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How was the Earth–Moon system formed? New insights from the geodynamo

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The most widely accepted scenario for the formation of the Earth–Moon system involves a dramatic impact between the proto-Earth and some other cosmic body. Many features of the present-day Earth–Moon system provide constraints on the nature of this impact. Any model of the history of the Earth must account for the physical, geochemical, petrological, and dynamical evidence. These constraints notwithstanding, there are several radically different impact models that could in principle account for all the evidence. Thus, in the absence of further constraints, we may never know for sure how the Earth–Moon system was formed. Here, we put forward the idea that additional constraints are indeed provided by the fact that the Earth is strongly magnetized. It is universally accepted that the Earth's magnetic field is maintained by a dynamo operating in the outer liquid core. However, because of the rapid rotation of the Earth, this dynamo has the peculiar property that it can maintain a strong field but cannot amplify a weak one. Therefore, the Earth must have been magnetized at a very early epoch, either preimpact or as a result of the impact itself. Either way, any realistic model of the formation of the Earth–Moon system must include magnetic field evolution. This requirement may ultimately constrain the models sufficiently to discriminate between the various candidates.

geodynamo | Earth–Moon system | giant impact theory

Roughly 4.5 billion years ago, a dramatic event led to the formation of the Earth–Moon system. Many models have been proposed that involve an impact between the proto-Earth and some other cosmic body. These range from grazing impacts that leave the interior of the proto-Earth relatively unscathed through to head-on collisions, in which the entire proto-Earth is vaporized. Of course, each of these models must ultimately account for the known properties of the Earth–Moon system, particularly the masses, densities, isotopic abundances, and angular momenta. However, a significant problem, as pointed out in the review (1), is that most of these models, suitably modified, may be able to satisfy all of the constraints, and thus, we might never know the details of the formation event.

In this paper, we argue that there is another requirement, one that has so far not been exploited, stemming from the fact that the Earth is not just magnetized but strongly magnetized, which provides additional and very powerful constraints. The possibility that the Earth's magnetic field is a remnant "fossil" field can be discounted by noting that the temperature of the solid inner core is above the Curie temperature for permanent magnetization and that the Ohmic decay time for the Earth's core is extremely small compared with the timescale for which there is paleomagnetic evidence that the Earth has been magnetized. Thus, the Earth's magnetic field has to be continually regenerated. Furthermore, the fact that the geomagnetic field undergoes sporadic reversals of sign points to the dynamic nature of the regeneration process. There is universal agreement that the Earth's magnetic field is thus maintained by a hydromagnetic dynamo; given that the inner core is solid and the mantle is electrically insulating, such a dynamo can be located only in the liquid outer core. The fluid motions that power the dynamo result from convection strongly influenced by the Earth's rapid rotation. Here, by "rapid," we mean that the rotational period (1 d) is very much less than the turnover time for the convection (of the order of 100 y). Indeed, because of the rotation, the dynamo has the distinctive property that it can maintain a pre-existing strong magnetic field but cannot amplify a weak field. If, somehow, the magnetic field were to disappear, then the convection would not be able to remagnetize the core. Conversely, if at some early epoch, the Earth were unmagnetized, it would remain unmagnetized, so long as the convection were strongly influenced by rotation. All evidence suggests that, post-impact, the Earth has been in this regime of rapid rotation, with a gradual slowdown from once every few hours to the current value of once every 24 h. This raises the question of how the Earth originally become strongly magnetized. There are two possibilities. Either the strong field existed pre-impact and was not destroyed by the impact, or the strong field resulted from the impact process itself or during its immediate aftermath. In the former case, there are constraints on both the processes that led to the formation of the proto-Earth and the nature of the impact. In the latter, there are severe constraints on the nature of the impact itself, namely that it must drive a very efficient dynamo capable of strongly magnetizing the core.

Here, we are going to elaborate on the idea that the Earth has to emerge from the impact strongly magnetized. We do this by recalling results from geodynamo theory relating to convection in rapidly rotating systems, coupled with results from bifurcation theory. Although many of these results are not new, their significance, taken together, has

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been overlooked in the context of the history of the Earth. Together, they provide a new conceptual framework to show how the requirement that the Earth be strongly magnetized constrains the various proposed scenarios for the history of the Earth and the formation of the Earth–Moon system.

