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Earth's Energy Budget and the "New Core Paradox"

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Abstract

Earth's magnetic field has existed for billions of years, sustained by a hydromagnetic dynamo operating in the liquid iron core. The fundamental question of how the dynamo has been powered over geological timescales has received renewed interest in recent years owing to advances in experimental and computational mineral physics. Much debate has surrounded the core's thermal conductivity, which could be high enough to pose significant problems for the classic model of core evolution where the dynamo is assumed to be powered by secular cooling before the growth of the solid inner core. The "New Core Paradox" refers to the failure of the classic model to predict sufficient power for the dynamo over geological time, in conflict with paleomagnetic observations. Here I review the basis for the "New Core Paradox" and then consider 4 proposed resolutions to the paradox that augment the classic model: radiogenic heating in the core; a hot initial core and low melting point; precipitation of light elements at the core-mantle boundary; and coupled thermo-chemical interactions between the core and a basal magma ocean. Finally I discuss the observations that might distinguish these different scenarios.

1. Introduction

Elucidating the origin of Earth's magnetic field is important for understanding planetary habitability and is widely recognised as a fundamental goal in the geosciences. The field has continuously shielded the surface environment from solar radiation for at least the last 3.5 billion years [67, 12] and interacts with the solar wind to produce space weather, which has a variety of impacts on modern society including disrupting telecommunications and degrading electrical devices aboard low-orbiting satellites [48]. The field also provides a window into the most remote region of our planet because it is generated 2900 km below the surface in the liquid iron core. The field generation process is a so-called hydromagnetic dynamo, which converts kinetic energy from the turbulent convecting fluid into magnetic energy. By building models of the dynamo that are consistent with observations it is possible to infer deep Earth structure, dynamics, and evolution over the past few billion years.

The classic model of long-term dynamo evolution was established over 40 years ago [e.g. 68, 14, 35, 66]. The core is an alloy of iron and nickel together with 10 wt% lighter elements such as silicon and oxygen [38]. Convection is assumed to efficiently mix the bulk core such that lateral variations in thermo-mechanical properties are minute compared to the horizontal average [65] and radial variations are given by an approximately uniform composition, adiabatic temperature, and hydrostatic pressure gradient [15, 50]. In the classic model, the dynamo is ultimately powered by the heat Q_{cmb} extracted at the core-mantle boundary (CMB) by convection in the overlying

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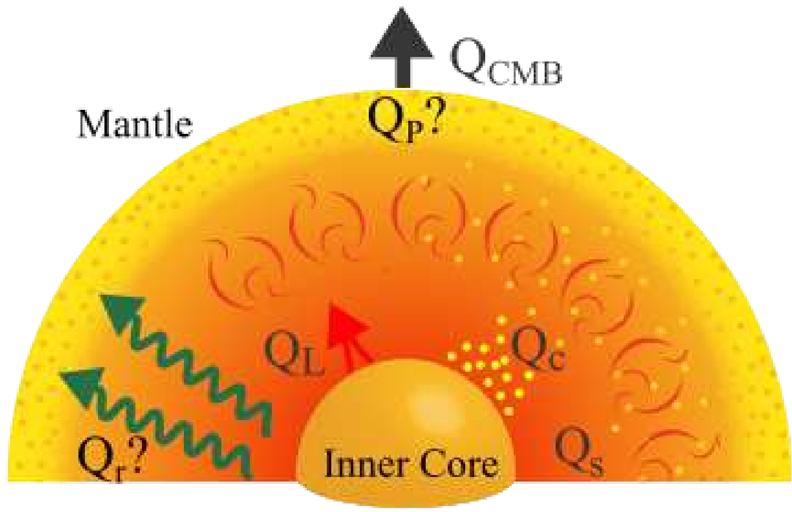

Figure 1: Cartoon showing the potential power sources to the geodynamo. In the classic picture of dynamo evolution the CMB heat flow, $Q_{\rm cmb}$, is balanced by the secular cooling $Q_{\rm s}$ and the release of latent heat $Q_{\rm L}$ and gravitational energy $Q_{\rm c}$ from inner core growth. Other potential heat sources are radiogenic heating $Q_{\rm r}$, e.g. from the decay of ^{40}K, and gravitational energy release from the precipitation of oxides below the CMB, $Q_{\rm P}$.

mantle. In the absence of freezing, $Q_{\rm cmb}$ is entirely balanced by the sensible heat $Q_{\rm s}$ stored in the core. Continued cooling due to CMB heat loss eventually leads to freezing of the liquid from the bottom up due to the steep slope of the melting point at the high pressure $P \sim 330$ GPa and temperature $T \sim 5000$ K of the iron alloy. Bottom-up freezing leads to the release of latent heat, $Q_{\rm L}$, and gravitational energy $Q_{\rm c}$ as some of the light elements partition preferentially into the liquid phase (Figure 1). These two power sources are much more efficient than sensible heat in terms of powering the dynamo [50] and so the time of inner core nucleation (ICN) is a key point in deep Earth evolution.

