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Review

Meteorite paleomagnetism - From magnetic domains to planetary fields and core dynamos

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Resumen

Los meteoritos condríticos representan los registros más tempranos de la evolución del Sistema Solar, proveyendo información sobre las condiciones, procesos y cronología de la formación de los primeros materiales sólidos, planetesimales y cuerpos diferenciados. La evidencia sobre los campos magnéticos en las etapas tempranas de evolución del sistema solar se ha obtenido a partir de estudios en meteoritos condríticos. Estos meteoritos se caracterizan por la abundancia de cóndrulos, que constituyen pequeñas esferas de silicatos de tamaño milimétrico, formadas a partir del polvo en la nebulosa y que fueron calentadas y enfriadas rápidamente. Los condrulos retienen un registro de magnetización remanente, que data del tiempo de calentamiento y enfriamiento durante la formación de cóndrulos y su acreción en planetesimales. Los estudios sobre las diferentes clases de meteoritos, incluyendo a los meteoritos condríticos ordinarios y los meteoritos condriticos carbonáceos han documentado resultados contrastantes con una rango amplio de magnitudes de los campos magnéticos en el disco protoplanetario. Ello ha dificultado definir la naturaleza de los campos magnéticos en las etapas iniciales de evolución. Los desarrollos recientes en instrumentación y técnicas de análisis de magnetismo de rocas y paleointensidades permiten una mayor precisión. Los análisis de micromagnetismo, geoquímica, petrografía y microscopía electrónica proveen de una alta resolución, previamente no disponible, para caracterizar las propiedades magnéticas e interacciones a escalas de dominio magnético. En este trabajo revisamos los estudios en cóndrulos del meteorito condrítico Allende, que revelan relaciones entre los parámetros magnéticos de histéresis y propiedades físicas. Los parámetros y cocientes de coercitividad, magnetización remanente y magnetización de saturación muestran correlaciones con la densidad y tamaño de los cóndrulos, los cuales están relacionados a la estructura interna, mineralogía, composición y morfología. Los cóndrulos compuestos, fragmentados y con anillos de recubrimiento se caracterizan por propiedades de histéresis magnética distintas, asociadas a la composición y arreglos mineralógicos y microestructuras. Los registros de magnetización remanente y las estimaciones de paleointensidades derivadas en estudios del Allende y otras condrítas carbonáceas apoyan adquisición de la magnetización bajo la influencia de campos magnéticos internos dentro de planetesimales. Los resultados apoyan una rápida diferenciación, siguiendo la formación de las inclusiones de calcio y aluminio y condrulos para formar los planetesimales. Los planetesimales se caracterizarían por una estructura diferenciada con núcleos metálicos con capacidad de dinamo autosustentable por periodos de varios millones de años. El meteorito condrítico Allende se formó y derivó de un planetesimal parcialmente diferenciado, con un núcleo de hierro capaz de sostener un campo magnético interno.

Palabras clave: Paleomagnetismo, meteoritos, campos magnéticos, dínamos, Sistema Solar.

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Abstract

Meteorites represent the earliest records of the evolution of the solar system, providing information on the conditions, processes and chronology for formation of first solids, planetesimals and differentiated bodies. Evidence on the nature of magnetic fields in the early solar system has been derived from chondritic meteorites. Chondrules, which are millimeter sized silicate spherules formed by rapid melting and cooling, have been shown to retain remanent magnetization records dating from the time of chondrule formation and accretion of planetesimals. Studies on different meteorite classes, including ordinary and carbonaceous chondrites, have however provided contrasting results with wide ranges for protoplanetary disk magnetic fields. Developments on instrumentation and techniques for rock magnetic and paleointensity analyses are allowing increased precision. Micromagnetic and an array of geochemical, petrographic and electronic microscopy analyses provide unprecedented resolution, characterizing rock magnetic properties at magnetic domain scales. We review studies on chondrules from the Allende meteorite that reveal relationships among hysteresis parameters and physical properties. Coercivity, remanent and saturation remanence parameters correlate with chondrule size and density; in turn related to internal chondrule structure, mineralogy and morphology. