Exoplanets: Detection, Formation and Dynamics
Proceedings IAU Symposium No. 249, 2007
Y.-S. Sun, S. Ferraz-Mello and J.-L. Zhou, eds.

doi:10.1017/S1743921308016542

Thermal evolution and magnetism of terrestrial planets.

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Abstract. We evaluate a numerical model on the thermal evolution of terrestrial planets to estimate life-time of planetary intrinsic magnetic field for various mass planets. In this model, we take into account the pressure-dependency of density profile of the planet by using *Birch-Murnaghun equation of state*, and simulate thermal evolution of the planet by means of *mixing length theory*. According to our numerical results, the planetary mass must be between 0.1 and 1.4 Earth mass to sustain the intrinsic magnetic field for 4.5Gyr. If existence of intrinsic magnetic field were a key factor to make the planet habitable, the mass range above indicates that super-Earths would not be habitable.

Keywords. Thermal evolution, terrestrial planet, habitability

1. Introduction

Since the first detection about a decade ago (Mayor and Queloz,1995), there are more than 260 exoplants detected so far. Although most of them are so-called gas-giant planet like Jupiter and Saturn, a wide variety of terrestrial planets would be detected in the next decade as is predicted by theoretical study (Ida and Lin,2004). Then, the next question is whether the rocky planets are habitable or not.

The habitability of exoplanets has been discussed mainly based on the stability of liquid water since it is neccesary for the life. In addition to the stability of liquid water, the existence of planetary intrinsic magnetic field must be an important key factor to be habitable for exoplanets. Without intrinsic magnetic field, the atmosphere would be easily blown off by stellar wind of the central star and/or the life on the surface of the exoplanet would be seriously harmed by the irradiation of the stellar wind and galactic cosmic ray.

There are several ways to create magnetic field. Among them, dynamo action would be most appropriate mechanism to create strong and stable magnetic field. Generation of magnetic field via dynamo action needs thermal and/or compositional convection within the metallic core. In other words, whether or not a planet could form intrinsic magnetic field depends on the thermal state, or thermal evolution, of the planet.

Stevenson *et al.*(1983) developed a numerical model on the thermal evolution of Earth, Venus, Mars, and Mercury, respectively. They discuss the formation of intrinsic magnetic field based on the resulting heat flux at the core-mantle boundary. However, it is doubtful whether or not thermal boundary layer model is applicable for convecting mantle with wide variaty of pressure and viscosity. Especially, since viscosity can vary several orders of magnitude through mantle, arbitral rule is needed to estimate heat flux through the thermal boundary layer.

In this study, we construct a numerical model on the thermal evolution of various sized terrestrial planets taking into account internal structure. In this model the internal structure is calculated by using Birch-Murnaghan equation of state (Valencia et al., 2006) and heat flux is estimated from local physical parameters by using mixing length theory (Sasaki and Nakazawa, 1986).

2. Model and Methods

In this study, we simulate thermal evolution of various sized terrestrial planets. The thermal structure evolution of mantle is simulated by using mixing length theory (Sasaki and Nakazawa, 1986). The surface temperature is fixed throughout simulation to be "habitable temperature", 300K. The temperature at the bottom of the mantle is set to be the same with the surface temperature of the core, which changes with time. Long-lived radioisotopes (^{40}K, ^{232}Th, ^{235}U, ^{238}U) are considered as internal heat sources. The amount of these radioisotopes are assumed to be the same with that of bulk-Earth. Density and viscosity distribution are calculated as a function of temperature and pressure by using Birch-Murnaghan equation of state and Arrhenius type equation, respectively. The internal structure and surface temperature of the core are calculated as a function of total internal energy of the core. Dynamo action is assumed to be driven until the heat flux from the core to the mantle exceeds a threshold value. We adopt the conductive heat flux along core adiabat as the threshold value (Stevenson *et al.*, 1983).

3. Numerical results

Figure 1 shows the numerical result for 1 Earth mass planets. The solid curves are for the case that impurity concentration in the core, x_0, is10wt%, the broken curves are for the case of x_0=15wt%, and the one-dotted chain is for the case of x_0=5wt%, respectively.

