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EVOLUTIONARY TRACKS OF THE CLIMATE OF EARTH-LIKE PLANETS AROUND DIFFERENT MASS STARS

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ABSTRACT

The climatic evolution of the Earth depends strongly on the evolution of the insolation from the Sun and the amount of the greenhouse gasses, especially CO_2 in the atmosphere. Here, we investigate the evolution of the climate of hypothetical Earths around stars whose masses are different from the solar mass with a luminosity evolution model of the stars, a mantle degassing model coupled with a parameterized convection model of the planetary interiors, and an energy balance climate model of the planetary surface. In the habitable zone (HZ), the climate of the planets is initially warm or hot, depending on the orbital semimajor axes. We found that, in the inner HZ, the climate of the planets becomes hotter with time owing to the increase in the luminosity of the central stars, while, in the outer HZ, it becomes colder and eventually globally ice-covered owing to the decrease in the CO_2 degassing rate of the planets. The orbital condition for maintaining the warm climate similar to the present Earth becomes very limited, and more interestingly, the planet orbiting in the outer HZ becomes globally ice-covered after a certain critical age (~3 Gyr for the hypothetical Earth with standard parameters), irrespective of the mass of the central star. This is because the critical age depends on the evolution of the planets and planetary factors, rather than on the stellar mass. The habitability of the Earth-like planet is shown to be limited with age even though it is orbiting within the HZ.

Key words: planets and satellites: surfaces

1. INTRODUCTION

The *Kepler* mission has confirmed that there are planets around stars whose spectrum type (i.e., mass) are different from a G-type star (i.e., our Sun). Previous works pointed out that planets occurrence rate is higher around low-mass stars (i.e., M- and K-type star) than around G-type stars (e.g., Howard et al. 2012; Mulders et al. 2015). According to RECONS[1], low-mass stars are the majority in the solar neighborhood: 248 stars out of 342 stars that exist within 10 pc around the Sun are M-type, and 44 stars are K-type. In addition, the evolution of a low-mass star affects its planets less than the evolution of a high-mass star (Kasting et al. 1993) owing to the longer main-sequence lifetime and the slower increase in the luminosity (e.g., Iben 1981). Therefore, low-mass stars are supposed to be more suitable for host stars of habitable planets.

Several works have discussed the habitable zone (HZ) and the climate of a planet around a star with different mass from the solar mass. Planets in the HZ around mid-to-early K-type stars are considered optimal for habitability because of their long lifetime and abundance, while those around late K- and M-type stars may be tidally locked (e.g., Dole 1964). The tidally locked planets were supposed to be uninhabitable (Kasting et al. 1993); however, previous studies revealed that those may also be habitable (e.g., Joshi et al. 1997). Because longwave insolation is less scattered and more absorbed by planetary atmosphere, the insolation limits for the HZ of a low-mass star is lower than those of a high-mass star (Kasting et al. 1993; Kopparapu et al. 2013). In addition, because longwave insolation is less scattered on the ice than shortwave insolation, a planet around a low-mass star can avoid the globally ice-covered state (i.e., the snowball state) by much lower insolation than that around a high-mass star (Shields et al. 2013).

On the other hand, the amount of greenhouse gases also controls the climate of a planet. On Earth, a negative feedback mechanism due to carbonate-silicate geochemical cycle (the Walker feedback) has controlled the amount of atmospheric CO_2; thus, Earth has maintained a warm climate on a long timescale (Walker et al. 1981). Because of this feedback mechanism, it is usually supposed that Earth (or an Earth-like planet) may have a warm climate even if the orbital condition and/or the spectrum type of the central star are different from the present Earth's conditions as long as it is orbiting within the HZ.

However, recent works revealed that Earth can be in the snowball climate when the CO_2 degassing rate (i.e., the rate of CO_2 supply to the surface) is less than 0.1 times the present rate (Tajika 2003, 2007; Kadoya & Tajika 2014). The CO_2 degassing rate may have decreased with time owing to cooling of the interiors of Earth. Therefore, the climate evolution of Earth may be controlled by competition between the increase in the luminosity of the central star and the decrease in the CO_2 degassing rate owing to the cooling of planetary interiors, that is, competition between the evolution of the central star and that of the planet. It remains unknown how the climate of Earth evolves when the orbital conditions and/or the spectral types of the central star are different from the present ones.

