Probability Distribution of Terrestrial Planets in Habitable Zones around Host Stars

Jianpo Guo\textsuperscript{1,2,3}, Fenghui Zhang\textsuperscript{1,2}, Xuefei Chen\textsuperscript{1,2}, and Zhanwen Han\textsuperscript{1,2}

\textsuperscript{1} National Astronomical Observatories/Yunnan Observatory, Chinese Academy of Sciences, Kunming, 650011, P.R. China
e-mail: guojianpo1982@hotmail.com
\textsuperscript{2} Key Laboratory for the Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, Kunming, 650011, P.R. China
\textsuperscript{3} Graduate School of the Chinese Academy of Sciences, Beijing, 100049, P.R. China

Published on Ap&SS; Oct. 2009

Abstract. With more and more exoplanets being detected, it is paid closer attention to whether there are lives outside solar system. We try to obtain habitable zones and the probability distribution of terrestrial planets in habitable zones around host stars. Using Eggleton’s code, we calculate the evolution of stars with masses less than 4.00 $M_\odot$. We also use the fitting formulae of stellar luminosity and radius, the boundary flux of habitable zones, the distribution of semimajor axis and mass of planets and the initial mass function of stars. We obtain the luminosity and radius of stars with masses from 0.08 to 4.00 $M_\odot$, and calculate the habitable zones of host stars, affected by stellar effective temperature. We achieve the probability distribution of terrestrial planets in habitable zones around host stars. We also calculate that the number of terrestrial planets in habitable zones of host stars is 45.5 billion, and the number of terrestrial planets in habitable zones around K type stars is the most, in the Milky Way.

Key words. Planets: general — Stars: evolution — Astrobiology

1. Introduction

Nowadays, more and more exoplanets have been indirectly detected, and they were even directly detected last year (Marois et al., 2008). And theories about planetary evolution point out that most of stars own planets. It is paid closer attention to whether there are lives around other stars, not only by astronomy filed, but also by many other realms. A planet which is suited to life survive must satisfy two factors, one is that it is a terrestrial planet, and the other is that it must be in the habitable zone (HZ) of its host star.

Terrestrial planets are rocky planets from one to ten Earth masses with the same chemical and mineral composition as the Earth (Valencia et al., 2006). However, others argued that the mass of terrestrial planet could be down to about 0.3 Earth mass, to retain its atmosphere over long geological timescales and to sustain tectonic activity as required for the carbon-silicate cycle to operate (Williams et al., 1997; Menou & Tabachnik, 2003).

Typically, stellar HZ is defined as region near the host star, where water at the surface of a terrestrial planet is in liquid phase (eg., Hart, 1978; Kasting et al., 1993; Franck et al., 2000; Noble et al., 2002; Jones et al., 2006). Previously, it is thought that the boundary flux of HZ depends on luminosity (eg., Kasting et al., 1993). However, it is pointed out that this flux also depends on stellar effective temperature $T_{\text{eff}}$ (Forget & Pierrehumbert, 1997; Williams & Kasting, 1997; Mischna et al., 2000; Jones 2004; Jones et al. 2006). As the greenhouse effect can raise the mean temperature of terrestrial planets (Clube et al., 1996), and the greenhouse effect is different for different radiation. For example, the lower $T_{\text{eff}}$, the more the infrared fraction in luminosity, and the more this fraction, the more the greenhouse effect for a given stellar flux (Jones et al., 2006). Thus, the distances at both inner and outer HZ boundaries are farther to host star, with lower $T_{\text{eff}}$, than they would have been if the $T_{\text{eff}}$ effect is not taken into consideration. And the distances are closer to host star with higher $T_{\text{eff}}$.

It is well known that HZ widths for different stars are different. For example, the HZ width for a M type star is...
only about one fifth to one fiftieth of the HZ width for a G type star (Tarter et al., 2007). However, it does not mean that the probability of terrestrial planet in HZ around a M type star is also about one fifth to one fiftieth of the probability around a G type star. Fortunately, planetary evolution has been calculated, which matched well with the observation data considering selective effects (Ida & Lin, 2004, 2005; Schlaufman et al., 2009). Ida & Lin (2005) gave the distribution of semimajor axis and mass of planets predicted by the Monte Carlo simulations. The masses of host stars are 0.20, 0.40, 0.60, 1.00 and 1.50 $M_\odot$, respectively. And this distribution can be used to calculate the probability of terrestrial planets in HZs around different host stars.