However, over the last decade the classical model has come under scrutiny, motivated by advances in experimental and computational mineral physics. The vast temperatures and pressures and the uncertain composition mean that establishing the material properties of Earth's core is (and continues to be) extremely challenging. Prior to 2012, key transport properties such as thermal conductivity k and electrical conductivity σ were extrapolated from accessible conditions based on theoretical considerations [e.g. 64]. However, from 2012, computational determinations of k and σ for pure iron and iron alloys were obtained at the $P-T$ conditions of the core without extrapolation [57, 25, 58]. These calculations found k and σ values that were 2-3 times larger than the extrapolated values. The increase was traced to saturation of the electrical resistivity at high T [34, 56], which arises when the inter-atomic distance becomes comparable to the electron mean free path, with the increase in k resulting from approximate validity of the Wiedemann-Franz law at high $P-T$ [57, 25].

In the past 10 years, many studies have investigated the thermal conductivity of solid and liquid iron alloys across a range of $P-T-$composition conditions. Some studies have argued for a return to the original "low" values of $k \sim 20-40$ W m^{-1} K^{-1} [43, 40], while others have supported the new "high" values of $k > 70$ W m^{-1} K^{-1} [52, 71, 72, 41]. The differences arise from myriad technical challenges and uncertainties in extrapolating some results to Earth's core conditions. Using a consistent extrapolation, Davies and Greenwood [19] found the range $k = 70 - 110$ W m^{-1} K^{-1} predicted from a number of recent k determinations. Pozzo et al. [60] found generally good agreement when directly comparing calculated and experimentally determined k and used this to infer $k \sim 80$ W m^{-1} K^{-1} at core conditions. While the debate surrounding Earth's core conductivity is certainly not over, there is presently substantial support for the 'high" values of $k \geq 70$ W m^{-1} K^{-1} and we will assume the lower limit in the rest of this paper. The geophysical consequences of these high conductivity values turns out to be profound.

Arguably the most fundamental requirement for the theory of geomagnetism is to explain the longevity of the field generation process. The viability of dynamo action depends critically on k. This is because the two main power sinks for the dynamo are viscous heating, which is probably minute in the core where magnetic forces are strong [6, 62], and the heat lost by thermal conduction, which is not available to drive convection and hence field generation. Within the classic model, maintaining the same power availability to the dynamo with the high k estimates requires an increase in core cooling [18, 50, 46]. The implications of this are illustrated in Figure 2, which shows results for varying k from classic core evolution models based on the energy balance $Q_{\mathrm{cmb}} = Q_{\mathrm{s}} + Q_{\mathrm{c}} + Q_{\mathrm{L}}$ (compare red, green and blue tracks). These models are integrated backwards in time from the present-day state of the core and Q_{cmb} is prescribed such that the dynamo power is zero prior to ICN [see 18, for details], which produces a conservative (low) cooling rate and inner core age. Increasing k decreases the inner core age and hence increases the early core temperature because the core must cool faster without the inner core in order to maintain the dynamo. With high k the early core was much hotter than estimates of the solidus of notional lower mantle assemblages [30, 4], indicating pervasive melting in the early lower mantle.

The results in Figure 2 demonstrate the importance of k for models of core evolution. However, in reality Q_{cmb} is set by mantle convection and cannot be imposed in order to ensure long-term maintenance of the geodynamo. Indeed, several studies have argued that the classic model predicts insufficient power available to maintain the ancient dynamo [54, 27], in obvious conflict with paleomagnetic observations. This scenario has been called the "New Core Paradox" [53]. The term paradox is used because the mineral physics results find an increase in both k and σ; the latter should be helpful for dynamo action by reducing the effect of magnetic diffusion. The implication is therefore that the hindering effect of increasing k can outweigh the benefit of increasing σ [28].

