

# A Space Charging Model for the Origin of Planets' Magnetic Fields

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Both theoretical models and experimental results have indicated that a body surrounded by plasma is negatively charged to a potential around 2-3 times greater than the thermal potential of the ambient plasma. This potential difference shows that the body holds some extra electric charge. In this paper, we formulate an expression to compute the extra electric charge from the ambient plasma. It is shown that the total electric charge on a body basically depends on its size and the characteristics of the ambient plasma. When the body size is big or the ambient plasma is dense, the extra electric charge is large. Since all solar planets are imbedded within the solar wind plasma, they may also be charged due to the same physics. Analyzing the charging behavior of planets, we find that the solar planets are significantly charged. The circular electric currents or charge flows caused by planets's spinning produce magnetic fields. The magnetic fields predicted by the present space charge model basically agree with the measurements on the global magnetic fields of planets (including the Moon). Also, the polarity biases and reversals of planet magnetic fields are discussed. Therefore, a possible explanation for the origin of the magnetic fields of planets is proposed.

## 1 Introduction

The origin of the geomagnetic field has been puzzling physicists for hundreds of years. In 1600, William Gilbert believed that the Earth is permanently magnetized, like a giant magnet. Albert Einstein considered the origin of the geomagnetic field to be one of the five most important unsolved problems in physics. So far, tons of data on the geomagnetism have been accumulated [1]. In general, the geomagnetic field resembles the field generated by a dipole magnet located at the center of the Earth. The locations of the north and south geomagnetic poles are randomly varied and reverse each other at irregular periods [2-4]. The intensity of the geomagnetic field is transiently changed and in average about 0.5 G, which is slowly decayed. It is generally believed that the geomagnetic field is affected by various external events, such as the tides, aurora, solar flares, sunspots, and so on.

In order to explain the geomagnetic phenomena, various models have been proposed, which are conveniently classified into dynamo and non-dynamo models. As a non-dynamo model, the permanent magnetization of the Earth could not explain the polarity reversals of the geomagnetic field. The charge separation arising from the thermoelectric effect is, however, relatively small in comparison with the geomagnetic field [5]. In addition, some other effects were suggested - such as the gyromagnetic effect, the hall effect, the galvanomagnetic effect, the differential rotation effect, the electromagnetic induction by magnetic storms, and the Nernst-Ettinghauser effect, etc. [6-11].

Larmor [12-13] was the first to suggest that large astronomical bodies might have magnetic fields that arise from a self-exciting dynamo process. However, Cowling [14]

showed that this disc dynamo was damped and cannot maintain such a field very long. Later, other dynamo theories were developed, such as magnetohydrodynamic dynamo, kinematic dynamo, turbulent hydromagnetic dynamo, and so on [15-22]. Although it is generally accepted today that the geomagnetic field arises from dynamo action in the Earth's liquid outer core, there is no viable hydrodynamic geodynamo model as described by McFadden and Merrill [23] because there are so many unclear parameters being included in the governing equations.

The study of the magnetic fields of planets offers the key to an understanding of the origin of the geomagnetic field. Until recently, information about the magnetic fields of planets came mostly from indirect measurements or from flyby missions. The measurements are generally sparse in both spatial and temporal distribution and only provide us a first-order picture of the magnetic fields of planets.

The solar planets can be conveniently classified into two types (type-I and type-II) according to their magnetic fields being local or global. A type-I planet has a weak global magnetic field, such as Venus, Mars, or Pluto (also the Moon). These planets are almost naked to the solar wind plasmas because of lack of (or very weak) magnetospheres [24]. Their atmospheres are usually not strong enough to sheath out the solar wind and partially ionized especially at the upstream. However, the type-II planets (including Mercury, Earth, Jupiter, Saturn, Uranus, and Neptune) have strong global magnetic fields. The solar wind plasmas are separated from these planets by their powerful magnetospheres except at their poles. The solar wind electric currents can still interact with the Earth through partially ionizing the neutral atoms in the atmosphere at the poles. The early measurements did

show that electric currents were observed in both the air and the Earth during aurora taking place [25-27].

Dynamo theorists suggested that the global magnetic fields of the type-II planets were excited due to their interior dynamo actions, which are critically dependent of the size and spin of the planets. The main reason Venus lacks a dynamo is because it spins slower than the Earth does. The reason Mars lacks a dynamo is because it is smaller than the Earth. However, Mercury probably has a dynamo action even though it is smaller and its spinning period is longer than Mars. A dynamo model may not easily answer why Mercury has a dynamo but Mars does not.

In this paper, a theoretical space charge model for the origin of the global magnetic fields of planets is proposed. The purpose of this paper is not to be against dynamo theories instead of to suggest another possibility. According to the space charge physics, a body floating in the space plasma will be charged. This phenomenon has been actually observed during space experiments. The electric charge on a large conducting spherical body is further derived. If the body is spinning, the electric charge will generate a circular electric current, which induces a magnetic field. It is shown that the induced magnetic field depends not only on the size and spin period of the body, but also on the characteristics of the ambient plasma. For very large bodies, such as planets, the induced magnetic fields could be as big as the measurements. Analyzing the magnetic fields and electric charging processes of the two types of planets results in a consistent explanation for the magnetic fields of all planets, including the Moon. The polarity biases and reversals of the planet magnetic fields are also discussed with this model. In addition, it should be noted that this model has not included the effects of atmosphere, body motion, and plasma instabilities on current collection. The relative motion between the body and the environmental plasma was shown to increase current collection along the magnetic field lines [28]. The field aligned current-driven instabilities was shown to greatly heat charged particles [29-30] and hence can also increase the current collected by the body.

## 2 Space Charging

Experimentally and theoretically, it has been shown that a satellite moving (or floating) in space plasmas itself becomes usually negatively charged, since the number of electrons incident on its surface is greater than the number of ions [31] (see Figure 1a). The absorption of electrons and ions essentially depends on the size of the body, the surface potential, the material properties of the body, and the state of the ambient plasma. In some special cases, a body may be positively charged.