In this study, we investigate the climatic evolution of the hypothetical Earth with different orbital semimajor axis in the HZ around stars with various mass, based on the evolution models of the stellar luminosity and the CO_2 degassing rate of the plant. We show the evolutionary tracks of climate of the hypothetical Earths as functions of time (age) and orbital semimajor axis for stars with different mass.

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[1] http://www.recons.org/

2. MODEL

We assume the hypothetical Earth has various orbital semimajor axis and various host stars, that is, we change the external conditions of the Earth. For simplicity we assume plate tectonics working throughout the history, the areal fraction of land to be 0.3, and latitudinally uniform distribution of land.

The evolution of luminosity of a central star is calculated by the formulae of Tout et al. (1996) and Hurley et al. (2000) that approximates the zero-age main-sequence luminosity and the evolution of luminosity as functions of stellar mass, metallicity, and time. In this study, we assume the metallicity so that the luminosity of a solar-mass star may evolve to the solar luminosity at 4.6 Gyr.

The evolution of the CO_2 degassing rate of the planet is calculated by the model of Kadoya & Tajika (2015). In this model, the evolution of the mantle temperature, T_m, is estimated using a parameterized convection mode (e.g., Tajika & Matsui 1992).

The CO_2 degassing rate depends on the magma (melt) generation rate and the carbon content in the mantle. The carbon in the mantle is the very large reservoir of carbon and one order of magnitude greater than the atmosphere, ocean, and sedimentary rocks combined together (Marty 2012); hence, we assume that the carbon content in the mantle is constant for simplicity. The CO_2 degassing rate is, therefore, proportional to the melt generation rate in this model. The melt generation rate is assumed to be proportional to the product of the seafloor spreading rate and the melt generation depth (e.g., Tajika & Matsui 1992). The seafloor spreading rate is estimated from the heat flow that is obtained by the thermal evolution model (e.g., Tajika & Matsui 1992). The melt generation depth is defined as the depth where the mantle temperature adiabatically intersects the solidus temperature of the upper mantle. The solidus temperature is estimated from an equation obtained by fitting the experimental results compiled by Hirschmann (2000).

The viscosity constant, ν_0, and the heat production constant, Q_0, is determined so that the mantle potential temperature and the mantle heat flow at $t = 4.6 \times 10^9$ years for the planet may be 1620 K and 100 mW m^{-2} (Turcotte & Schubert 2002; Herzberg et al. 2007). The other parameters are determined according to Tajika & Matsui (1992). See Kadoya & Tajika (2015) for more details of the model.

We estimate the climate of the hypothetical Earth with a one-dimensional energy balance climate model coupled with a carbonate-silicate weathering model, assuming that a balance between the insolation and the planetary radiation, and a balance between the CO_2 degassing rate via volcanic activities and the CO_2 uptake rate via silicate weathering may be estimated (Kadoya & Tajika 2014). Although the rate of CO_2 uptake via silicate weathering depends on surface temperature, land area, runoff, existence of land plant, and so on (e.g., Berner 2006), only the dependences on surface temperature and land area are considered here for simplicity. We do not consider the effect of the CO_2 cloud in this study because it may have both cooling and warming effects, depending on the conditions (e.g., Caldeira & Kasting 1992; Mischna et al. 2000). We regard the "maximum greenhouse limit" (Kasting et al. 1993; Kopparapu et al. 2013) as the outer limit of the HZ.