Conditions for Dynamo Action

Currently, the Earth's core consists of a solid, predominantly iron, inner core and a liquid outer core, which is in a state of convection. It is the fluid motions that result from convection that drive the dynamo. The energy sources for the motions are either compositional or thermal. Early in the Earth's history, when there was no solid inner core, the energy source had to be thermal, whereas for the current Earth, it is commonly believed that the energy source is mostly compositional (2). For the arguments expounded in this paper, the precise nature of the energy source is immaterial.

Given that the Earth's magnetic field is maintained by a hydromagnetic dynamo, we continue by discussing the conditions under which dynamo action is possible. There are two processes that affect the evolution of the magnetic field: induction and diffusion. Induction is associated with the stretching and folding of magnetic field lines by the motions of an electrically conducting fluid. Ohmic diffusion is associated with the finite electrical conductivity of the medium. Dynamo action succeeds if the inductive processes are stronger than those associated with diffusion. A measure of the relative strength of these two processes is given by the magnetic Reynolds number defined as $Rm = U\ell/\eta$, where U and ℓ are characteristic velocity and length scales and η is the magnetic diffusivity. This dimensionless number is defined by analogy with the fluid Reynolds number but with magnetic diffusivity taking the place of kinematic viscosity. Hence, for dynamo action to succeed, Rm must exceed some critical value Rm_c. The precise value of Rm_c depends on the specifics of the system, such as the geometry, the boundary conditions, and the structure of the velocity; typically, it is of the order of a few hundred.

Clearly, the next step is to estimate Rm for a planetary core, such as the Earth. A characteristic convective velocity U can be derived from the motion of geomagnetic anomalies, which gives an estimate of ≈ 2m/h, somewhat slower than a lethargic snail (3, 4). The magnetic diffusivity η is estimated to be of the order of $1\text{m}^2/\text{s}$, although its precise value is still a matter of some debate (5). In convection, the length scale ℓ is related to the size of the typical convective structure. This quantity is determined by the balance of forces acting on the fluid. In a planetary liquid core, the fluid is essentially incompressible; therefore, the fluid velocity $\boldsymbol{u}$ satisfies $\nabla \cdot \boldsymbol{u} = 0$. The force balance is captured by the incompressible Navier–Stokes equation. In a frame rotating with constant angular velocity $\boldsymbol{\Omega}$, this may be expressed as

$$\underbrace{\left(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u}\cdot\nabla\boldsymbol{u}\right)}_{\text{interia}} + \underbrace{2\boldsymbol{\Omega}\times\boldsymbol{u}}_{\text{Coriolis}} = \underbrace{-\frac{1}{\rho_0}\nabla p}_{\text{pressure}} + \underbrace{\frac{\delta\rho}{\rho_0}\boldsymbol{g}}_{\text{buoyancy}} + \underbrace{\frac{1}{\mu_0\rho_0}(\nabla\times\boldsymbol{B})\times\boldsymbol{B}}_{\text{magnetic}} + \underbrace{\nu\nabla^2\boldsymbol{u}}_{\text{viscous}}. \quad [1]$$

Here, $\boldsymbol{u}$ is the velocity in the rotating frame, $\boldsymbol{B}$ is the magnetic field intensity, μ_0 is the magnetic permeability, $\boldsymbol{\Omega}$ is the angular velocity, ρ_0 is a uniform reference density, $\delta\rho$ is the variation in the density, p is the pressure (relative to some background state), $\boldsymbol{g}$ is the acceleration due to gravity, and ν is the kinematic viscosity. Eq. **1** is simply Newton's second law for a fluid. The inertia term on the left-hand side represents the rate of change of velocity in a rotating frame; the Coriolis term arises from motion in a rotating frame. The terms on the right-hand side are the forces per unit mass acting on the fluid: pressure forces, buoyancy, magnetic (Lorentz) forces, and viscous stresses.