The amount of electric charges and the absolute value of potential increase as long as the number of electrons and the number of ions being absorbed on its surface are not identical. Since the increasing potential slows down the electric

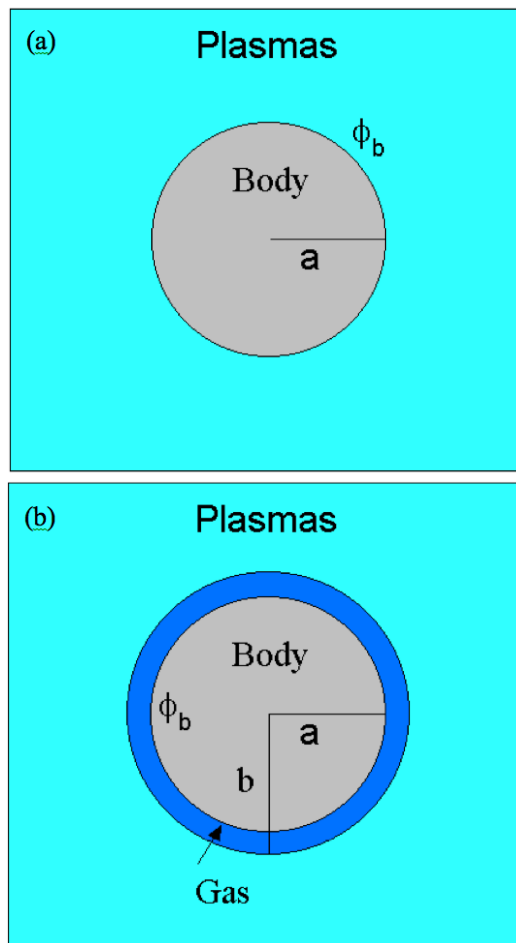


Fig. 1: Schematic diagrams for space charge model. (a) Without a neutral gas layer; (b) with a neutral gas layer.

accumulating processes, an "equilibrium" state for charge accumulating (i.e. a state in which the total electric current incident on the body is equal to zero) is finally attained if the ambient plasma is vast. In this situation, the electric potential at the surface of the body, is determined by

$$\phi_0 \approx -\frac{k_B T_e}{e} \ln \sqrt{\frac{2k_B T_e}{\pi m_e V_0^2}} = -\alpha \phi_{th}. \tag{1}$$

Here the potential at infinite distance (or outside the plasma sheath) has been chosen to be zero;  $k_B$  is the Boltzmann constant;  $e$  is the proton electric charge; the subscript  $e$  refers to the electron species;  $T_e$  is the electron temperature;  $m_e$  is the electron mass;  $V_0$  is the velocity of the body relative to the ambient plasma - which is generally much larger than the ion thermal velocity and less than the electron thermal velocity;  $\phi_{th}$  is the thermal potential which is defined by  $k_B T_e / e$ ; and  $\alpha$  is the factor which is given by the nature logarithm in Eq. (1). For example, we consider that a spherical body is

moving in the ionosphere plasma. The thermal potential is  $\phi_{th} \sim 0.11$  V if  $T_e \sim 0.1$  eV is chosen for the plasma. The factor  $\alpha$  is  $\alpha \sim 2.58$  if  $V_0 = 8$  km/s is chosen for the body. Then the electric potential at the body surface is estimated as  $\phi_0 \sim -0.3$  V, which is in agreement with space measurements. For a motionless or slowly moving body (i.e.,  $V_0 = 0$  or much smaller than the ion thermal velocity), the result is  $\phi_0 \sim 2.57$  V [32].

If the body is separated from the plasma by a thin layer of neutral gas (see Figure 1b), the region of neutral gas will get extra electrons since the electrons incident into the neutral gas region are more than the ions. For a quasi-neutral plasma the number of electrons entering the neutral gas in a unit time through a unit area is determined as the electron flux ( $n_0\bar{v}_e/4$ ), which is much greater than that of ion ( $n_0\bar{v}_i/4$ ). Here  $n_0$  is the number density of electron (or ion) of the quasi-neutral plasma;  $\bar{v}_e$  and  $\bar{v}_i$  are the mean velocity of electrons and ions, respectively. These extra electrons will diffuse toward the body because both the electron density and the electric potential have gradients. That is to say, the body will be charged. The total amount of electric charge distributed on the body and within the neutral gas should be generally greater than that without the gas layer. In present study, we limit our analyses in cases of very thin layer and hence ignore the effects of neutral gas on the charge of the body.

If the electric potential distribution is given, the electric charge on the body can be obtained. For a spherical body within a medium (including free space, dielectric medium, plasma, etc.), the density of electric charge distributed on the body surface is given by

$$\sigma_b = -\epsilon \left. \frac{d\phi}{dr} \right|_{r=a}, \quad (2)$$

where  $a$  is the radius of the body;  $\phi$  is the electric potential distribution;  $r$  is the radial coordinate; and  $\epsilon$  is the dielectric permittivity. For a static (or slowly moving) electrically conducting body, the density of electric charge on the surface is constant. Hence, the total electric charge of the body is

$$Q_b = -4\pi\epsilon a^2 \left. \frac{d\phi}{dr} \right|_{r=a}, \quad (3)$$

In the free space, a spherical body with  $a = 1$  m and  $\phi_0 = -0.2$  V will be charged to  $Q_b = 4\pi\epsilon_0 a \phi_0 \sim -2 \times 10^{-11}$  Coulomb.

If the medium is plasma, however, the relationship between the total electric charge and the electric potential of the body will be complex. The total electric charge or the numbers of electrons and ions being absorbed by a body essentially depends not only on the potential and size of the body, but also on the state of plasma. In this case, the electric potential distribution must be generally determined through

solving the Poisson equation,

$$\nabla^2 \phi = -\frac{1}{\epsilon} \sum_{j=i}^{j=e} n_j q_j. \quad (4)$$

For a body with size much greater than the Debye length, however, the potential near the body can be approximately obtained only by solving the one-dimensional Poisson equation,

$$\frac{d^2 \phi}{dr^2} = -\frac{n_{e0} e}{\epsilon} (e^{-\phi/\phi_{th}} + e^{\phi/\phi_{th}}). \quad (5)$$

