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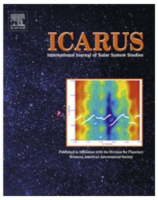

Explaining Mercury's density through magnetic erosion

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ABSTRACT

In protoplanetary disks, dust grains rich in metallic iron can attract each other magnetically. If they are magnetized to values near saturation, the magnetically induced collision speeds are high enough to knock off the non-magnetized, loosely bound silicates. This process enriches the surviving portions of the dust grains in metallic iron, which further enhances the magnetically mediated collisions. The magnetic enhancement to the collisional cross-section between the iron rich dust results in rapid grain growth leading to planetesimal formation. While this process of knocking off silicates, which we term "magnetic erosion", occurs only in a very limited portion of a protoplanetary disk, it is a possible explanation for Mercury's disproportionately large iron core.

1. Introduction

It has long been known that Mercury is anomalously dense compared to the other rocky planets in our Solar System (Ash et al., 1967; Howard et al., 1974; Anderson et al., 1987). Mercury must contain on the order of 70% iron by mass for models of its interior to match its density (Lyttleton, 1969; Harder and Schubert, 2001), more than double the ~30% iron by mass of the Earth and Venus (Morgan and Anders, 1980). Unsurprisingly, several models have been put forth to explain this oddity, covering all the stages of planet formation, from the very condensation of the pre-Mercury solids (Lewis, 1972; Ebel and Alexander, 2011) to the stripping of silicates from an initially more Earth-like young Mercury. Such stripping could be due to the evaporation of Mercury's silicate surface in a hot solar nebula (Cameron, 1985) or, perhaps more crudely, it could be the consequence of a giant impact (Benz et al., 1988; Stewart et al., 2013).

The *MESSENGER* mission's recent measurements of Mercury's K/Th ratio has ruled out many models for Mercury's iron content however, so in this paper we introduce a new model that acts during the very first stages of planet formation, when tiny dust grains collide and stick. By considering the implications of metallic iron's electrical conductivity and, crucially, its ferromagnetism, we find that ambient magnetic fields induce magnetic dipole moments in dust grains rich in metallic iron which lead to those dust grains colliding preferentially and violently. The violence of the collisions can knock silicates off the metallic iron rich grains in a process we name "magnetic erosion", and if so, any planetesimal formed from the surviving grains will be enriched in iron. The ambient magnetic field requirement combines with iron's Curie temperature to strongly limit the orbital positions where magnetic erosion can act. This is appropriate: of the rocky planets, only Mercury is so iron rich.

2. Existing models for Mercury

2.1. Conventional models

The *MESSENGER GRS* instrument found terrestrial K/Th ratios on the surface of Mercury (Peplowski et al., 2011). Thorium has a 50% condensation temperature ~1660 K, significantly higher than the ~1000 K and ~1350 K of potassium and silicon respectively (Lodders, 2003). Any model for Mercury's abundances that relies on condensation or evaporation of silicates would predict a very low K/Th ratio because the potassium is more volatile than silicon: evaporating silicon means also evaporating potassium. Thus, the *MESSENGER* measurements contradict volatility based models for Mercury's high iron/silicate mass ratio.

This rules out most of the conventional models excepting perhaps the giant impact model. As discussed in Stewart et al. (2013), even though a giant impact would remove a significant amount of the proto-Mercury's surface material, that (volatile depleted) material need not have been reaccreted onto Mercury. Note that the volatile depleted material that became the Moon did not reaccrete onto the Earth. In such a scenario, if the depleted material was not reaccreted, then Mercury's K/Th ratio would not have been affected. One should however consider that the scenario requires about a full Mercury's mass worth of depleted material.

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That posited material is clearly not present today; and it is not obvious how to remove that much mass if it, like Earth's Moon, remained gravitationally bound.

2.2. Photophoresis

While the giant impact model remains a promising candidate for explaining Mercury's iron content, it is also possible that the iron enrichment occurred far earlier in Mercury's formation history, when tiny dust grains were first assembled into larger boulders and planetesimals. A recently introduced model that acts during that early formation stage relies on a key difference between iron metal and silicates: iron conducts heat far more rapidly. This causes photophoresis to treat the two differently (Wurm et al., 2013). Photophoresis relies on the creation and maintenance of a temperature gradient through dust grains and that work suggests that the higher thermal conductivity of iron metal erased any temperature gradient in metallic iron rich grains in the solar nebula. While photophoresis transported silicate grains outwards, the metallic iron rich grains stayed behind, forming Mercury.

However, photophoresis relies on dust grains not rotating rapidly, which would smooth out the dust's internal temperature gradient (but see van Eymeren and Wurm, 2012). Further, photophoresis could only process dust in optically thin regions of the solar nebula which saw sunlight (Wurm et al., 2013). The high opacity of gas–dust mixtures places strong limits on where photophoresis can act: for example photophoresis can operate near the dust sublimation radius because the opacity of the dust free gas interior to that position is low; and it can operate in the surface layers of a disk where the column densities to the star are low. Surface layers however are thin and contain only a small fraction of the vertically integrated solid material, while the sublimation radius is at a specific location (albeit one which should vary with time).