In the remainder of this paper we discuss four proposals to resolve the "New Core Paradox" (Section 2). We focus on results from coupled core-mantle evolution models since these provide a physics-based (though simplified) description of Q_{cmb}. Successful models of core evolution must satisfy two primary constraints: 1) predict positive power available to the dynamo for at least the last 3.5 Gyrs; 2) match the present day inner core boundary (ICB) radius of 1221 km. Linking these results to observations is more challenging, so we defer this topic to Section 3. Conclusions are presented in Section 4.

2. Proposed Resolutions to the "New Core Paradox"

In order to keep the presentation concise we will not review the methods used to investigate the long-term coupled evolution of the core and mantle—the interested reader may refer to [50] and [42] for detailed treatments. Briefly, we consider parameterised models of the core and mantle energy balance, which are coupled through the core temperature and CMB heat flow. The energy

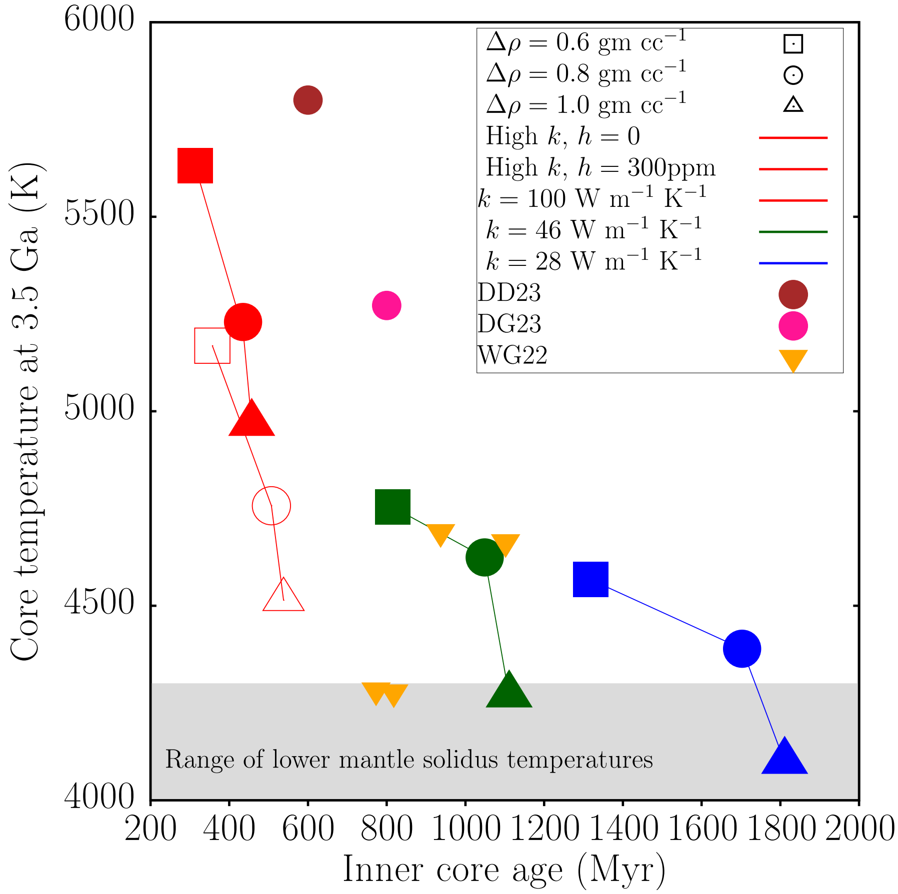

Figure 2: Predictions of the inner core nucleation age and ancient core temperature from different scenarios for core evolution. Symbols linked by lines use the same model setup and set Q_{cmb} in order to obtain a marginal dynamo ($E_{\mathrm{J}} = 0$) prior to inner core nucleation [20]. These runs show the effect of increasing k; the inner core density jump $\Delta\rho$ sets the core composition and gives an indication of the uncertainty in the calculation. Other symbols demonstrate results from the scenarios in Table 1: "Radiogenic', open symbols using 300 ppm ^{40}K; "Hot core", Driscoll and Davies (DD23, [27]); "BMO", Davies and Greenwood (DG23, [19]); "Precipitation", Wilson et al. (W22, [69]). The range of lower mantle solidus temperatures from [30] and [4] are highlighted by the shaded region.

balances provide the core and mantle cooling rates, which determine the thermal history, while an entropy balance takes the core cooling rate and outputs the entropy $E_{\rm J}$ that is available for dynamo action. The core is assumed to by hydrostatic, adiabatic and chemically well-mixed, while the heat flows from the core and the convecting mantle are parameterised using boundary layer theory. The constraint of continuous dynamo generation requires $E_{\rm J} > 0$ for the past 3.5 Gyrs, while the ICB radius $r_{\rm i}$ evolves over time as determined by the intersection of the core temperature T with the melting temperature $T_{\rm m}$ of the iron alloy. Details of the specific model implementation that will be considered are given in [26, 18] and [27].

Classic coupled core-mantle evolution models tend to produce a steeper temporal decrease in $Q_{\rm cmb}$ compared to the heat flows used to obtain the red/green/blue results in Figure 2, which drastically reduces the space of solutions that can match the constraints on $E_{\rm J}$ and $r_{\rm i}$ [27]. With a nominal set of reference parameters (defined in [27]) the CMB heat flow declines rapidly and $E_{\rm J}$ falls below zero (indicating loss of dynamo action) before the core has cooled to the melting point. The dynamo thus fails prior to inner core formation before returning (in the sense of $E_{\rm J} > 0$) from ICN until the present day. Therefore, while this model matches the present ICB radius, the failure of the dynamo clearly contradicts paleomagnetic evidence. However, the obvious solution, i.e. to increase $Q_{\rm cmb}$ prior to ICN, results in an enhanced cooling rate, which causes the inner core to form early and grow too large by the present day, contradicting seismic observations. The challenge is to satisfy the delicate balance imposed by the two constraints in the high k limit.

Name	Requirements	Reservations
Radiogenic	$\gtrsim 250$ ppm ^{40}K in core	^{40}K partitions weakly into metal
Hot core	$T_c^{\rm init} \sim 6000$ K & $T_{\rm m} \sim 5200$ K	Required $T_{\rm m}$ on low end of current range
Precipitation	MgO/SiO_2 become super-saturated early in core's history	Uncertainties on bulk core & mantle composition & equilibrium behaviour
BMO	$k \lesssim 70$ W m^{-1} K^{-1} & weak FeO partitioning	Physics of BMO evolution

Table 1: Summary of proposed scenarios to overcome the "New Core Paradox". See text for details.

We will consider 4 potential solutions to the challenge outlined above, which are summarised in Table 1. The first augments the classic model by invoking the incorporation of radiogenic elements such as ^{40}K into the core [51, 26]. The additional heating $Q_{\rm r}$ provided by radioactive decay (Figure 1) is not particularly efficient as an entropy source for the dynamo; its utility arises from slowing the core cooling rate for a given $Q_{\rm cmb}$ (see Figure 2). Driscoll and Bercovici [26] found that 2 TW or more of present-day heat from ^{40}K could satisfy the constraints on $E_{\rm J}$ and $r_{\rm i}$. Their model predicts an IC age of $\sim$500 Ma and a hot early core with a CMB temperature $T_{\rm c}^{\rm init} \sim 5800$ K. However, the key problem is that both experimental and computational studies of chemical partitioning show that radiogenic elements partition strongly into the silicate mantle during the differentiation of the core [17, 9, 70]. The present-day heat released from the predicted core concentrations of radioactive species is much less than 1 TW [9], and therefore cannot provide the power required by evolution models.

The second potential solution to the "New Core Paradox" relies on tuning parameters in the classic core-mantle evolution model. Driscoll and Davies [27] found their models could match the $E_{\rm J}$ and $r_{\rm i}$ constraints with a hot initial CMB temperature of $T_{\rm c}^{\rm init} \sim 6000$ K and a value of $T_{\rm m} \sim 5200$ K at the present ICB radius. These values allow the rapid cooling that is required to maintain the dynamo prior to ICN, while also allowing the inner core to form late enough that it grows to its correct present-day size. The solution with $k = 70$ W m^{-1} K^{-1} predicts an inner core age of $\sim$600 Myrs and a very hot early state that implies pervasive melting of Earth's deep interior. The problem with this scenario is that it is not robust to changes in input parameters. The melting point of iron at ICB conditions is predicted by several experimental and computational studies to be $T_{\mathrm{m,Fe}} \sim 6350 \pm 150$ K [see 3, 5]. The melting point depression is largest for impurities like O [2] that partition almost entirely into the liquid on freezing; however, even then it is hard to reduce $T_{\mathrm{m,Fe}}$ by more than 1000 K, leaving a lower value of $T_{\mathrm{m}} \sim 5300$ K at the ICB [20], which is not compatible with the required value of $T_{\mathrm{m}} \sim 5200$ K. However, some studies predict a lower $T_{\mathrm{m,Fe}}$ of $\sim$5500 K [63], which lowers T_{m} to 4800 K. Therefore, while this proposed scenario is not favoured in terms of the generally accepted values for T_{m}, it is not ruled out and will hopefully receive further scrutiny.