Here the Boltzmann number density distributions have been applied for both electrons and ions. Integrating Eq. (5) one times with respect to  $r$ , we obtain

$$\frac{d\phi}{dr} = \sqrt{\frac{2n_{e0} e \phi_{th}}{\epsilon} (e^{-\phi/\phi_{th}} + e^{\phi/\phi_{th}} - 2)}. \quad (6)$$

At the surface of the body (i.e. at  $r = a$ ), it becomes

$$\left. \frac{d\phi}{dr} \right|_{r=a} = \sqrt{\frac{2k_B T_e n_{e0}}{\epsilon} (e^{-\alpha} + e^{\alpha} - 2)}. \quad (7)$$

By substituting Eq. (7) into Eq. (3), we obtain a formula to estimate the electric charge of a large conducting body floating in space plasmas

$$Q_b = -4\pi a^2 \sqrt{2\epsilon_0 k_B T_e n_{e0} (e^{-\alpha} + e^{\alpha} - 2)}, \quad (8)$$

where the dielectric permittivity has been replaced to that of free space, since we do not consider a very dense plasma. Therefore, the body is in general to be negatively charged. The amount of charge on the body depends not only on the size and potential of the body but also on the temperature and density of the ambient plasma.

Now we consider the case in which a body is moving relative to the ambient plasma. When the velocity of the body is in the range of,  $v_{Te} \gg V_0 \gg v_{Ti}$ , the number density of ions near the body is no longer the Boltzmann distribution, where  $v_{Te}$  and  $v_{Ti}$  are the thermal velocities of electrons and ions. In the upstream, the number density of ions is not interfered by the body if the body surface does not reflect particles. In the downstream, however, the number density of ions is almost zero since the ions slowly respond to the motion of the body. In this case, the total electric charge on the body surface (or Eq. 3) is similarly derived as

$$Q_b = -2\pi\epsilon_0 a^2 \left( \left. \frac{d\phi^F}{dr} \right|_{r=a} + \left. \frac{d\phi^R}{dr} \right|_{r=a} \right), \quad (9)$$

where  $\phi^F$  and  $\phi^R$  are the electric potential distributions in the upstream and downstream, respectively. The electric potential distributions can be determined by

$$\frac{d^2 \phi^F}{dr^2} = -\frac{n_{e0} e}{\epsilon_0} \left[ 1 - \exp\left(\frac{\phi^F}{\phi_{th}}\right) \right], \quad (10)$$

$$\frac{d^2\phi^R}{dr^2} = \frac{n_{e0}e}{\epsilon_0} \exp\left(\frac{\phi^R}{\phi_{th}}\right). \quad (11)$$

By integrating both Eq. (10) and Eq. (11) with respect to  $r$  once, we obtain the electric fields at the surface as

$$\left.\frac{d\phi^F}{dr}\right|_{r=a} = \sqrt{\frac{2k_B T_e n_{e0}}{\epsilon_0}} (e^\alpha - \alpha), \quad (12)$$

$$\left.\frac{d\phi^R}{dr}\right|_{r=a} = \sqrt{\frac{2k_B T_e n_{e0}}{\epsilon_0}} (e^\alpha - 1). \quad (13)$$

By substituting Eq. (12) and Eq. (13) into Eq. (9), we obtain the total electric charge of the body as

$$Q_b = -2\pi a^2 \sqrt{2\epsilon_0 k_B T_e n_{e0}} (\sqrt{e^\alpha - \alpha} + \sqrt{e^\alpha - 1}). \quad (14)$$

This expression gives a value much greater than that from Eq. (8) if  $\alpha \ll 1$ . When  $\alpha$  is not small, however, the result from Eq. (14) approaches that from Eq. (8).

If the body is spinning, the electric charge on the body surface will generate an electric circular current. This current then induces a magnetic field with poles on the spinning axis. The maximum value of the magnetic field is derived as

$$B = -\frac{\pi}{4} \mu_0 \frac{Q_b}{\tau}, \quad (15)$$

where  $\mu_0$  is the permeability of free space,  $\mu_0 = 4\pi \times 10^{-7}$  H/m;  $\tau$  is the spin period of the body; and  $Q_b$  is given by either Eq. (8) or Eq. (14) according to the motion of the body.

Since the circular current is induced by the self-rotation of a charged body other than by the electric charges moving on the body, the magnetic field induced by the circular current (Eq. 15) is independent of the conductivity of the body surface. If the body surface is made of insulate (i.e., infinite conductivity) material, the density of electric charge will not be constant. In this case, we need to integrate Eq. 2 on the entire body surface to obtain the total charge. It is generally believed that all solar planets are not made of insulate materials. Therefore, this magnetic field formula (Eq. 15) can be generally employed to predict the induced magnetic field of a self-rotated large conducting body, such as an orbit satellite, the Moon, and the solar planets. The required parameters are the radius of the body, the spinning period of the body, the velocity of the body relative to plasma flow, the electron temperature of the ambient plasma, and the non-perturbed density of the ambient plasma. The induced magnetic field will be great when the body is large, the spin is fast, and the plasma is dense. According to the presented model the Mercury magnetic field could be greater than the Mars magnetic field because the solar wind plasma around Mercury is much denser than that around Mars.

For an orbit satellite with a conducting spherical surface, the typical required parameters are,  $a = 1$  m,  $T_e = 1500$  K,

$n_{e0} = 10^6$  cm<sup>3</sup>, and  $V_0 = 8$  km/s. Substituting  $T_e$  and  $V_0$  into Eq. (1) we show that the conducting satellite is charged to a potential equal to  $\sim -2.6\phi_{th}$ ; that is,  $\alpha \sim 2.6$ . Substituting  $a$ ,  $T_e$ ,  $n_{e0}$ , and the value of  $\alpha$  into Eq. (8) (or Eq. 14) we obtain the electric charge of the satellite,  $Q_s \simeq 2 \times 10^{-8}$  Coulomb, which is much larger than that in the free space. Furthermore, if the satellite is self-rotated with a spin period,  $\tau_s = 1$  seconds, the induced magnetic field, from Eq. (9), will be  $B_s = 2 \times 10^{-11}$  Gausses, which is quite small. It should be noted that the rotation of the satellite does not significantly affect the ambient plasma because the linear speed at the surface due to body rotation is much smaller than the thermal velocities of ions and electrons. The presented model does not include the magnetic field effect on the body charging (or current collection) process. If the magnetic field or the body electric potential is not high, such effect is negligible [33].