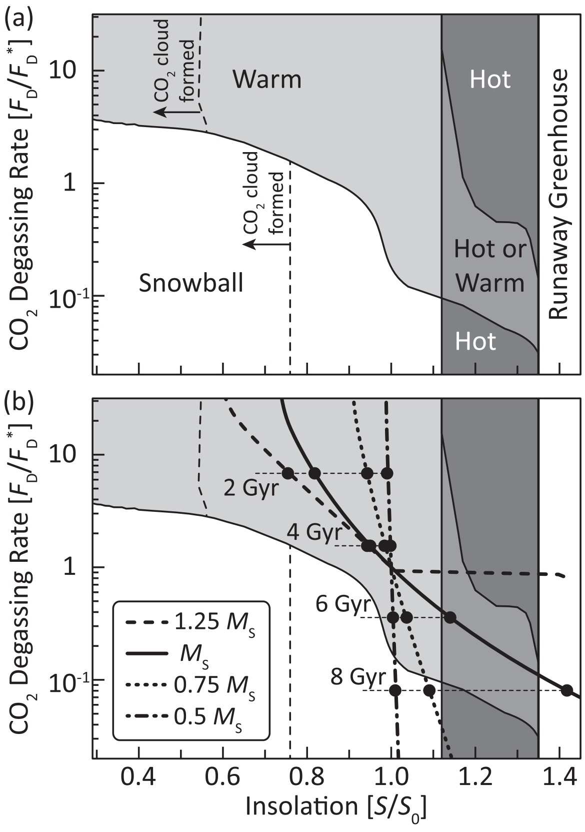

Figure 1. (a) Climate mode diagram (Kadoya & Tajika 2014). (b) Evolutionary tracks in the climate mode diagram. The chain, dotted, solid, and dashed lines represent the evolutionary tracks of the hypothetical Earths around stars whose mass are 0.5, 0.75, 1, and 1.25 times the solar mass, respectively. For comparison, semimajor axes of the planets are set so that they may receive as much insolation as the solar constant at 4.6 Gyr. The thin dashed lines in the warm and snowball climate mode regions represent the CO_2 cloud limit that is estimated based on Caldeira & Kasting (1992). Note that the insolation (horizontal axis) and the CO_2 degassing rate (vertical axis) are normalized by the present solar constant, S_0, and the present CO_2 degassing rate of the Earth, F_D^*, respectively.

3. RESULTS AND DISCUSSION

The climate of the hypothetical Earth in the HZ is classified into three climate modes: warm, hot, and snowball climate modes (Kadoya & Tajika 2014; Figure 1(a)). First of all, the basic characteristic features of this climate mode diagram are summarized briefly.

When the insolation is lower than 1.12 S_0, and the CO_2 degassing rate is relatively high ($>$0.1–4 $\times F_D^*$), the planet is in the warm climate mode. The warm climate mode is similar to the climate of the present Earth, that is, liquid water can exist on its surface even though there may be a partial ice-cap. The partial pressure of the atmospheric CO_2 (pCO_2) is controlled by the carbonate-silicate geochemical cycle.

When the insolation is higher than 1.12 S_0, the planet is in the hot climate mode, which corresponds to the moist greenhouse condition proposed by Kasting (1988). In the hot climate mode, liquid water can also exist on the surface, but pCO_2 is very low ($<10^{-7}$ bar) and the major component of the atmosphere is H_2O vapor owing to high surface temperature ($>$400 K). There are multiple solutions for the hot and warm climate modes when the insolation is higher than 1.12 S_0, but the hot climate mode is found to be more stable than the warm climate mode (Kadoya & Tajika 2014).

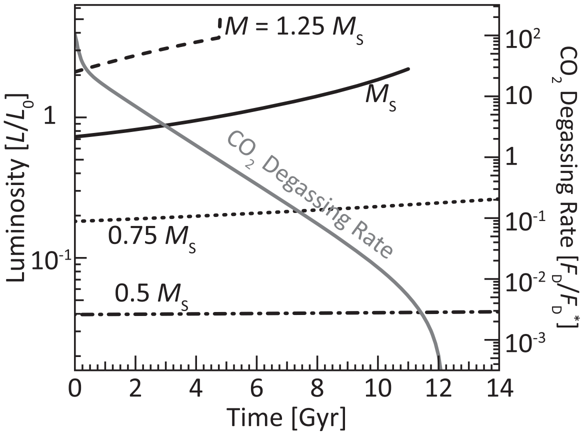

Figure 2. Luminosity and CO_2 degassing rate as functions of time. The black solid line represents the luminosity of the solar-mass star, and the chain, dotted, and dashed lines represent the evolution of stars whose masses are 0.5, 0.75, and 1.25 times the solar mass. The gray solid line represents the CO_2 degassing rate. Both of the luminosity and CO_2 degassing rate are standardized by the present values of the Earth.