The third potential solution to the "New Core Paradox involves the precipitation of light elements at the top of the core. The idea is that certain elements incorporated into the core during its formation could become super-saturated during cooling and separate from the liquid, perhaps as a new stable oxide phase. If this precipitation happens at the CMB, as is expected for both MgO [10] and SiO_2 [39, 69], then the removal of light material will leave behind a dense Fe-rich liquid that inevitably sinks via Rayleigh-Taylor instability, presumably mixing the core [55]. Precipitation offers a potentially abundant power source for the dynamo; its thermodynamic efficiency is comparable to Q_{c} and it can begin early in Earths history. Adding precipitation to core thermal evolution models lowers the cooling rate, which increases the predicted inner core age and lowers ancient core temperatures [55, 19, 69]. Precipitation models that satisfy the constraints on E_{J} and r_{i} predict ICN around $\sim$1 Ga and early core temperatures comparable to or higher than current estimates of the lower mantle solidus (Figure 2).

The onset time and rate of precipitation depend on the bulk composition of the core and mantle and the equilibrium concentrations at the CMB. Equilibrium is set by the partitioning behaviour of elements between metal and silicate, which depends on P, T, and the composition on both sides of the CMB. The state of play has been recently reviewed by Davies and Greenwood [19] and we do not attempt to reproduce the technical details here. To briefly summarise, it is important to first point out that major progress is being made, with large high $P - T$ experimental partitioning datasets showing consistent behaviour for MgO [8] and SiO_2 [69] and good agreement with calculations conducted at CMB conditions [21, 59, 69]. It is also clear that partitioning depends relatively weakly on P [10, 8] and strongly on T and composition [29, 69]. The problem with this scenario is that so many uncertainties affect the results, including the core and mantle compositions, determination of partition coefficients at high $P - T$, and the assumed reactions used to model the partitioning data. The net result for both MgO and SiO_2 is that, within these uncertainties, it is possible that precipitation: began straight after core formation; has not yet begun; provided abundant power to sustain the magnetic field; provided only a minor contribution to the dynamo power [19]. Nevertheless, the premise for this scenario is highly promising and constraints on the precipitation onset time and rate will inevitably improve in the coming years.

The final potential solution to the "New Core Paradox involves a basal magma ocean (BMO) and chemical interactions between the core and mantle [19]. The idea is to follow the spirit of the classic model and retain the minimum number of physical processes (thus ignoring radiogenic heating and precipitation) while maintaining consistency with the basic predictions of high k thermal evolution models. These models find early core temperatures that far exceed current estimates of the lower mantle solidus [20], implying the existence of a BMO above the core. A revised version of the BMO model of Labrosse et al. [45] is used and coupled self-consistently to a classic parameterisation of solid state mantle convection [26]. It is also well established that chemical interactions at the CMB lead to the transfer of O into the core, where it forms a stably stratified layer [31, 16, 22]. This chemical transfer is strongly enhanced in the presence of a BMO compared to the solid mantle [23]. In terms of the basic physics, release of latent and radiogenic heat in the BMO act to insulate the core and slow its cooling while FeO loss increases the BMO cooling such that it completely freezes by 2.5 Ga, after which more rapid core cooling due to solid mantle convection is able to maintain the dynamo until the inner core forms at around 800 Ma.

The coupled core-BMO-mantle model of [19] with $k = 70$ W m^{-1} K^{-1} satisfies the constraints on E_J and r_i and additionally matches the estimated present potential temperature and convective heat flow of the solid mantle. The model predicts a present-day stable layer below the CMB of $\sim$ 100 km thickness, which is slightly thinner than some inferences from seismology [37] but of comparable strength. The problem with this scenario is again that it is not robust to changing some parameter values. While an exhaustive parameter search has not yet been conducted, the model fails for $k > 70$ W m^{-1} K^{-1}, in the absence of a BMO, and with strong FeO partitioning (partition coefficient above 1). However, the parameters selected are still well within the range from recent published literature.