### 3 The magnetic fields of the Moon and planets

Now, employing the space charging model proposed above, we study the magnetic fields of the Moon and planets. The predictions on the magnetic fields are compared with the measurements.

According to the space charge model, the magnetic field of a body is determined by giving the five parameters: the size and spin period of the body, the density and temperature of the plasma, and the velocity of the plasma flow. Table 1 shows the interplanetary conditions for the Moon and planets [34-35]. The solar wind velocity, density, and temperature are shown in the third to fifth column. The magnetic field of the solar wind near each planet and the distance between the Sun and each planet are also shown in this table (see the sixth and second columns). The radii and spin periods of the Moon and planets are shown in the second and third columns in Tables 2 and 3.

As mentioned in the Introduction, the Moon and type-I planets (e.g. Venus, Mars, and Pluto) are almost naked to the

Table 1: Interplanetary properties: Distance to the Sun  $L_{Sun}$  (AU), Solar Wind Velocity  $V_{SW}$  (km/s), Density  $n_{SW}$  (cm<sup>-3</sup>), Temperature ( $10^4$  K), and Magnetic Field (nT).

Planet	$L_{Sun}$	$V_{SW}$	$n_{SW}$	$T_{SW}$	$B_{SW}$
Mercury	0.4	430	50	20	35
Venus	0.7	430	14	17	10
Earth (or Moon)	1	430	7	15	6
Mars	1.5	430	3	13	3
Jupiter	5.2	430	1/4	9	1
Saturn	9.6	430	1/16	7	1/2
Uranus	19	430	1/50	6	1/4
Neptune	30	430	1/160	5	1/7
Saturn	39	430	1/200	4	1/10

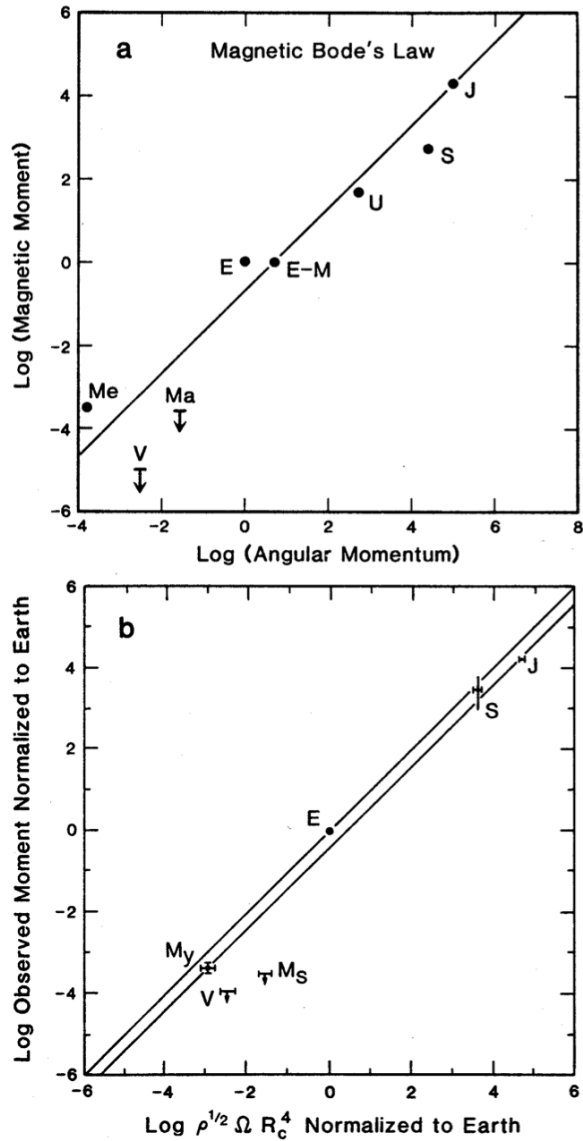


Fig. 2: (a) Relationship between planetary magnetic moment and angular momentum by the original magnetic Bode's law (Russell 1987). (b) Relationship between planetary magnetic moment and the core radius by the dynamo theory-based scaling law (Busse 1976).

solar wind plasmas (actually, they have very thin and weak gas (or atmosphere) layers). The condition,  $v_{Te} \gg V_0 \gg v_{Ti}$ , which is used for the deduction of Eq. 14, is generally satisfied for the Moon and the type-I planets. In this case, the ambient plasma is the solar wind, which has speed  $\sim 400$  km/s and temperature  $T_e \sim T_i \sim 10^5$  K. It is not difficult to show that the solar wind speed is much smaller than the electron thermal speed but much greater than the ion thermal speed. Therefore, the space charging model proposed in the previous section (i.e. Eq. 14) can be directly employed to quantita-

tively predict their present magnetic fields. For the Moon, the required five parameters are,  $a = 1.738 \times 10^6$  m,  $T_e \sim 1.5 \times 10^5$  K,  $n_{e0} \sim 7$  cm $^{-3}$ ,  $V_0 = 430$  km/s, and  $\tau_M = 2.36 \times 10^5$  seconds. At first, using  $T_e$  and  $V_0$ , we show, from Eq. 1, that the Moon is charged to a potential equal to  $\sim -\phi_{th}$  (that is,  $\alpha \sim 1$ , with this value of  $\alpha$ , the Eq. 14 predicts a result without a significant difference from Eq. 8). Then, substituting  $a$ ,  $T_e$ ,  $n_{e0}$ , and the value of  $\alpha$  into Eq. 8 (or Eq. 14), we can obtain the electric charge of the Moon,  $Q_M \sim -640$  Coulomb. Finally from Eq. 9, the induce lunar magnetic field ( $B_M$ ) predicted by the present model is about  $B_M \sim 3$  nT. The measurements actually indicate that the intensity of the global magnetic field of the Moon does not exceed 2 to 3 nT (Table 2; [36]).

For Venus, the prediction on the magnetic field by the present model is about 6 nT, which agrees with the measurements. Space experiments indicated that the intrinsic value of the magnetic field at the surface of Venus could not be greater than 5 nT [37].

For Mars, the prediction on the magnetic field by the present model is about 200 nT. In the 1970s, the soviet Mars 3 and 5 probes measured a field about 30 - 60 nT near the equator, at periaipis (at an altitude of 1500 km) [38-40]. Since the magnetic field of Mars on its surface is several times greater (for the Earth, the factor is  $\sim 2 - 4$ ) than that measured at an altitude of 1500 km, the Mars' magnetic field could be as big as 150 nT, which also agrees with the present model prediction.

We also predict the magnetic field for Pluto although we have not had any measurement available so far. Based on the present model, the Pluto's magnetic field is estimated to be about 0.1 nT, which is ordinarily the same as the magnetic field of the solar wind there. Therefore, the predictions by the space charge model on the magnetic fields of the Moon and the type-I planets basically agree with the measurements (see Table 2, [36-40]).

For the type-II planets (such as the Earth), however, we cannot directly obtain the present magnetic fields from Eqs. 1, 8, and 9 because the solar wind plasmas are separated from these planets by their strong magnetospheres. But, we can apply the present model to estimate the ancient magnetic fields of planets if the characteristics of the initial solar wind are known. The following gives some analyses for the type-II

Table 2: Model predictions on  $B$  for the type-I planets including Moon and Pluto in comparison with data  $B_0$ .

Planet	$R$ (km)	$\tau$ ( $10^5$ s)	$B_0$ (nT)	$B$ (nT)
Venus	6055	210	$\leq 5$	6
Moon	1738	23.6	$\leq 3$	3
Mars	3398	0.886	$\sim 150$	200
Pluto	1150	5.519	$\sim$	0.1

planet magnetic fields based on the evolutionary characteristics of solar system. In the next section, the type-II planet magnetic fields are further discussed through considering the polar aurora plasmas as their charging sources. If so, the present model can still be used and predicts results closer to the measurements.

It is widely believed that the Sun went through FU Orionis and T-Tauri phases of evolution [1, 41]. A T-Tauri (in the pre-main sequence) star is partially characterized by violent outbursts of material, very strong magnetic field, and an increased luminosity of about six magnitudes. Observations actually indicated very massive winds from these early-type stars [42]. Preliminary results from the studies of meteorites and lunar rocks also indicated that the average solar wind speed might have been considerably greater some  $3 - 4 \times 10^9$  years ago [42,43].

Thus, it is reasonable to assume that the Sun initially emitted a strong solar wind. During that time period, all our planets were greatly charged from such massive solar wind plasmas and induced magnetic fields with different intensities due to their different sizes and rotation speeds. If the initial solar wind is  $\sim 10^3 - 10^6$  times denser than the present solar wind, the ancient (or initial) magnetic fields are some tens to thousands times greater than the present fields for the Moon and the type-I planets. For the type-II planets, the ratios of the ancient fields to the present fields are in the range of  $\sim 1 - 100$ . Thus, the planets with small size and slowly spinning (such as the Moon and type-I planets) also excited considerably great intrinsic magnetic fields, which probably had magnetosphere-like structures during early periods. However, their magnetic fields are easily decayed as the solar wind becomes weak due to their weak abilities to maintain such fields. Large, fast spinning planets (such as the type-II planets) developed very strong magnetic fields and formed powerful magnetospheres - which are also decayed, but relatively more stable than the type-I planets, because they last a longer time in the decaying process.

Observations show that the planet's magnetic field is stronger if its magnetosphere is bigger. According to the presented model, the denser the ambient plasma is, the more charge the body is charged, which is proportional to the induced magnetic field. For the type-II planets (e.g. the Earth), the nearest ambient plasma is the plasmasphere (ionosphere) or the aurora plasma in the pole regions. For these plasmas (see [44]), the electron or ion density is  $\sim 10^5$  to  $10^6$   $\text{cm}^{-3}$  which is much denser than the solar wind plasma. The electron or ion temperature is  $\sim 10^3$  to  $10^4$  K. In these regions, most of ions are  $\text{O}^+$ , which has a thermal velocity around 1 km/s, which is much less than the minimum speed ( $\sim 8$  km/s) for a particle to escape out by overcoming the Earth gravitation. Therefore, the Earth's (as well as other type II planets') gravity may maintain its magnetic field (or magnetosphere) through trapping the particles of plasmasphere or plasma in the aurora regions. The magnetic field itself also

helps the planet to trap the particles of magnetosphere. The electrons can be trapped by the ions although the electron thermal velocity may be greater than the minimum escaping speed. Within a relative stable solar wind, the value of the magnetic field or the size of the formed magnetosphere actually depends on the planet gravity. The bigger the gravity is, the stronger the magnetic field is or the bigger the magnetosphere forms if the other parameters are the same.

The results predicted by the present model are very high in absolute values under the assumption that the ancient solar wind density varied in the range of  $10^3 - 10^6$  times denser than the present value. During such a long time interval, the planets' magnetic fields were greatly decreased when the solar wind density was greatly decreased. For the type-II planets, we have compared (in the following several paragraphs) the relative results predicted by the present model on the ancient magnetic fields of planets with the measurements and found a good agreement between them.

The fourth column of Table 3 shows the measurements of the magnetic fields for the type-II planets, which are normalized by dividing the geomagnetic field. A 300 nT magnetic field was measured for Mercury [45]; a 15 Gauss magnetic field at the north pole was measured for Jupiter [46]; and orderly  $\sim 1$  Gauss magnetic fields were measured for Saturn, Uranus, and Neptune [47]. The fifth column of Table 3 shows the predictions of the ancient magnetic fields for the type-II planets, which are normalized by the ancient geomagnetic field. Comparing the fourth column with the fifth column of Table 3, we found that the normalized ancient magnetic fields of planets predicted by the space charging model basically agree with the present field measurements [45-48]. The Saturn's magnetic field (or magnetosphere) could be decayed more than the Jupiter's probably due to the lower gravity (or density) of Saturn.

The decays of planet magnetic fields were probably affected by their gravitation. It is reasonable to assume that a planet with large gravity has more power to maintain its magnetosphere through trapping its particles. To consider such gravity effect, we propose a formula for the present magnetic field of a type-II planet by introducing an arbitrary coefficient,

Table 3: Model predictions on  $B/B_e$  for ancient magnetic field for the type-II planets in comparison with data  $B_0/B_e$  for present magnetic field.