When the insolation is lower than 1.12 S_0 and the CO_2 degassing rate is relatively low (<0.1–$4 \times F_D^*$), the planet is in the snowball climate mode. In this mode, the planet is basically in the snowball state, although the global ice-cover melts periodically. In the snowball state, liquid water cannot exist on the surface, but it may exist under the ice layer (Tajika 2008). On the other hand, when the insolation is larger than the critical value for the runaway greenhouse (1.35 S_0 in our calculation), the planet is out of the HZ. For further discussion, see Kadoya & Tajika (2014).

Figure 1(b) shows the evolution of the luminosity of the central star and the CO_2 degassing rate of the planet on the climate diagram. The luminosity increases with time, while CO_2 degassing rate decreases owing to the decrease in the mantle temperature (Figure 2; see Kadoya & Tajika 2015). As a result, the evolutionary tracks essentially move from top left to bottom right in Figure 1(b). Because the low-mass star increases its luminosity more slowly than the high-mass star, the slope of the evolutionary tracks of the low-mass star is steeper than that of the high-mass star. Note that the evolutionary tracks on the climate diagram represent the long-term evolutionary trend of the planetary climate.

There are two important levels of the CO_2 degassing rate: 0.1 F_D^* and 4 F_D^* (Figure 1). The former corresponds to the critical value separating the warm and snowball climate modes at the critical insolation for the moist greenhouse condition (the hot climate mode), and the latter corresponds to the critical value separating the warm and snowball climate modes at the outer limit of the HZ. Hereafter, we call these values the critical CO_2 degassing rate for the inner and outer HZ, respectively. Note that the critical CO_2 degassing rates depend on the planetary factors, such as the land fraction, the land distribution, and the background pressure of atmosphere (i.e., the efficiency of the meridional heat transport).

The stellar mass affects the climate mode boundaries through the difference in the spectrum. According to Kasting et al. (1993) and Kopparapu et al. (2013), the insolation from the low-mass star (i.e., the redder insolation) is less scattered and more absorbed by the atmosphere, and the insolation limit of the HZ around the low-mass star is slightly lower (i.e., farther in its orbit) than those of the high-mass star; for example, the difference in the runaway greenhouse limits between the Sun and Gl 581 (0.31 M_s) are 0.2 S_0 (Kopparapu et al. 2013). Therefore, it is supposed that the insolation for the climate mode boundaries is also lower for the planets around a low-mass star. However, it is supposed that the critical CO_2 degassing rate for the outer limit of the HZ would be unaffected by the spectrum type of the central star because the critical rate depends on the pCO_2 for the maximum greenhouse limit at which the atmosphere becomes opaque to planetary radiation (Kasting et al. 1993).

Figure 3 shows the evolution of the climate mode of the hypothetical Earths around stars whose masses are 0.5, 0.75, 1, and 1.25 times the present solar mass. The climate of the planet in the HZ is initially warm or hot, and the liquid water can exist: the pCO_2 is high enough owing to high CO_2 degassing rate from planetary interiors in its early evolution even though the insolation is low owing to the low luminosity of the young star (Figure 2). The climate of the planet in the inner region of the HZ changes to the hotter climate modes (the hot climate and runaway greenhouse modes) as the luminosity of the central star increases with time (Figure 2). The climate of the planet in the outer region of the HZ, however, changes to the snowball climate mode owing to a decrease in the CO_2 degassing rate of the planet (Figure 2).

According to Figure 3, we found that there is a critical age for the evolution of the planetary climate. Before $t \sim 3$ Gyr, a hypothetical Earth in the HZ is warm and has liquid water on its surface; after $t \sim 3$ Gyr, however, the climate of the planet in the outer HZ becomes the snowball climate mode, irrespective of the mass of the central star. This is because the CO_2 degassing rate of the planet decreases below the critical CO_2 degassing rate at $t \sim 3$ Gyr. In other words, the climate evolution of the Earth-like planets in the outer HZ of the planetary system would be determined by the evolution of planets, rather than that of the central stars. On the other hand, in the inner HZ, the climate of a hypothetical Earth is warm for a longer time, but becomes warmer in the hot and then runaway greenhouse modes owing to the increase in the luminosity of the central star.