Photophoretic sorting is a tentative but exciting proposal for explaining Mercury's iron content that does not contradict the *MESSENGER* observations. It also suggests we should also consider other differences between iron rich and iron poor grains beyond their thermal conductivity, linking the outcome of planet formation back to the first stages of dust growth. In this paper, we consider the electrical conductivity and ferromagnetism of iron rich dust.

3. Overview

3.1. Dust dynamics

The first stage of planet formation (in the core accretion scenario) is collisional coagulation of small dust grains (Blum and Wurm, 2008). During this stage, dust grains collide and stick, growing from sub-micron initial sizes to decimeter sizes or larger. Once they grow that large, collective processes such as the streaming instability (Johansen et al., 2007) can establish themselves, leading to a rapid concentration of the dust and subsequent gravitational collapse of the dust concentrations.

The collisional growth phase is generally taken to have two subphases: very small (up to several tens of microns across) dust grains collide due to Brownian motion, while larger dust grains cease to couple perfectly to the disk turbulence, and so collide with each-other because of that turbulence (Voelk et al., 1980). The turbulence induced dust–dust collisions are much faster than those due to Brownian motion, and the turbulence induced dust–dust collision speed increases as dust grains grow in size: larger dust grains can partially slip through larger scale, faster moving turbulent structures. We will refer to dust grains small enough that they collide primarily due to Brownian motion as "microphysical", while "macrophysical" dust grains collide due to turbulence.

Protoplanetary disks are generally assumed to be turbulent, because whatever drives the accretion flow is either turbulence itself, or will also drive turbulence. In the standard α formalism (Shakura and Sunyaev, 1973), the turbulent viscosity is parameterized as $\nu_t = \alpha c_s H$ where H is the local gas scale height. At 0.387 AU from the proto-Sun, assuming a minimum mass solar nebula (MMSN, Hayashi et al., 1985) and $\alpha = 10^{-4}$, this implies that the smallest, dissipation scale turbulence had time and velocity scales of $t_\eta \simeq 73$ s and $v_\eta \simeq 27$ cm/s respectively.

Dust grains moving through gas feel a drag force, so that

$$\frac{\partial \boldsymbol{v}}{\partial t} = -\frac{\boldsymbol{v} - \boldsymbol{u}}{\tau}, \tag{1}$$

where $\boldsymbol{v}$ and $\boldsymbol{u}$ are the dust and gas velocities respectively and τ is a friction timescale that lengthens as the dust gets larger and more massive. While the effect of turbulence on collisions between very small grains (i.e. grains with frictional stopping times τ shorter than the smallest turbulent timescale t_η) is as yet unclear (Pan and Padoan, 2013), dust grains of radius $a \sim 0.06$ cm and density $\rho = 3$ g/cm^3 have a frictional stopping time $\tau \sim t_\eta$. This means that they are macroscopic in our terms, and will collide with much smaller grains with a turbulently induced collisional speed similar to that of the smallest scale turbulence, $v_\eta \sim 27$ cm/s, and with each other at significantly lower, but still macroscopic, speeds (Hubbard, 2012, 2013). We will therefore use $a = 0.06$ cm as an order-of-magnitude lower bound on the size of the larger participant in a turbulently induced dust–dust collision.

3.2. Disk parameters

The currently preferred driver for observed accretion flows through protoplanetary disks is the Magneto-Rotational Instability (MRI, Velikhov, 1959; Balbus and Hawley, 1991), which requires a minimum ionization fraction on the order of 10^{-13} to 10^{-12} (Gammie, 1996). While protoplanetary disks are mostly neutral, they are nevertheless weakly ionized and can, in at least part of their volume, support the MRI. This ionization fraction can be met and surpassed in the inner disk at fractions of an AU where the temperature is above $T = 1000$ K (thermal ionization of alkali metals), in the surface layers of the disk (UV and Xray photo-ionization) and in the outer disk, beyond 10–30 AU (cosmic ray ionization). The ionization also plays a role in dust collisions as will be discussed in Section 4.

Where the MRI is active, it naturally amplifies magnetic fields to plasma-β values near 10, depending on the height above the midplane (Flock et al., 2011). That β value means that the magnetic fields have an energy density one tenth of the gas' thermal energy density. Extrapolating from a MMSN surface density profile, and assuming a background temperature of 1000 K, $\beta = 10$ implies a magnetic field[1] of $B = 33$ G for a surface density of 7000 g/cm^{-2}, appropriate at Mercury's orbit. This is more than 10^{-3} times the saturation field for iron (Weast, 1975) at room temperature, which is itself more than the saturation field for iron at 1000 K. The relative permeability of iron at that temperature range is several thousand (Weast, 1975), so by multiplying those values together, we see that the ambient field is adequate to magnetically saturate iron. This will become important in Section 5, but means that iron grains are expected to interact magnetically even when the grains have many magnetic domains.

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[1] Accretion disks have too few solids for their magnetization to play a dynamical role on disk scales, so the B and H fields are interchangeable. The B field is standard but we are considering magnetized solids so the ambient field is more correctly reported as $H = 33$ Oe.