Planet	$R$ (km)	$\tau$ ( $10^5$ s)	$B_0/B_e$	$B/B_e$
Mercury	2439	51	$\sim 1/100$	1/130
Earth	6371	0.864	$\leq 1$	1
Jupiter	71600	0.354	$\sim 30$	45
Saturn	60000	0.368	$\sim 2$	13
Uranus	25600	0.621	$\sim 1$	1
Neptune	24765	0.567	$\sim 1/2$	1/2

$f(g)$ , to the Eq. 15 as

$$B = -\frac{\pi}{4}\mu_0 f(g)\frac{Q_b}{\tau}, \quad (16)$$

where  $g$  is the gravity at the planet surface and  $Q_b$  is the body charge of the planet, which is given by either Eq. 8 or Eq. 14. Then, the magnetic moment of the planet can be derived as

$$M = -\frac{2\pi}{3}a^2 f(g)\frac{Q_b}{\tau}. \quad (17)$$

It can be seen that the magnetic moment of the planet is proportional to  $a^4$  because of  $Q_b \propto a^2$ . It is also proportional to the square root of the solar wind pressure and inversely proportional to the planet spin period. On the other hand, the magnetic Bode's law also called the Shuster or the Blackett hypothesis established that the magnetic moments of the planets were proportional to their angular moments (see Figure 2a and [49-50]). The scaling law predicted that the planet magnetic moments were proportional to the rotation rates times the fourth power of the core radius (see Figure 2b and [51]).

In order to compare the results predicted by the present space charging model with the predictions by either the magnetic Bode's law or by the scaling law, we plot our model predictions on the magnetic moments of the type-II planets versus the observations in Figure 3. The magnetic moments from both the model predictions and the observations are normalized to the Earth and are shown in log scales. Figure 3a has not included the gravitation effect and Figure 3b gives the results with the gravitation effect by assuming that the coefficient is linearly proportional to the gravity ( $f(g) \propto g$ ). The observation data are from [1].

#### 4 Discussions and Conclusions

In this section, we briefly discuss the following items: 1) current collection of planets with magnetospheres and 2) the polarity biases and reversals of the magnetic fields of planets. Then, we give our conclusions of this study.

Although the Earth and other type-II planets are not completely naked to the solar wind plasmas, their poles are widely opened to the outer space due to the double funnel magnetic structures. The solar and interstellar winds as well as the energetic particles can easily, through the magnetic field lines (or double funnels), come down into the polar regions of the planets to excite and to ionize the gases near the surfaces. This is the phenomena of aurora. The aurora plasmas are much denser than the solar wind plasma. The density of a typical aurora plasma could be as high as  $\sim 10^5$  to  $10^6 \text{ cm}^{-3}$  which is much denser than the solar wind plasma with density less than  $\sim 100 \text{ cm}^{-3}$  [44]. Therefore, these planets are probably charged at their poles especially during aurora taking place. The early experimental measurements showed that electric currents were actually observed in the air and in the

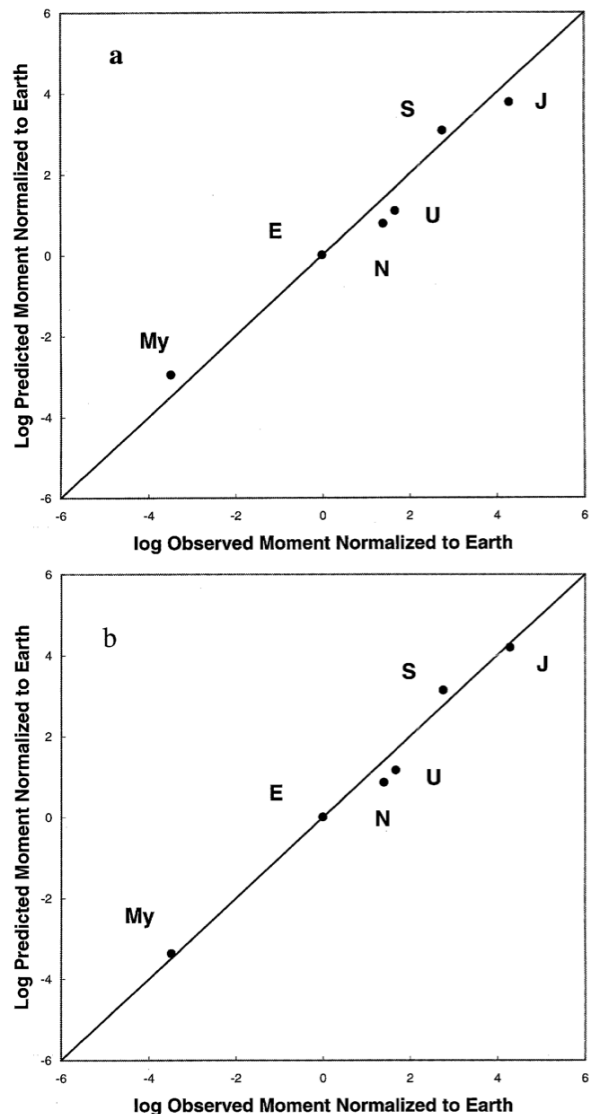


Fig. 3: Planetary magnetic moments normalized to the Earth predicted by the space charge model versus those from measurements. (a) Without the gravity effect; (b) with the gravity effect.

Earth while the aurora was taking place [25-27]. The correlation between the Earth current and the geomagnetic activity was also found. It is interesting that if we consider the aurora plasma as the source plasma to charge the Earth, the present model predicts a result very closer to the measurement.

For the Earth, observation records show that the aurora events asymmetrically occur at the two (i.e. North and South) poles [52]. The Northern aurora events are generally more frequent and intense than the Southern aurora events. The reason is probably due to that the spinning geomagnetic field lines drift the entering (or coming down) electrons apart from the axis of spinning at the North but towards the axis of spin-

ning at the South. That is to say, the charging process at the North is faster than that at the South. This difference leads to an electric current from pole to pole. If the conductivity is different from place to place (or non-uniform) on the Earth's surface, the electric current from pole to pole will not be uniformly distributed on the Earth's surface. This polar current and the circular current will generate a total magnetic field, which biases from its rotation axis. Both the biases and the value of the induced magnetic field are transiently changed because the space charging process is transient.