The absolute value for the critical age should depend on the planetary conditions, because, as described earlier, the critical CO_2 degassing rate depends on the planetary factors. For example, Figure 4 shows the evolution of the climate mode of the hypothetical Earths with a land fraction of 0.1 (dashed line), 0.3 (solid line), and 0.5 (dotted line). It is assumed that all of them are latitudinally uniform distribution of land. Boundaries of the runaway greenhouse mode and the moist greenhouse mode (i.e., the hot climate mode) are independent from the land fraction because the boundaries depends only on the insolation. The boundaries between the warm and snowball climate modes, however, depend on the land fraction: if the land fraction is 0.1 (0.5), the duration of the planet in the warm climate mode is 1.5 Gyr longer (0.5 Gyr shorter) owing to the smaller (larger) land area than the planet with a land fraction of 0.3. These changes may be actually much smaller. For one thing, we assumed here that the silicate weathering rate depends on land area linearly although the internal region of the large continent tends to be dry and may not be weathered effectively. For another, we assumed here that all of the CO_2

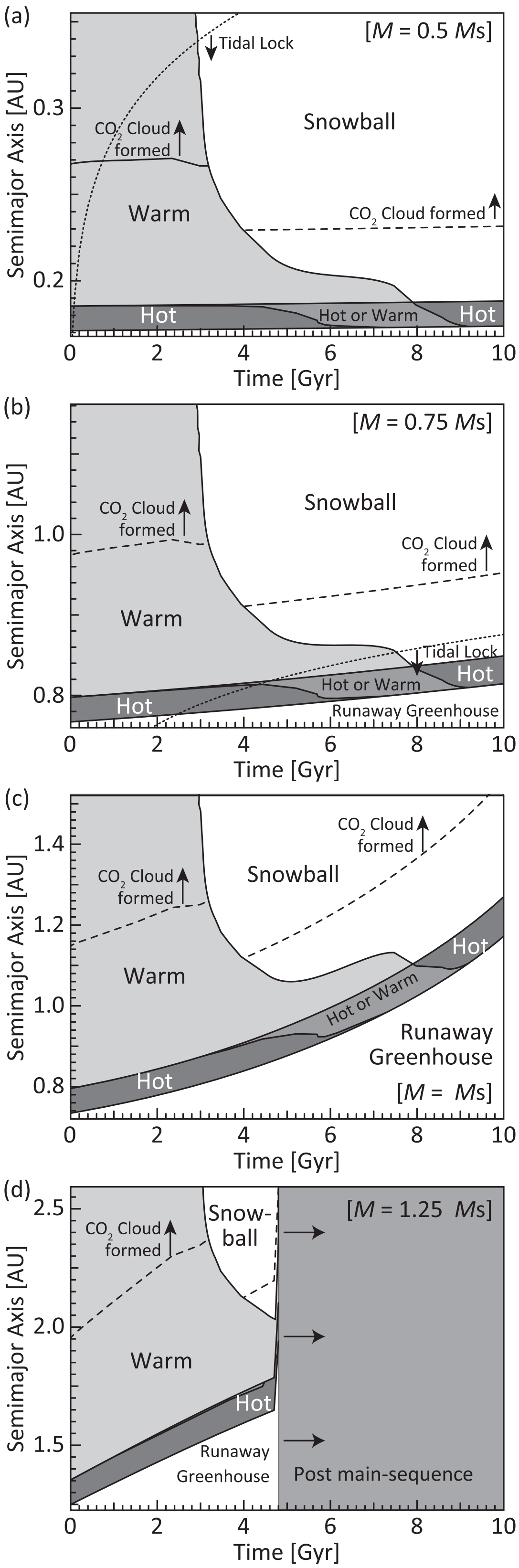

Figure 3. Climate mode evolutions of the hypothetical Earths around stars whose masses are (a) 0.5, (b) 0.75, (c) 1, and (d) 1.25 times the solar mass as a function of both time and orbital semimajor axis. Dotted lines are boundaries for a tidally locked planet estimated by the model of Peale (1977).