Jones et al. (2006) gave the HZ flux at both inner and outer boundaries, as a function of $T_{\text{eff}}$, but did not give the flux for host stars. Using Eggleton’s code, we calculate stellar evolution and achieve the relationship between stellar mass and $T_{\text{eff}}$. We get the HZ flux, at both inner and outer boundaries, for host stars at zero age main sequence (ZAMS) and at the terminal of main sequence (TMS). And the HZ flux for host star with mass 4.00 $M_\odot$ is about five times more than that of host star with mass 0.40 $M_\odot$ at inner boundary and about four times at outer boundary. Then we obtain the HZs of host stars with masses from 0.08 to 4.00 $M_\odot$ at ZAMS and at TMS, taken the $T_{\text{eff}}$ effect into consideration.

Using the distribution of semimajor axis and mass of planets (Ida & Lin, 2005), we obtain the probability distribution of terrestrial planets in HZs around host stars. Then, we calculate that the number of terrestrial planets in habitable zones of host stars is 45.5 billion in the Milky Way. And the number of terrestrial planets in HZs for M, K, G and F type stars are respectively as 11.548 billion, 12.930 billion, 7.622 billion and 5.556 billion, in the Milky Way.

The outline of the paper is as follows: we present some input descriptions in Section 2, give our results in Section 3, present some discussions in Section 4, and then finally in Section 5 we give our conclusions.

2. Input descriptions

2.1. The least lifetime of the main sequence for host stars

Life emergence needs habitable environment with long enough time. Jones et al. (2006) thought that it needed at least 1.0 Gyr. And planets cover a presumed heavy bombardment phase as on Earth, at the first 700 Myr (Jones, 2004; Lal, 2008). Hence, The lifetime of the main sequence (MS) for host stars is at least 1.7 Gyr, according to this issue.

However, this requirement may be too strict. The isotopic signature of carbon granules in the Isua formation (more than 3.7 Gyr) is interpreted as evidence for prokaryotic life (Rosing, 1999). And there is evidence that there was liquid water on Earth about 4.3 Gyr ago (Mojsis et al., 2001). It is well known that the solar age is about 4.57 Gyr (Bahcall et al., 1995). These mean that archaic life had come forth when our solar was about 800 Myr old, and the environment on Earth may be suited to biological evolution when solar was about 200-300 Myr old. Hence, we adopt that the least lifetime of MS for host stars is about 200 Myr.

2.2. Input physics of stellar evolution

We use the stellar evolution code of Eggleton (1971, 1972, 1973), which has been updated with the latest input physics over the last three decades (Han et al., 1994; Pols et al., 1995, 1998). We set the convective overshooting parameter, $\delta_{\text{OV}} = 0.12$ (Pols et al., 1997; Schröder et al., 1997). We adopt metal mixture by Grevesse & Sauval (1998).

We use OPAL high temperatures opacity tables (Iglesias & Rogers, 1996; Eldridge & Tout, 2004) in the range of $4.00 < \log(T/\text{K}) \leq 8.70$, and the new Wichita state low temperature molecular opacity tables (Ferguson et al., 2005) in the range of $3.00 \leq \log(T/\text{K}) < 4.00$. And we have made the opacity tables match well with Eggleton’s code (Chen & Tout, 2007; Guo et al., 2008).

In our calculation, the value of metallicity is 0.02. As the lifetime of MS for star with mass 4.00 $M_\odot$ is about 183 Myr, we calculate the evolution of stars with masses less than 4.00 $M_\odot$. Stars with masses less than 0.50 $M_\odot$ are spaced by $\Delta M = 0.05M_\odot$, and stars with masses more than 0.50 $M_\odot$ are spaced by $\Delta M = 0.10M_\odot$.