The observations indicated that the geomagnetic field varies in two (long and short) time scales. In the long time (usually greater than about 100 years) scale, the field strength is decreased and the biased angle (or the orientation) of the field also changes in a certain regulation (see [1] and reference therein). On the other hand, the geomagnetic field changes transiently or in a short time scale [53]. The presented model do predict a magnetic field with such kinds of variations because the solar wind plasma transiently (short time) changes and slowly (long time) decays its plasma density. That is, according to the presented model, the planet magnetic fields should have the two time scale variation behaviors. For the type-I planets (including the Moon), the transient changes of the fields are significant because they are directly charged from solar wind plasmas (or they get extra electrons directly from the solar wind plasmas). For the type-II planets, however, the transient changes of the fields may not be significantly affected by the variation of the solar wind parameters because they do not get extra electrons directly from the solar wind plasmas. The global field does not significantly change because it is impossible for the huge magnetosphere to follow the changes of the solar wind even with the daily and season effects.

According to the present model, the original magnetosphere is arisen due to the proposed mechanism for the unmagnetized body. The unmagnetized body collected extra electric charges from the initial solar wind and formed a strong magnetosphere. If there were no solar wind later, the originally formed magnetosphere would have not existed for such a long time because of the charge being quickly released. In fact, the solar wind only slowly becomes weak. It resists (slows) the releasing of the body charge through refilling some electric charge to the body. This refilling process is actually the current collection process of a magnetized body, which can collect extra electric current (or charge) along its field lines (or at its pole regions). Therefore the energy source of the magnetosphere (or the planet magnetic field) is the solar wind. The gravity of the body also helps to maintain the magnetosphere through trapping its particles as we have discussed above.

The present model predicts that all the solar planets (including the Earth and the Moon) are negatively charged. This conclusion is in agreement with measurements if we analyze the orientation of the magnetic field and the spin direction for

each planet. On the other hand, space experiments have indicated that a spacecraft could be positively charged when it has a special environment (e.g. when it goes to a great distance) [54]. Thus if the Earth becomes positively charged due to some special solar wind conditions, the orientation of its magnetic field will be reversed. But how and in what special conditions the Earth becomes positively charged is open for further study.

By the way, it should be noted that there are really a lot of current systems in the planet's magnetosphere, such as currents on the magnetospheric boundary, magnetotail currents, the ring currents, the field-aligned currents and so on. Since any plasma current will locally form a return current in the plasma, it will not have a significant contribution to the planet's global magnetic field.

In summary, we have developed a theoretical model for the origin of the magnetic fields of planets. According to the space charging physics, we have shown that a body spinning within plasma is charged and generates a dipole magnetic field. The field intensity depends on the size, the spinning speed of the body, and the state of the ambient plasma. For a large and fast spinning body in dense and hot plasma, the generated magnetic field is big. The model predictions on the present magnetic fields of the Moon, Venus, Mars and Pluto agree with the measurements; and the relative magnetic fields of Mercury, Earth, Jupiter, Saturn, Uranus, and Neptune predicted by the present model also agree with the measured data. Furthermore, this model offers an understanding of the polarity biases and reversals of the planets' magnetic fields, and hence may provide a new possible explanation for the origin of the magnetic fields of planets.

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### References

1. Merrill R.T., McElhinny M.W., McFadden P.L. The magnetic field of the Earth (Academic Press, Inc.), 1996.
2. McFadden P.L. *et al.* Reversals of the earth's magnetic field and temporal variations of the dynamo families. *Journal of Geophysics Research*, 1991, v. 96, 3923–3933.
3. Mary C., Courtillot V.A. Three-Dimensional Representation of Geomagnetic Reversal records. *Journal of Geophysics Research*, 1993, v. 98, 22461–22475.
4. Cortini M., Barton C.C. Chaos in geomagnetic reversal records: A comparison between Earth's magnetic field data and model disk dynamo data. *Journal of Geophysics Research*, 1994, v. 99, 18021–18033.
5. Merrill R.T., McElhinny, M.W., Stevenson D.J. Evidence for long-term ,asymmetries in the Earth's magnetic field and possible implications for