First of all, we note that in an incompressible fluid, the pressure gradient plays no dynamical role other than to enforce the requirement that $\nabla \cdot \boldsymbol{u} = 0$. Furthermore, in a rotating fluid, the structure of the convection depends crucially on the ratio of the magnitude of the inertia terms to that of the Coriolis term. This ratio is denoted by the Rossby number Ro, with rapidly rotating systems having small Ro. For convection in the Earth's outer core, Ro can be estimated as the ratio of the rotation period to the convective overturning time. The former, currently, is 24 h. The latter can be calculated from the depth of the outer core ($\ell_d \approx 2{,}400$ km) and the characteristic convective velocity U, which gives an overturning time of the order of a century. For these parameters, $Ro \approx 2 \times 10^{-5}$. In regimes in which $Ro \ll 1$, the Coriolis force is dominant and can balance practically instantaneously the resultant force on the right-hand side of Eq. **1**; consequently, the fluid moves as if it had no inertia. Thus, the force balance, which ultimately determines the scale ℓ, depends on only four dynamical ingredients. As we shall argue presently, the outcome is radically different depending on whether the fluid is weakly or strongly magnetized.

Weakly Magnetized Core Convection

In order to understand to what extent convection in the core can amplify a weak magnetic field, it is necessary first to consider the structure of convection in the absence of a magnetic field. In a rapidly rotating system, fluid motions arrange themselves so as not to vary in the direction of the rotation axis—formally known as the Taylor–Proudman theorem. For the case of rapidly rotating convection, in the absence of magnetic field, the motions, therefore, organize themselves into columnar structures (6–8), as sketched in Fig. 1. We emphasize here that Fig. 1 is just a schematic representation of the flow to illustrate its basic geometry in the form of convective columns. In reality, for rotation rates representative of the Earth, the number of columns in an unmagnetized core would be enormous.

For this type of columnar convection, the relevant length scale that appears in Rm is the width of the columns, ℓ_t. As we have discussed above, ℓ_t is determined by the balance of forces in Eq. **1**. In the absence of a magnetic field and neglecting inertia terms owing to rapid rotation, the only remaining forces are the viscous forces (V), the buoyancy (Archimedean) force, and the Coriolis force. For a force balance, all of these three ingredients must be of comparable magnitude—what is often referred to as VAC balance. We note that the magnitude of the viscous stresses

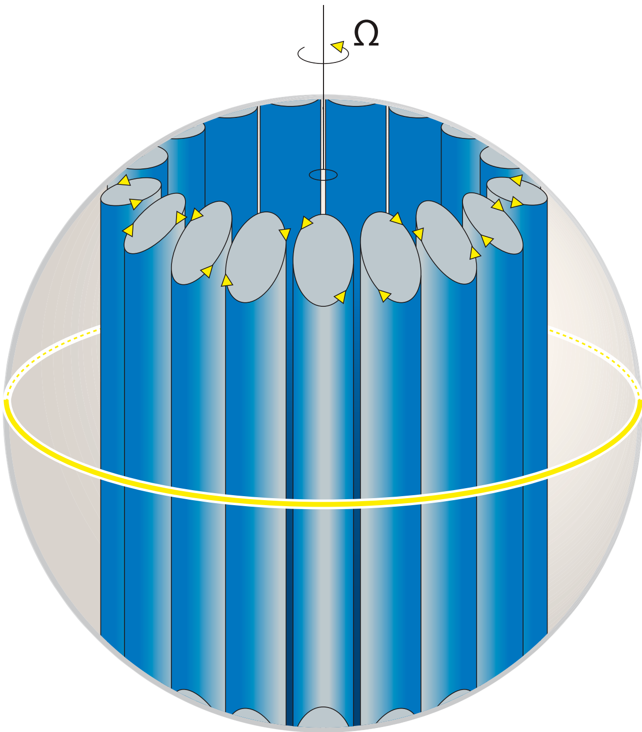

Fig. 1. Columnar convection. Schematic representation of the pattern of convection in an unmagnetized rapidly rotating spherical shell. The purpose of the figure is to introduce the basic geometry of the convective structures—Taylor columns. The height of the columns is comparable with the radial extent of the fluid layer, ℓ_d; the width of the columns is ℓ_t. For realistic parameters appropriate to an unmagnetized Earth, there would be hundreds of thousands of such columns.

depends on scale, increasing with decreasing scale, whereas the buoyancy and Coriolis forces are scale independent. It is, therefore, reasonable to expect that if the viscosity is small, as is the case in planetary cores, VAC balance will be achieved at some small scale, which determines ℓ_t. This argument can be made more precise by introducing the Ekman number, which is a measure of the rotational to viscous timescales and is defined by $E = \nu/2\Omega\ell_d^2$; as above, ℓ_d represents the depth of the fluid layer, which is itself comparable with the height of the convective columns. A straightforward argument shows that, for small Ekman number, VAC balance is achieved when $\ell_t \sim E^{1/3}\ell_d$ (9).

With knowledge of the kinematic viscosity as $\nu = 10^{-6}\mathrm{m}^2\mathrm{s}^{-1}$ (10), the Ekman number for the current Earth is estimated to be $E \approx 10^{-15}$. The width of the columns ℓ_t is thus 10^{-5} times their height, giving $\ell_t \approx 24$ m. In terms of Fig. 1, this would imply that if the Earth's core were unmagnetized, convection would consist of hundreds of thousands of extremely thin columns. The corresponding magnetic Reynolds number for this type of convection is, therefore, $Rm \approx 10^{-2}$. This value of Rm is four orders of magnitude smaller than is required for dynamo action. Even accounting for the possible uncertainties in U, ν, and η, it is highly unlikely that these will raise Rm to the level of Rm_c.

The estimate for ℓ_t relies on the assumption that the inertia terms can be neglected. Clearly, this depends on the scale considered. There will always be scales below which the influence of rotation is not felt (i.e., scales for which the local Rossby number is no longer small) and in which the balance of terms in Eq. **1** is then different. For the parameters relevant to the Earth that we used above, this scale is comparable with ℓ_t. Although the introduction of inertia terms will of course lead to more complex dynamics on scales smaller than or comparable with ℓ_t, it does not fundamentally change the estimate for ℓ_t and hence, Rm.

The above estimates were obtained assuming that the Earth has a solid inner core, which of course, is correct for the current Earth. Clearly in the past, the solid inner core was smaller than it is today, and in an earlier epoch, there was no inner core at all. This has two consequences. One is that the size of ℓ_d was bigger in the past; the other is that when the core was entirely liquid, the source of buoyancy was thermal—mostly due to radioactive decay—and not compositional. Even taking these factors into account, the core convection has always been overwhelmingly rotationally constrained, particularly given that the Earth's rotation rate was higher in the past. Thus, although the estimate for ℓ_t may have changed in the past, it would be at most by factors of order unity and certainly not sufficient to change Rm by several orders of magnitude. Regardless of the precise form of the convection, the inescapable conclusion is that if the Earth's core were not magnetized, then the convective flows would not be able to sustain dynamo action and hence, would not be able to magnetize the Earth.

Strongly Magnetized Core Convection

The Earth undeniably does have a magnetic field. So, how can this fact be reconciled with the argument given above? In order for a dynamo to operate, Rm must exceed Rm_c. What argument could one bring forth greatly to justify a much larger estimate of Rm? We note that if a strong magnetic field were present—where "strong" here means that the Lorentz force is comparable with the other forces—then this would open up the possibility of a very different force balance in Eq. **1**. In particular, there could be a balance in which the magnetic (M), buoyancy (Archimedean), and Coriolis forces are comparable and in which the viscous terms are negligible—the so-called MAC balance (10–12). With such a balance, the size of the convective structures becomes independent of the viscosity and hence, of the Ekman number; thus, the relevant length scale of the convection could become comparable with the depth of the layer ℓ_d. This has the important consequence that Rm for such a configuration would be $O(10^3)$, five orders of magnitude greater than the corresponding value for the weakly magnetized case and definitely large enough to sustain dynamo action. This argument, applied to the Earth, illustrates a type of large-scale convection that can maintain a strong field by dynamo action. It is important, however, to recognize that such dynamo action relies on a bootstrapping effect. The convection can maintain a magnetic field because of its large scale, but the convection itself can be maintained at a large scale only by virtue of the strong magnetic field. Thus, this dynamo can operate only provided that a strong field is there in the first place.