3. Observational Constraints on Core Evolution

A key discriminator between the 4 potential resolutions to the 'New Core Paradox" discussed above should come in the form of observational evidence (Table 1). The radiogenic and hot core scenarios do not appear to produce unique products that could be searched for in the present Earth. For the radiogenic heating scenario, the evidence must come from partitioning experiments and calculations and here the message is currently rather clear: little ^{40}K enters the core during formation. For the hot core scenario, the evidence is from the melting point, which is still not well known for iron alloys, though this situation will undoubtedly improve in the coming years. For the precipitation scenario, the obvious "smoking gun" would be the detection of precipitation products in the present Earth. However, this appears to be challenging because the precipitates are probably lighter than mantle material and will buoyantly rise and mix into the mantle [36]. Even if precipitates do stay at the CMB they will likely form a thin layer that will be hard to detect seismically [though see 61] and should have little expression in gravity or geomagnetic fields. The unique test of the BMO scenario would come from definitive links between the magma ocean and either the present prominent lower mantle structures such as Large Low Velocity Provinces (LLVPs) or the stable layer at the top of the core. However, at present, there are still many competing hypotheses for the origin of LLVPs [32] and the cores stable layer [47, 19], if indeed it exists [1, 33].

One line of observational enquiry that has received significant recent attention is the paleomagnetic signature of inner core formation. Numerical geodynamo simulations and theory suggest that the dipole field strength should increase sharply (geologically speaking) at ICN [7, 24] and this feature can be investigated using large compilations of paleointensity data. Some studies [11, 73] have argued that the most prominent rise in paleointensity occurred around 1.1 Ga, which is too old to be consistent with high k predictions from the radiogenic or hot core scenarios, but can be fit with precipitation models and classic core evolution models using old low conductivity values. Alternatively, other studies have argued that a large intensity rise occurs around 0.5 Ga [13, 74], which is compatible with the high k radiogenic and hot core scenarios. Such a young inner core might also work with the BMO and precipitation scenarios though this has not been investigated.

There are significant challenges associated with obtaining reliably recorded paleointensities that are suitable constraints for the relatively long time-scale (millions of years) variations in field strength that are of interest. Nevertheless it is interesting to consider the consequences of rapid increases in field strength both at $\sim$1.1 Ga and $\sim$0.5 Ga. In the radiogenic and hot core scenarios, only ICN can produce such a large and rapid increase [see 24] and so the definitive determination of two sharp intensity rises would seem to rule out these possibilities. In the precipitation scenario, modelling suggests that a sharp rise in field strength will occur whenever a new species begins to precipitate [49]. Given that MgO, SiO_2, and even FeO have been suggested as precipitates there are plenty of options for producing multiple intensity rises. Moreover, owing to the uncertainties on bulk and equilibrium compositions discussed above, it is currently possible to 'tune' a precipitation model to produce rapid rises whenever they are suggested by data. The BMO scenario produces two peaks: one at the end of BMO freezing and another at ICN. This scenario has not been investigated in detail and the only solutions [19] do not produce rises at the times inferred from paleomagnetism. Whether this is possible can be determined by future work.

Finally, it is worth mentioning that all approaches addressed so far begin by establishing a physical model of coupled core-mantle evolution and comparing its results to observations. An alternative approach is to parameterise the CMB heat flow itself and establish the models that produce field intensity variations in best agreement with paleomagnetism. A recent attempt on these lines [24] found $Q_{\mathrm{cmb}} = 11 - 16$ TW at present day, increasing to $Q_{\mathrm{cmb}} = 17 - 22$ TW at 4 Ga. This increase with age is much lower than predicted by many (though not all [44]) parameterisations of mantle convection. This favours scenarios that reduce the core cooling rate, and here the leading candidate is precipitation.

4. Conclusions

Here I have tried to succinctly review the basis for the "New Core Paradox", the challenges it presents, and the potential solutions. Each scenario comes with its own benefits and drawbacks (summarised in Table 1), which will hopefully help eventually discriminate between the different possibilities. In tandem, refined estimates of the transport properties of iron alloys at high pressure and temperature will help to determine the extent of the problems posed by high conductivity. Ultimately, any model of Earth's thermal history must be validated by observations. The utility of a given model will be determined not just by its consistency with available data, but the unique features that allow it to be observationally distinguished from other models.

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