2.3. The initial mass function of stars

In the Milky Way, it is well known that the number of stars with different masses is different. In our calculation, we adopt the initial mass function of Kroupa et al. (1993).

$$\xi(M) = \left\{ \begin{array}{ll} c_1M^{-1.3}, & 0.08 \leq M < 0.5, \\ c_2M^{-2.2}, & 0.5 \leq M < 1.0, \\ c_3M^{-2.7}, & 1.0 \leq M < \infty, \end{array} \right. \quad (1)$$

where $\xi(M)\text{d}M$ is the probability of stars with masses between $M$ and $M + \text{d}M$, in solar units. The mass function is normalized according to

$$\int_{0.08}^{\infty} \xi(M)\text{d}M = 1, \quad (2)$$

so that $c_1 = 0.255508$ and $c_2 = 0.138704$.

3. Results

3.1. Fitting formulae for stellar luminosity and radius

The fitting formulae of stellar luminosity and radius have been completed by formers (Tout et al., 1996; Hurley et al., 2000). However, the studies before 2005 used the old Wichita state low temperature molecular opacity tables (Alexander & Ferguson, 1994), and there are some errors for the old opacity tables (Weiss et al., 2006). Therefore, it is required to fit these formulae over again.
obtained from the former shapes (Tout et al., 1996), and achieve a series of new fitting coefficients.

For stellar luminosity and radius at ZAMS, we modify the former shapes (Hurley et al., 2000) and fit again, and the fitting coefficients are seen in Tab. 1, as Fig. 1.

3.1.1. Stellar luminosity and radius at ZAMS

For stellar luminosity and radius at ZAMS, we fully use the former shapes (Tout et al., 1996), and achieve a series of new fitting coefficients.

\[ L_{\text{ZAMS}} = a_1 M^{5.5} + a_2 M^{11} \]
\[ R_{\text{ZAMS}} = a_8 M^{2.5} + a_9 M^{6.5} + a_{10} M^{11} + a_{11} M^{19} + a_{12} M^{19.5} \]

where \( L_{\text{ZAMS}} \) and \( R_{\text{ZAMS}} \) are stellar luminosity and radius at ZAMS, respectively, both in solar units. And \( M \) is stellar mass, also in solar units, the same as Eqs. in what follows. The fitting coefficients are seen in Tab. 1, the same as Eqs. (5), (6) and (14). And stellar \( T_{\text{eff}} \) can be obtained from \( L = 4\pi R^2 \sigma T_{\text{eff}}^4 \). Hence, we can achieve the relationship between stellar mass and \( T_{\text{eff}} \) at ZAMS, seen in Fig. 1.

3.1.2. Stellar luminosity and radius at TMS

For stellar luminosity and radius at TMS, we modify the former shapes (Hurley et al., 2000) and fit again, and the expressions are

\[ L_{\text{TMS}} = a_{17} M^{2.5} + a_{18} M^{3} + a_{19} M^{4} + a_{20} M^{a_{21} + 1.8} \]
\[ R_{\text{TMS}} = \begin{cases} \frac{104 + 111 M^{12} + 434 M^{14}}{434 + 111 M^{14}}, & M < 1.4, \\ \frac{174 + 183 M^{10} + 203 M^{10 + 1.5}}{21 + M^7}, & M \geq 1.4. \end{cases} \]

Table 1. The fitting coefficients for Eqs. (3), (4), (5), (6) and (14), eg., \( a_{20} = 2.281557 \times 10^2 \).

| Names | Values |
|-------|--------|
| \( a_{1} - a_{4} \) | 5.799011(−1) 1.975333(+1) |
| \( a_{5} - a_{4} \) | 4.062986(−4) 9.883841(+0) |
| \( a_{11} - a_{12} \) | −1.117310(−1) 1.704116(+1) |
| \( a_{9} - a_{10} \) | 6.263268(−1) 8.677444(+1) |
| \( a_{11} - a_{12} \) | −3.431214(+0) 5.031012(+0) |
| \( a_{13} - a_{14} \) | 1.209713(−1) 3.072570(+1) |
| \( a_{15} - a_{16} \) | 1.559054(+2) 8.999767(−1) |
| \( a_{17} - a_{18} \) | 2.323133(+1) −5.638277(+1) |
| \( a_{19} - a_{20} \) | 5.744080(+1) 2.281557(+2) |
| \( a_{21} - a_{22} \) | 7.253992(−1) 1.308659(+2) |
| \( a_{23} - a_{24} \) | 7.658900(−0) 2.603165(+3) |
| \( a_{25} - a_{26} \) | 1.567244(+1) 1.617766(+0) |
| \( a_{27} - a_{28} \) | 2.598418(+3) −5.173614(−3) |
| \( a_{29} - a_{30} \) | 6.812527(+0) −2.372715(+0) |
| \( a_{31} - a_{32} \) | −3.766510(−1) 2.528181(+0) |
| \( a_{33} - a_{34} \) | 5.607602(+0) −7.590386(−3) |
| \( a_{35} - a_{36} \) | −1.874021(−1) 3.915412(+0) |
| \( a_{37} - a_{38} \) | 4.871755(+0) 6.316666(−2) |
| \( a_{39} - a_{40} \) | 7.910809(−1) 5.999996(−1) |
| \( a_{41} \) | 2.052252(−1) |

