johnson, C. McCarthy, and H. Isaacson, 2008, Five Planets Orbiting 55 Cancri, *Astrophys. Journal*, **675**, 790-801.

Fogg, M. J., 1992, An Estimate of the Prevalence of Biocompatible and Habitable Planets, *Journal of the British Interplanetary Society*, **45**, 3-12.

Isaacman, R., and C. Sagan, 1977, Computer Simulation of Planetary Accretion Dynamics: Sensitivity to Initial Conditions. *Icarus*, **31**, 510-533.

Jones, B.W., P. N. Sleep, and D. R. Underwood, 2006, Habitability of known exoplanetary systems based on measured stellar properties, *Astrophys. Journal*, **649**, 1010-1019.

Kasting, J.F., D. P. Whitmire, and R. T. Reynolds, 1993, Habitable Zones Around Main Sequence Stars. *Icarus*, **101**, 108-128.

Léger, A., *et al.*,, 2009, Transiting exoplanets from the CoRoT space mission. VIII. CoRoT-7b: the first super-Earth with measured radius, *Astron. & Astrophys.*, **506**, 287-302.

Queloz, D., *et al.*, 2009, The CoRoT-7 planetary system: two orbiting super-Earths, *Astron. & Astrophys.*, **506**, 303-319.

Satyaningsih, S., 2007, *Habitable Zone* di Sekitar Bintang yang Dideteksi Memiliki Planet, *Master Thesis*, Program Studi Astronomi Institut Teknologi Bandung.

Schneider, J., 2009, *Extrasolar Planet Catalog*. (http://exoplanet.eu).

Udry, S., Bonfils, X., Delfosse, X., Forveille, T., Mayor, M., Perrier, C., Bouchy, P., Lovis, C., Pepe, F., Queloz, D., Bertaux, J. -L., 2007, *Astron.& Astrophys.* **469**, L43-L47.

Yamani, A. 2007, Pemodelan Sistem Keplanetan: Tinjauan Sistem Tata Surya dan Sistem 47 Ursa Mayoris, *Master Thesis*. Program Studi Astronomi, FMIPA, ITB.

Yamani, A., Hidayat, T., Satyaningsih, R., and Dermawan, B., 2010, A Monte Carlo Modeling of Planetary Formation: A Case of 47 Ursae Majoris System, *Jurnal Matematika dan Sains*, **15:2**, 64-70.