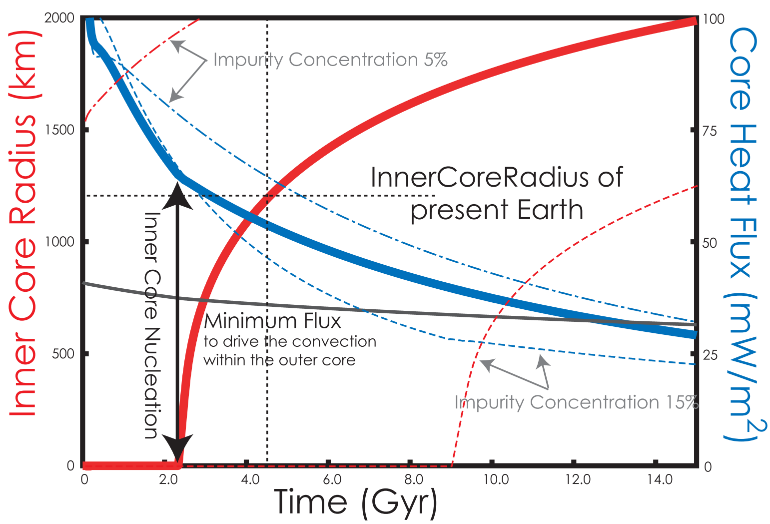

Figure 1. The evolution of core heat flux and inner core radius (M_p =1 $M_\oplus$).

https://doi.org/10.1017/S1743921308016542 Published online by Cambridge University Press

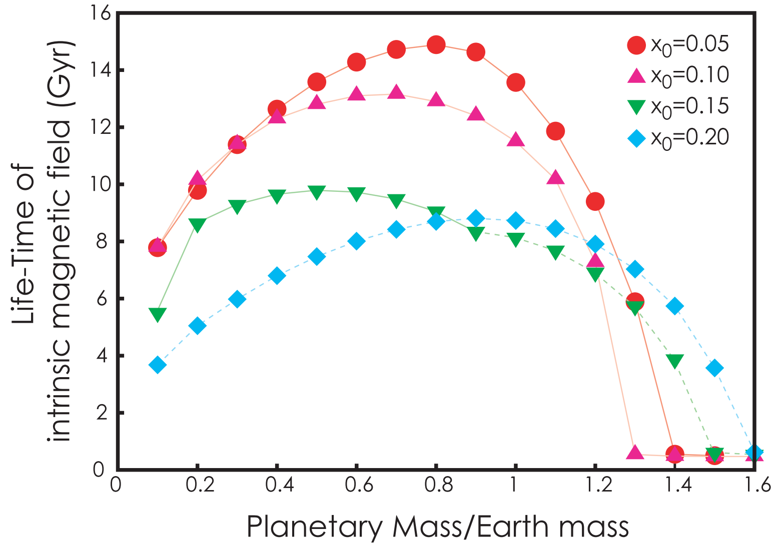

Figure 2. Life-time of intrinsic magnetic field for various sized planets.

For the case of x_0=10wt%, an inner core forms at 2.2Gyr. Since then reduction rate of core heat flux becomes moderate because of gravitational energy and latent heat released at the surface of inner core. These results indicate that the inner core nucleation enhance the subsequent heat flux from the core. Core heat flux exceeds the minimum flux to drive the convection within the outer core until about 12.0 Gyr, i.e. planet can drive dynamo action and can sustain its intrinsic magnetic field for 12.0 Gyr.

We carry out the numerical simulation for various sized planets to estimate the life-time of magnetic field as a function of planetary mass. Figure 2 shows the relationship between life-time of the intrinsic magnetic field and planetary mass. Each curve represent the life-time of intrinsic magnetic field for different initial impurity concentration in the core. Generally, these curves show convex upward configuration. Note that solid curve shows the cases with inner core formation and dashed curve shows the cases without inner core formation.

When planetary mass is less than 0.5 Earth mass, life-time of the field becomes shorter for smaller planet. This is because of the smaller planet cools down more quickly and thermal energy of the core decrease within short period. On the other hand, when planetary mass is more than Earth-mass, life time of the field becomes shorter with larger planet. This is because of depression of heat transport efficiency. Since the viscosity of the mantle depends on the pressure, the viscosity at the bottom of the mantle becomes higher for heavier planet. In this case such a viscous mantle can not sustain large heat flux from the core to invoke vigorous convection within outer core while the core remains hot.

According to our numerical results, the planetary mass must be between 0.1 and 1.4 Earth mass to sustain the intrinsic magnetic field for more than 4.5Gyr. If existence of intrinsic magnetic field were a key factor to make the planet habitable, the mass range above indicates that super-Earths would not be habitable.

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