Weak and Strong Dynamo Branches

Above, we have described two very different types of convection that could exist in the Earth's liquid core: one in which the dominant convective structures are columnar with a small transverse scale controlled by viscosity and, at most, a weak magnetic field, and the other in which the dominant convective structures are large scale, viscosity plays no role, and the magnetic field is strong. It is imperative to understand how these very different configurations are related; this is best illustrated by consideration of a bifurcation diagram. Fig. 2 shows one such diagram appropriate to dynamo action driven by core convection. On the horizontal axis, the parameter R is a measure of the convective driving; for the Earth's core, this would be the strength of the thermal and compositional buoyancy parameterized, for instance, by some appropriate Rayleigh number. On the vertical axis, the quantity A is a measure of the amplitude of the response of the system; here, it can be identified with some measure of the magnetic field strength, such as its rms intensity. The $A = 0$ axis represents the system with no magnetic field and with the convection in columnar form for all values of R shown. There is, of course, a value of R below which the driving is so weak that it cannot even sustain convection; this value is way to the left of our figure. Furthermore, way to the right of our figure, the convection is so vigorous that the inertia terms in Eq. **1** become important and the convection ceases to be columnar. Neither of these extreme cases is pertinent to the Earth at any time of its evolution.

Every point in the (R, A) plane can be thought of as an initial condition for a convective system with a given driving and a given level of magnetization. The blue lines in this diagram represent the stationary solutions; the solid lines denote attracting stable solutions, and the dashed lines denote repelling unstable solutions. The red lines show the evolution in time of a given initial configuration, noting that all initial conditions must ultimately end up on a stable stationary branch of solutions. It should be noted that the ultimate state of magnetization of any initial condition depends on how the magnetic Reynolds number Rm changes during the evolution. For a given working fluid (i.e., fixed η), Rm can be increased by increasing either the vigor of the convection or its spatial scale; in terms of Fig. 2, the former corresponds to moving to the right, whereas the latter is more related to moving upward.

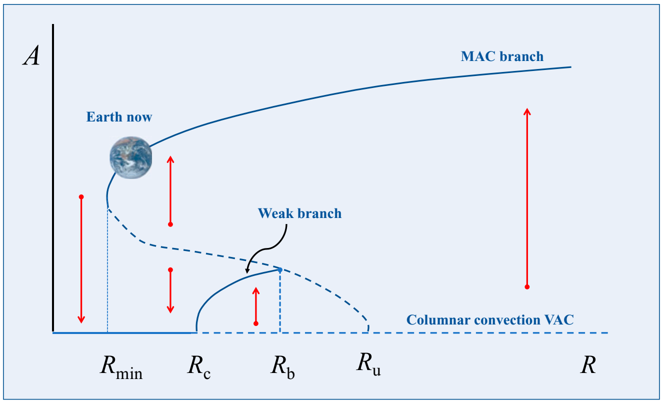

Fig. 2. Bifurcation diagram for different branches of dynamo solutions (after ref. 13). The parameter R is a dimensionless measure of the convective forcing; the quantity A represents a measure of the degree of magnetization, with the horizontal axis corresponding to an unmagnetized state. Solid blue lines correspond to stable solutions, and dashed lines correspond to unstable solutions. The red lines show the direction of the evolution of initial perturbations. R_{min} is the smallest value for which magnetization is possible, R_c is the smallest value for which infinitesimal magnetic perturbations can grow, R_b marks the end of the small-amplitude stable branch, and R_u is where the subcritically unstable branch comes into existence. We incorporate R_u here for mathematical completeness, even though in the current context, it has no physical significance. The position of the current Earth in the diagram is as shown.

The clearest way of interpreting Fig. 2 is to consider what happens for specific ranges of the parameter R. For $R < R_{min}$, the convective velocity is so feeble that it cannot sustain dynamo action, and for any initial condition, the magnetic field eventually decays to zero. By contrast, for $R > R_b$, the columnar convection is sufficiently vigorous that any magnetic perturbation, however small, will be amplified to such an extent that the system will evolve to the large-scale strongly magnetized configuration. Between these two extremes (i.e., $R_{min} < R < R_b$), the ultimate fate of the system depends crucially on the strength of the initial field. For $R_{min} < R < R_c$, initial conditions below the dashed line decay to the unmagnetized, small-scale columnar convection, whereas for initial conditions above the dashed line, the magnetic field is sufficiently strong to alleviate the rotational constraints and allow the system to evolve to large-scale strongly magnetized convection. For the purposes of this discussion, we define a dynamo of this type that operates for R below R_c as subcritical. For $R_c < R < R_b$, the situation is further complicated by the presence of an additional branch of stable weak field solutions. In this range, as before, any initial condition above the finite-amplitude dashed line will evolve to the strongly magnetized configuration. Every initial condition below the dashed line will evolve to a state of weak magnetization and slightly modified small-scale columnar convection.