where both \( L_{\text{TMS}} \) and \( R_{\text{TMS}} \) are in solar units.

3.2. HZs of host stars

The inner HZ boundary is determined by the loss of water via photolysis and hydrogen escape. And the outer HZ boundary is determined by the condensation of CO crystals out of the atmosphere (von Bloh et al., 2007). Jones et al. (2006) gave the HZ flux at both inner and outer boundaries, as a function of \( T_{\text{eff}} \).

\[ \frac{S_{\text{in}}}{S_\odot} = 4.190 \times 10^{-8} T_{\text{eff}}^2 - 2.139 \times 10^{-4} T_{\text{eff}} + 1.296, \]  
\[ \frac{S_{\text{out}}}{S_\odot} = 6.190 \times 10^{-9} T_{\text{eff}}^2 - 1.319 \times 10^{-5} T_{\text{eff}} + 0.2341, \]

where \( S_\odot \) is solar constant and \( T_{\text{eff}} \) is in Kelvin. As we have obtained the relationship between stellar mass and \( T_{\text{eff}} \), we can obtain the HZ boundary flux of host stars with masses from 0.08 to 4.00 \( M_\odot \), seen in Fig. 2. The more massive is the host star, the higher is \( T_{\text{eff}} \), and the more is the HZ flux at both inner and outer boundaries.

As \( L = 4\pi d^2 S \), and the three parameters are just as \( L_\odot \), AU and \( S_\odot \), for our Earth. Hence, the distances at both inner and outer HZ boundaries are given by

\[ \frac{d_{\text{in}}}{AU} = \left( \frac{L}{L_\odot} \right)^{1/2} \left( \frac{S_{\text{in}}}{S_\odot} \right)^{1/2}, \]  
\[ \frac{d_{\text{out}}}{AU} = \left( \frac{L}{L_\odot} \right)^{1/2} \left( \frac{S_{\text{out}}}{S_\odot} \right)^{1/2}. \]

According to the data of Fig. 2 and Eqs. (3), (9) and (10), we can obtain the distances of HZs around host stars with masses from 0.08 to 4.00 \( M_\odot \) at ZAMS, seen in Fig. 3. Using the same method, we achieve the distances of HZs around host stars at TMS, also seen in Fig. 3.
3.3. Probability distribution of terrestrial planets in HZs around host stars

We take that terrestrial planet is the planet with mass from 0.3 to 10 Earth masses (Williams et al., 1997; Menou & Tabachnik, 2003; Valencia et al., 2006), and semimajor axis is the distance between the planet and its host star. Using the data of Fig. 2a in Ida & Lin (2005), we count the number of terrestrial planets whose semimajor axis lie in the HZs of the host stars at ZAMS, noted as np(M). The masses of host stars are 0.20, 0.40, 0.60, 1.00 and 1.50 M⊙, respectively. And we denote the probability of terrestrial planets in HZs around host stars as p(M). As the evolution of a total of 20000 planets is calculated for each run, the relationship between p(M) and np(M) is

\[ p(M) = kp \times np(M)/20000. \]  