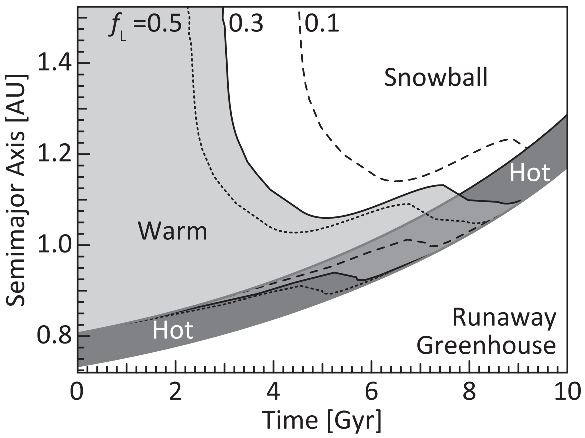

Figure 4. Climate mode evolutions of the hypothetical Earths around a solar-mass star as a function of both time and orbital semimajor axis. The solid lines represent the climate boundaries for the hypothetical Earth whose land fraction (f_L) is 0.3. The dashed and dotted lines represent the climate boundaries for the hypothetical Earth whose land fraction is 0.1 and 0.5, respectively.

uptake is due to the land weathering, although the seafloor weathering may also contribute to the CO_2 uptake, and the decrease/increase in the seafloor weathering may largely compensate the increase/decrease in the land weathering (Abbot et al. 2012). Planetary mass also changes the timescale of cooling of planetary interiors and the evolution of the CO_2 degassing rate. However, such effects could be compensated by the difference in the silicate weathering rate with different surface area among planets with different size; hence, the effect of the planetary mass on the climate evolution may be small (Kadoya & Tajika 2015). In addition, the uncertainty for the silicate weathering model affects the critical age: varying parameters of the silicate weathering model in the allowable range of uncertainty that is assumed for the Earth, the critical age may change from 0.6 to 4.4 Gyr. It is, however, noted that the characteristic features obtained from this study do not change in the cases with different parameter values: the duration for a hypothetical Earth to have a warm climate similar to the present Earth is very limited, even though the planet is orbiting within the HZ and the duration is determined by the planetary evolution, rather than the stellar evolution in the case of Earth-like planets orbiting in the outer HZ of the planetary system. While M- and K-type stars have been considered suitable host stars of a habitable planet in terms of their abundance and long lifetime, the duration of the planet to have a warm climate should be limited and not necessarily longer than those around G-type stars.

The planet in the HZ around a low-mass star is considered to be tidally locked (e.g., Dole 1964). In Figure 3(a), dotted lines represent boundaries for the region of the tidally locked planets estimated by the model of Peale (1977). The boundary of the tidally locked planet extends outward with time, on the order of 10^9 years, which is the same timescale as the duration of the warm climate mode. Therefore, the Earth-like habitable planets in the outer HZ around low-mass stars could be in the snowball climate mode before being tidally locked (Figure 3(a)).

In any case, it is strongly suggested that the age of the planetary system is a very important factor for finding Earth-like planets in extrasolar planetary systems.

4. CONCLUSIONS

We examine the climatic evolution of hypothetical Earths around stars with various masses (0.5, 0.75, 1, and 1.25 times the solar mass) along with the evolutions of the luminosity of the stars and the CO_2 degassing rate of the planets. There is a critical age for the climatic evolution. The planet in the wide region of the HZ of the planetary system is in the warm climate in its earliest evolution. After the critical age (3 Gyr for the case of the hypothetical Earth with standard parameters), however, the planet in the wide region of the outer HZ is in the snowball climate mode, irrespective of the mass of the central stars. This is because, in the outer HZ, the CO_2 degassing rate of the planet decreases to the critical value at this age. After this critical age, the orbital condition for the planet to have a warm climate is limited to the inner HZ. The planet in the inner HZ attains, however, runaway greenhouse mode owing to the increase in the luminosity of the central stars.

Although the planet around the low-mass star is supposed to be tidally locked, it takes on the order of 10^9 year timescale. Therefore, the Earth-like planet in the outer HZ around a low-mass star could avoid being tidally locked, and then could be in the snowball climate mode before it is tidally locked. While M- and K-type stars have been considered suitable host stars of a habitable planet in terms of their abundance and long lifetime, the duration of the planet to have a warm climate should be limited and not necessarily longer than those around G-type stars. The age of the planetary system also would be an important factor for finding Earth-like planets in the extrasolar planetary systems.

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