In terms of the dynamical balances discussed earlier, VAC balance is achieved on and near the horizontal axis, where the influence of the magnetic field is weak, whereas MAC balance occurs in the vicinity of the upper branch. This implies that for the same Rayleigh number R, the value of the magnetic Reynolds number Rm near the $A = 0$ axis (columnar convection) and its value on the upper branch are very different, with the latter being much larger than the former. The reason is not primarily because of the vigor of the convection but rather, because the characteristic scale of convection is widely different in the two cases. As discussed above, the ratio of these scales is $O(E^{1/3})$.

An understanding of the Earth's magnetic field hinges on where the Earth sits in Fig. 2. In the discussion above, we argued that if the Earth's convection were in the columnar configuration, its magnetic Reynolds number Rm would be orders of magnitude smaller than what is required for dynamo action. That said, the Earth is magnetized and has been for a long time. Therefore, it must sit on the upper branch of solutions, to the right of R_{min} and considerably to the left of R_c; in other words, the Earth's dynamo is strongly subcritical. The location of the Earth on the bifurcation diagram has an extremely important consequence. As long as the energy source for the dynamo is convection in the liquid core, the initial conditions that would lead to today's magnetic configuration must be above the dashed line.

Constraining Models for the Formation of the Earth

The preceding arguments demonstrate that the Earth's dynamo, for as long as it has been driven by convective motions, must have been strongly subcritical in the sense described above. This property arises from the rapid rotation of the Earth and applies equally if the convection is driven thermally or compositionally and if the Earth does or does not have an inner core. This justifies our assertion that if the Earth's liquid core had not been magnetized when it settled down to a convective state, then it would still be unmagnetized today. So, how and when did the Earth become strongly magnetized? Clearly, some event or events in the Earth's early history led to its strong magnetization.

All histories of the Earth involve a dramatic event 4.5 billion years ago, resulting in the formation of the Moon. Most theoretical descriptions of this event assume some sort of impact, the details of which are still hotly debated (1). For example, different models can differ substantially in their impact velocity. At the "slow" end are the so-called "graze and merge" models, in which the impactor approaches at the free-fall velocity, the impact is off-center, and the impactor merges with the proto-Earth (14–17). At higher approach velocities, the impactor can escape, leaving a rapidly spinning Earth—such models can be categorized as "hit and run" (18–20). In models with even higher approach velocities, a very rapidly rotating proto-Earth collides head on with a very high–velocity impactor. The collision can be so energetic that both the Earth and the impactor are vaporized; the material then expands to form an extended torus (the synestia) that subsequently recondenses to form the Earth and the Moon (21, 22).

We now argue that the requirement that the Earth be strongly magnetized can discriminate between different models and help resolve this debate. It is not our objective here actually to resolve the debate but rather, to show how this may be achieved. From the point of view of magnetic field generation, broadly speaking we can identify four epochs during which distinct dynamo processes could have taken place: formation of the proto-Earth from disk accretion, liquid core convection before the impact, the impact itself, and the immediate aftermath of the impact. If magnetic field generation takes place in a particular epoch, then it definitely constrains the dynamical processes characteristic of that epoch and may also constrain other epochs. The causal connections between processes in different epochs are shown schematically in Fig. 3, which shows four possible scenarios leading to the current Earth being strongly magnetized. The different scenarios are distinguished by the epoch in which dynamo processes magnetize the Earth's core (shown in orange). The blue boxes highlight all of the other epochs that are constrained in a particular scenario. Fig. 3 is not exhaustive; one can conceive of more complicated scenarios in which, for example, the Earth is magnetized, demagnetized, and then, remagnetized.