In order to obtaining the value of kp, we need the data about planets in our solar system. The number of planets with masses more than 0.1 Earth mass, for the host star with mass 1.00 M⊙, is 6429, according to the data of Fig. 2a in Ida & Lin (2005). And there are 8 planets with masses more than 0.1 Earth mass, in our solar system. Hence, we can get the value of kp from

\[ 8 = kp \times 6429/20000, \]  

so that \( kp = 24.88723 \). Therefore, we get the linear relationship between p(M) and np(M), just as

\[ p(M) = 24.88723 \times np(M)/20000 = 1.2443615 \times 10^{-3} \times np(M). \]  

For the host star with mass 0.20 M⊙, the distances at both inner and outer HZ boundaries are 0.081288 and 0.162912 AU, respectively. And the np(M) is 52, so that p(M) = 0.064707, according to Eq. (13). Using the same method, we also get the np(M) and the p(M) for host stars with masses 0.40, 0.60, 1.00 and 1.50 M⊙, seen in Tab. 2. According to the p(M) for these five stars, we obtain p(M) around host stars with masses from 0.08 to 4.00 M⊙, seen in Eq. (14) and Fig. 4.

\[ p(M) = \begin{cases} a_{38} M^{a_{37}} + a_{38}, & M \leq 0.60, \\ a_{39} (M - a_{40})^{a_{41}} + a_{41}, & M > 0.60. \end{cases} \]  

It may be too rough that p(M) is obtained by extrapolation, with stellar mass more than 1.50 M⊙. However, it is seen that p(M) increases with increasing stellar mass and the increasing trend becomes slower and slower, for host stars with masses from 0.60 to 1.50 M⊙. And p(M) lasts this increasing trend, for host stars with masses more than 1.50 M⊙. In addition, the value of \( \xi(M) \) for stars with masses more than 1.50 M⊙ in the Milky Way is very low. Therefore, it is acceptable that the formula is fitted from five points, although it is not very perfect.

3.4. Probability distribution of terrestrial planets in HZs around host stars in the Milky Way

We use Prob(M) to denote the probability of terrestrial planets in HZs around host stars in the Milky Way. Therefore, Prob(M) is equal to p(M) multiplied by \( \xi(M) \) seen in Eq. (1).

\[ Prob(M) = p(M) \times \xi(M). \]
decreasing stellar mass. When stellar mass is less than 0.35 $M_\odot$, $p(M)\propto 1/(M_\odot)^{1.6}$, and from 0.80 to 1.05 $M_\odot$ and from 1.05 to 1.40 $M_\odot$ (Grießmeier et al., 2005), respectively. Therefore, the number of terrestrial planets in HZs for M, K, G and F type stars are 11.548 billion, 12.930 billion, 7.622 billion and 5.556 billion, respectively.

These mean that the number of terrestrial planets around K type stars is the most in the Milky Way. Because both the number of K type stars and the $p(M)$ around K type stars are great. And the $p(M)$ around M type stars is very low, although the number of M type stars is huge. On the contrary, the number of G type stars is minor, although the $p(M)$ around G type stars is high.

In order to estimating the number of terrestrial planets with lives or even intelligent lives in the Milky Way, we use the critical step model of biological evolution (Cater & McCrea, 1983; Watson, 2008). The model assumes that biological evolution needs sequentially pass several critical steps. And the successful probability for each step is very low, eg., 10% (Watson, 2008). The five step model is perfect, as it matches well with the observed date. Watson (2008) pointed out that the five critical steps are life emergence (primary life), prokaryotes to eukaryotes, asexual clones to sexual populations, cell differentiation (complex life) and primate societies to human societies (intelligent life).

As the number of terrestrial planets in HZs of host stars in the Milky Way is about 300 billion. And observations tell us that upwards of 50% of the stars populating galaxies are expected to be in binary or higher-order multiple systems (eg., Duquennoy & Mayor, 1991; Richichi et al., 1994). Previously, it was generally thought that these systems are not suited to life survive. Recently, it was pointed out that terrestrial planets may be stable in binary systems for a long time (eg., David et al., 2003; Fatuzzo et al., 2006; Saleh & Rasio, 2009). Hence, the number of host stars that may be suitable for life survive in the Milky Way is about 200 billion, noted $N$ as the follows. Therefore, the number of terrestrial planets in HZs of host stars in the Milky Way is

$$N_{\text{planet}} = N \int_{0.08}^{4.00} p(M)\xi(M)\mathrm{d}M = 4.5507 \times 10^{10}. \quad (16)$$