- dynamo theories. *Physics of the Earth and Planetary Interiors*, 1979, v. 20, 75–82.
6. Barnett S.J. Gyromagnetic effects, theory and experiments. *Physica*, 1933, v. 13, 24–58.
  7. Vestine E.H. The earth's core. *Transactions of the American Geophysics Union*, 1954, v. 35, 63–72.
  8. Inglis D. R. Theories of the Earth's Magnetism. *Reviews of Modern Physics*, 1955, v. 27, 212–248.
  9. Chatterjee J.S. The Crust as the Possible Seat of Earth's Magnetism. *Journal of Atmosphere and Terrestrial Physics*, 1956, v. 8, 233–239.
  10. Stevenson D. Planetary magnetism. *Icarus*, 1974, v. 22, 403–415.
  11. Hibberd F.H. The origin of the Earth's magnetic field. *Proceedings of Royal Society of London - Mathematical and Physical Sciences*, 1979, v. A369, 31–45.
  12. Larmor J. Possible Rotational Origin of Magnetic Fields of Sun and Earth. *Electrical Review*, 1919, v. 85, 412.
  13. Larmor J. How Could a Rotating Body such as the Sun become a Magnet. *Reports of British Association*, 1919, v. 87, 159–160.
  14. Cowling T.G. The magnetic field of sunspots. *Monthly Notices Royal Astronomical Society*, 1933, v. 94, 39–48.
  15. Elsasser W.M. Induction effects in terrestrial magnetism part I. Theory. *Physical Review*, 1946, v. 69, 106–116.
  16. Bullard E.C. The magnetic field within the Earth. *Proceedings of the Royal Society of London*, 1949, v. A197, 433–453.
  17. Bullard E.C., Gellman D. Homogeneous Dynamos and Terrestrial Magnetism. *Philosophical Transactions of the Royal Society of London*, 1954, v. A247, 213–278.
  18. Roberts G.O. Spatially periodic dynamos, *Philosophical Transactions for the Royal Society of London*, 1970, v. A266, 535–558.
  19. Roberts G.O. Dynamo action of fluid motions with two-dimensional periodicity. *Philosophical Transactions for the Royal Society of London*, 1972, v. A271, 411–454.
  20. Gubbins D. Theories of the geomagnetic and solar dynamics. *Reviews of Geophysics and Space Physics*, 1974, v. 12, 137–154.
  21. Bullard E.C., Gubbins D. Generation of magnetic fields by fluid motions of global scale. *Geophysical and Astrophysical Fluid Dynamics*, 1977, v. 8, 43–56.
  22. Moffatt H.K. Magnetic field generation in electrically conducting fluids (Cambridge University Press, New York), 1978.
  23. McFadden P.L., Merrill R.T. Inhibition and geomagnetic field reversals. *Journal of Geophysics Research*, 1993, v. 98, 6189–6199.
  24. Bagenal F. in *Solar System Magnetic Fields* (E. R. Priest, Ed., D. Reidel Publishing Company, Holland), 1986, pp. 224–254.
  25. Hessler V.P., Wescott, E.M. Correlation between Earth-current and geomagnetic disturbance. *Nature*, 1959, v. 184, 627.
  26. Fleming J.A. *Terrestrial Magnetism and Electricity* (J. A. Fleming, Ed., Dover Publications, Inc., New York), 1949, pp. 49–58
  27. Helsley C.E. Magnetic properties of lunar dust and rock samples. *Science*, 1970, v. 167, 693–695.
  28. Zhang T.X. *et al.* Current collection by tethered satellite TSS-1R. Seminar Presentation at Center for Space Plasma and Aeronomic Research, 1999.
  29. Zhang T.X. Solar 3He-rich events and ion acceleration in two stages. *Astrophysical Journal*, 1995, v. 449, 916–929.
  30. Zhang T.X. Solar 3He-rich events and electron acceleration in two stages. *Astrophysical Journal*, 1999, v. 518, 954–964.
  31. Al'pert Y.L., Gurevich A.V., Pitaevskii L.P. Space physics with artificial satellites (Consultants Bureau, Now York), 1965, 63–105.
  32. Herr J. L., K. S. Hwang, and S. T. Wu, *Proceedings of the 26th AIAA Plasmadynamics and Lasers Conference* (San Diego), 1995.
  33. Parker L.W., Murphy B.L. Potential buildup on an electron-emitting ionospheric satellite. *Journal of Geophysics Research*, 1967, v. 72, 1631–1636.
  34. Slavin J.A., Holzer R.E. Solar wind flow about the terrestrial planets. I - Modeling bow shock position and shape. *Journal of Geophysics Research*, 1981, v. 86, 11401–11418.
  35. Russell C.T., Baker D.N., Slavin J.A. The magnetosphere of Mercury, in Mercury (F. Vilas, C. R. Chapman, and M. S. Matthews, Eds., The University of Arizona Press, Tucson), 1988, pp. 514–561.
  36. Colburn D.S., in *The Moon* (S. K. Runcorn and H. C. Urey, Eds., D. Reidel Publishing Company, Dordrecht, Holland), 1971, pp. 355–371.
  37. Burgess E., *Venus, an Errant Twin* (Columbia University Press, New York), 1985, pp. 47–48.
  38. Mutch T.A. *et al.* *The Geology of Mars* (Princeton University Press, New Jersey), 1978, pp. 39–40.
  39. Russell C.T. The magnetic field of Mars - Mars 3 evidence re-examined, *Geophysical Research Letters*, 1978, v. 5, 81–84.
  40. Russell C.T. The magnetic field of Mars - Mars 5 evidence re-examined, *Geophysical Research Letters*, 1978, v. 5, 85–88.
  41. Taylor S.R. *Solar system evolution: A new perspective* (Cambridge Univ. Press, Cambridge U.K.), 1992, pp. 58–59.
  42. Holzer T. E., in *The Solar system plasma physics*, V.I. (C. F. Kennel, L. J. Lanzerotti, and E. N. Parker, Eds., North-Holland Publishing Company, Amsterdam-New York-Oxford), 1979, pp. 101–176.
  43. Heymann D., in *The solar output and its variation* (O. R. White et al. Eds., Colorado Associated University Press, Boulder), 1978, pp. 405–427.
  44. Al'pert Y.L. *Space plasma* (Cambridge University Press, Now York), 1983.
  45. Connerney J. E. P. and N. F. Ness, in *Mercury* (F. Vilas, C. R. Chapman, and M. S. Matthews, Eds., The University of Arizona Press, Tucson), 1988, pp. 494–513.
  46. Encrenaz T., Bibring T.P., Blanc M. *The solar system* (Spring-Verlag Berlin Heidelberg), 1990, pp. 211–214.
  47. Burgess E. *Uranus and Neptune* (Columbia University Press, New York), 1988, pp. 82–83.
  48. Bergstrahl J.T., Miner, E.D. in *Uranus* (J. T. Bergstrahl, E. D. Miner, and M. S. Matthews Eds., The University of Arizona Press, Tucson), 1991, pp. 3–25.
  49. Luhmann J.G., Russell C.T., Brace L. H., Vaisberg O.L. The Intrinsic Magnetic Field and Solar-Wind Interaction of Mars, in *Mars* (The University of Arizona Press, Tucson & London), 1992, pp. 1090–1134.
  50. Russel C.T. Planetary magnetism. In *Geomagnetism*, (J. A. Jacobs ed., Orlando Academic Press), 1987, v. 2, 458–523.
  51. Busse F. H. Generation planetary magnetism by convection. *Physics of the Earth and Planetary*, 1976, v. 12, 350–358.
  52. Laundal K.M. Ostgaard N. Asymmetric auroral intensities in the Earth's Northern and Southern hemispheres. *Nature*, 2009, v. 460, 491–493.
  53. Matsushita S., Campbell, W.H. *Physics of geomagnetic phenomena* (Academic Press INC., New York), 1967.
  54. Whipple E.C. Potentials of surfaces in space. *Reports on Progress in Physics*, 1981, v. 44, 1197–1250.
  55. Chapman S. *Solar plasma geomagnetism and aurora*. Gordon and Breach, Science Publishers, Inc., New York, 1964.