From the point of view of our analysis, the four scenarios in Fig. 3 can be split into two broad categories: those in which the Earth's core is already strongly magnetized at the time of impact (Fig. 3, *Upper*) and those for which it is not (Fig. 3, *Lower*). Scenarios in the first category (Fig. 3, *Upper*) not only require strong magnetization preimpact but also, require that the magnetization is not destroyed by the impact or its aftermath. Here, the magnetization requirement constrains most of the Earth's history from its formation onward. By contrast, the magnetization of the scenarios in the second category (Fig. 3, *Lower*) occurs either during the impact or its aftermath; as such, the magnetization requirement places no strong constraints on the preimpact evolution.

It is now helpful to discuss some of the physical processes that would be characteristic of the different epochs. In the first scenario in Fig. 3, the nascent proto-Earth is magnetized as it forms from the disk. This imposes strong constraints

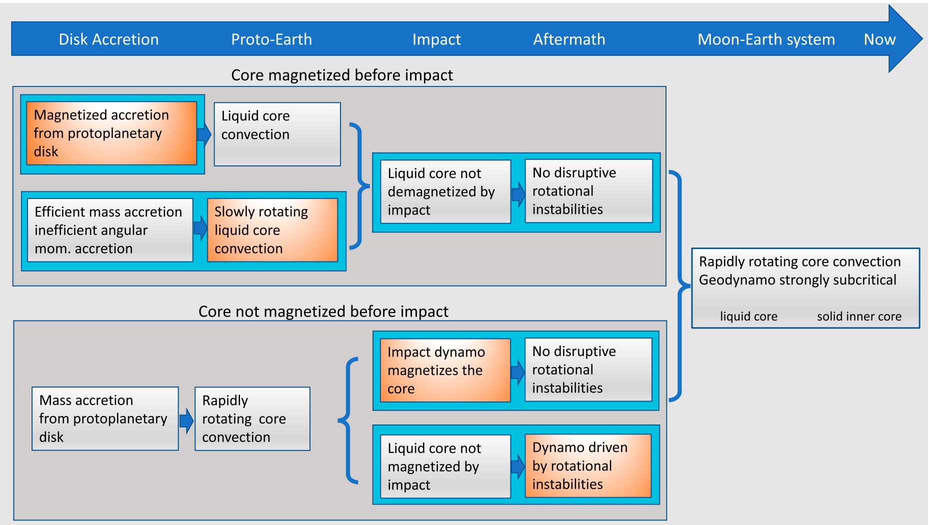

Fig. 3. Schematic representation of time line of events leading to a magnetized Earth today. We identify four different epochs in which magnetic fields can be generated or destroyed: formation of the proto-Earth by accretion from the disk, core convection taking place in the newly formed proto-Earth before the impact, the impact itself, and the immediate aftermath of the impact. The four time lines correspond to scenarios that differ in the epoch in which magnetization takes place, indicated by the orange boxes. The blue boxes highlight all of the other epochs that are constrained in a particular scenario. The top two time lines correspond to scenarios in which the Earth is magnetized before the impact and must not be demagnetized by the impact or its aftermath. By contrast, the bottom two time lines correspond to scenarios in which the Earth is not magnetized before the impact and therefore must be magnetized by the impact or its aftermath. These four are the simplest scenarios; one could conceive of more complicated cases in which there are multiple episodes of magnetization and demagnetization.

on both the disk properties and the accretion process; the disk material must be magnetized, and the accretion process must provide an efficient transport of magnetic field onto the emerging proto-Earth. Following the formation of a strongly magnetized proto-Earth, some form of core convection is needed to maintain the magnetic field. This scenario, provided that the magnetic field of the proto-Earth is strong, places no requirements on the rotation rate of the proto-Earth; the magnetization will be maintained for both slow and rapid rotation, and hence, there are no constraints on angular momentum accretion. Alternatively, as in the second scenario in Fig. 3, the proto-Earth may be formed in such a way as to be only weakly magnetized. In this scenario, the strong magnetization arises after formation and from dynamo action driven by core convection. Here, the proto-Earth cannot be rotating too fast; otherwise, as argued above, the dynamo would be strongly subcritical. The need for at most moderate rotation requires efficient mass accretion and inefficient angular momentum accretion, thus providing constraints on the structure of the disk itself (23).