When stellar mass is less than 0.35 $M_\odot$, $p(M)$ increases gently, but $\xi(M)$ decreases dramatically. Hence, $\text{Prob}(M)$ decreases with increasing stellar mass. When stellar mass is from 0.35 to 0.62 $M_\odot$, $p(M)$ increasing rate is more than $\xi(M)$ decreasing rate, so that $\text{Prob}(M)$ increases with increasing stellar mass. And $\text{Prob}(M)$ meets a peak value, with stellar mass 0.62 $M_\odot$. When stellar mass is more than 0.62 $M_\odot$, $\xi(M)$ decreasing rate is more than $p(M)$ increasing rate, so that $\text{Prob}(M)$ decreases with increasing stellar mass.
are terrestrial planets (Ida & Lin, 2005). And the HZs of host stars with masses about 0.10 $M_\odot$ is approximately just as 0.03 AU. Hence, there must be many terrestrial planets in the HZs for these stars. Considering that there is huge number of stars with masses about 0.10 $M_\odot$, the probability of terrestrial planets in HZs around these stars must be very high in the Milky Way.

In the Monte Carlo simulations of planet formation processes before 2008 (eg., Ida & Lin, 2005), it neglected the effects of type I migration of protoplanetary embryos due to their tidal interaction with their nascent disks. And it is found that the type I migration provides a self-clearing mechanism for planetesimals in the terrestrial planet region (Ida & Lin, 2008), which may modulate the distribution of semimajor axis and mass of planets.

Ultraviolet radiation is a double-edged sword to life. If it is too strong, the terrestrial biological systems will be damaged. And if it is too weak, the synthesis of many biochemical compounds can not go along (Buccino et al., 2006). In our future work, we are also plan to study the ultraviolet habitable zones of host stars.

5. Conclusion

Firstly, we obtain the HZs of host stars with masses form 0.08 to 4.00 $M_\odot$ at ZAMS and at TMS, considering the $T_{\text{eff}}$ effect. Secondly, we give the probability distribution of terrestrial planets in HZs of host stars. Thirdly, we calculate the number of terrestrial planets in HZs of host stars is 45.5 billion in the Milky Way, and find that the number of terrestrial planets around K type stars is the most in the Milky Way. Finally, we present discussions about the host stars with masses about 0.10 $M_\odot$ and the effects of type I migration, and introduce our future work. One may also send any special request to guojianpo1982@hotmail.com or guojianpo16@163.com.

Acknowledgements. This work is supported by the National Natural Science Foundation of China (Grant Nos. 10773026, 10821061 and 2007CB815406), the Chinese Academy of Sciences (Grant No. KJCX2-YW-T24) and Yunnan Natural Science Foundation of China (Grant Nos. 10773026, 10821061 and 2007CB815406), the Chinese Academy of Sciences (Grant No. KJCX2-YW-T24) and Yunnan Natural Science Foundation of China (Grant No. KJCX2-YW-T24) and Yunnan Natural Sciences (Grant No. KJCX2-YW-T24). Jianpo Guo thanks Prof Ida, Prof Watson and Prof Jones for help.

References

Alexander, D. R., & Ferguson, J. W. 1994, ApJ, 437, 879
Bahcall, J. N., Pinsonneault, M. H., & Wasserburg, G. J. 1995, Rev. Mod. Phys., 67, 781
Buccino, A. P., Lemenchand, G. A., & Mauas, P. J. D. 2006, Icarus, 183, 491
Carter, B., & McCrea, W. H. 1983, Phil. Trans. R. Soc. Lond. A, 310, 347
Chen, X. F., & Tout, C. A. 2007, ChJAA, 7, 2, 245
Clube, S. V. M., Hoyle, F., Napier, W. M., & Wickramasinghe, N. C. 1996, Ap&SS, 245, 43
David, E.-M., Quintana, E. V., Fatuzzo, M., & Adams, F. C. 2003, PASP, 115, 825
Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485
Eggleton, P. P. 1971, MNRAS, 151, 351
Eggleton, P. P. 1972, MNRAS, 156, 361
Eggleton, P. P. 1973, MNRAS, 163, 279
Eldridge, J. J., & Tout, C. A. 2004, MNRAS, 348, 201
Fatuzzo, M., Adams, F. C., Gauvin, R., & Proszkow, E. M. 2006, PASP, 118, 1510
Ferguson, J. W., Alexander, D. R., Allard, F., et al. 2005, ApJ, 623, 585
Forget, F., & Pierrehumbert, R. T. 1997, Science, 278, 1273
Franck, S., von Bloh, W., Bouman, C., et al. 2000, J. Geophys. Res., 105, 1651
Grevesse, N., & Sauval, A. J. 1998, SSRv, 85, 161
Grießmeier, J.-M., Stadelmann, A., Motschmann, U., et al. 2005, Astrobiology, 5, 5, 587
Guo, J. P., Zhang, F. H., Chen, X. F., & Han, Z. W. 2008, ChJAA, 8, 3, 262
Han, Z. W., Podsiałowski, Ph., & Eggleton, P. P. 1994, MNRAS, 270, 121
Hart, M. H. 1978, Icarus, 33, 23
Hurley, J. R., Pols, O. R., & Tout, C. A. 2000, MNRAS, 315, 543
Ida, S., & Lin, D. N. C. 2004, ApJ, 604, 388
Ida, S., & Lin, D. N. C. 2005, ApJ, 626, 1045
Ida, S., & Lin, D. N. C. 2008, ApJ, 673, 487
Iglesias, C. A., & Rogers, F. J. 1996, Ap&SS, 245, 43
Jones, B. W. 2004, Life in the Solar System and Beyond (London: Springer)
Jones, B. W., Sleep, P. N., & Underwood, D. R. 2006, ApJ, 649, 1010
Kasting, J. F., Whitmire, D. P., & Reynolds, R. T. 1993, Icarus, 101, 108
Kroupa, P., Tout, C. A., & Gilmore, G. 1993, MNRAS, 262, 545
Lal, A. K. 2008, Ap&SS, 317, 267
Marois, C., Macintosh, B., Barman, T., et al. 2008, Science, 322, 1348
Menou, K., & Tabachnik, S. 2003, ApJ, 583, 473
Mischna, M. A., Kasting, J. F., Pavlov, A., & Freedman, R. 2000, Icarus, 145, 546
Mojzsis, S. J., Harrison, T. M., & Pidgen, R. T. 2001, Nature, 409, 178
Noble, M., Musielak, Z. E., & Cuntz, M. 2002, ApJ, 572, 1204
Pols, O. R., Tout, C. A., Eggleton, P. P., & Han, Z. W. 1995, MNRAS, 274, 964
Pols, O. R., Tout, C. A., Schröder, K.-P., et al. 1997, MNRAS, 289, 869
Pols, O. R., Schröder, K.-P., Hurley, J. R., et al. 1998, MNRAS, 298, 525
Richichi, A., Leinert, Ch., Jameson, R., & Zinnecker, H. 1994, A&A, 287, 145
Rosing, M. T. 1999, Science, 283, 674
Saleh, L. A., & Rasio, F. A. 2009, ApJ, 694, 1566
Schlaufman, K. C., Lin, D. N. C., & Ida, S. 2009, ApJ, 691, 1322
Schröder, K.-P., Pols, O. R., & Eggleton, P. P. 1997, MNRAS, 285, 696.
Tarter, J. C., Backus, P. R., Mancinelli, R. L., et al. 2007, Astrobiology, 7, 1, 30
Tout, C. A., Pols, O. R., Eggleton, P. P., & Han, Z. W. 1996, MNRAS, 281, 257
Valencia, D., O’Connell, R. J., & Sasselov, D. 2006, Icarus, 181, 545
von Bloh, W., Bouman, C., Cuntz, M., & Franck, S. 2007, A&A, 476, 1365
Watson, A. J. 2008, Astrobiology, 8, 1, 175
Weiss, A., Salaris, M., Ferguson, J. W., & Alexander, D. R.
2006, preprint, astro-ph/0605666
Williams, D. M., & Kasting, J. F. 1997, Icarus, 129, 254
Williams, D. M., Kasting, J. F., & Wade, R. A. 1997, Nature, 385, 234