In both of the above scenarios, the Earth is magnetized at the moment of impact, so the key requirement is that the impact and its immediate aftermath must not disrupt the magnetization. To be precise, no process must occur that causes the amplitude of the magnetic field to fall below the dotted line in Fig. 2. This places the very strong constraint that the impact cannot lead to a significant disruption of the liquid core; by this, we mean that the impact must not cause anti-inductive processes that lead to its demagnetization. For instance, it has been proposed that a giant impact may have caused the cessation of magnetic activity on Mars (24). By their very construction, graze and merge models are good candidates to satisfy this constraint. Thus, were the Earth to have been magnetized preimpact, then this magnetization could survive the impact. Subject to stricter constraints, hit-and-run models may also be accommodated within the scenarios in which the proto-Earth is magnetized preimpact. Here, the issue is not that the core is disrupted but that the aftermath of the impact leaves behind a very rapidly rotating Earth and an Earth–Moon system with substantially more angular momentum than it has today. According to these models, the excess angular momentum is then lost on a short timescale (of the order 10^4 y). In this case, any processes put forward to account for the rapid angular momentum loss, such as evection resonances, must not drive instabilities in the liquid core that can lead to its demagnetization. For the most extreme models, in which the Earth is vaporized, it is hard to envisage how the magnetic field would survive; thus, such models cannot readily be accommodated in scenarios in which the core is not significantly disrupted.

The second broad category in Fig. 3 consists of the third and fourth scenarios, in which the proto-Earth is unmagnetized at the time of impact. Here, the current magnetization of the Earth provides constraints only on the postimpact evolution. Two possibilities naturally arise. In one, the impact itself drives a dynamo that magnetizes the core, and any ensuing rotational instabilities do not demagnetize it (scenario 3 of Fig. 3). In the other, the impact itself does not magnetize the Earth, and the dynamo is driven by rotational instabilities that develop in the aftermath (scenario 4).

Graze and merge models can be accommodated in this category provided that it is the impact that magnetizes the Earth. This could be achieved if the core convection modified by the impact acts as a dynamo to magnetize the core in a relatively short time. Since such models do not require any substantial angular momentum transfer postimpact, one can rule out the possibility of magnetization by rotational instabilities. Hit-and-run models could also be accommodated in this category provided that the dynamo is driven either by the impact-induced motions or by subsequent instabilities associated with angular momentum loss. In the most extreme cases, in which a synestia is formed, magnetization, if it is possible at all, must occur during the process of recondensation and subsequent angular momentum loss.

Given all the above considerations, it is clear that the fact that the Earth is strongly magnetized today is a powerful new constraint. From the point of view of modeling the history of the Earth, an important new direction is afforded by incorporating the evolution of the magnetic field. Incorporating constraints related to the magnetization of the Earth brings into play a lot of new physics, hitherto ignored. Clearly, the valuable new insights provided can only help in discriminating between different models. One can envision an exciting range of problems involving magnetohydrodynamical (MHD) processes in general and dynamo theory in particular, some of which are as follows.

- What are the conditions under which disk accretion leads to the formation of a strongly magnetized protoplanet?
- What kinds of impact will leave a liquid core strongly magnetized?
- Conversely, what kinds of impact can lead to the strong magnetization of the liquid core?
- Can the removal of the crust and/or mantle by a giant impact create the conditions for vigorous convection in the core?
- Can the instabilities driven by rapid angular momentum loss lead to strong magnetization of the core?
- Can the recondensation of accretion tori, such as synestia, lead to dynamo action?

Indeed, aspects of some of these problems have already been considered. In the context of dynamo action, of particular interest is the work of Le Bars et al. (25), who investigated whether an impact-driven dynamo could have magnetized the early Moon. In the context of the formation of the Earth–Moon system, Mullen and Gammie (26) have incorporated MHD into their computational models and have shown that magnetic fields can be dynamically significant. Current theories of the Earth's formation seek to account for the physical, geochemical, petrological, and dynamical evidence. We have argued that it is crucial that they must also account for the Earth's state of strong magnetization. It would be great to see hydromagnetic studies of the Earth extended to the specific problem of how the Earth became magnetized during its early history.

Data, Materials, and Software Availability. There are no data underlying this work.

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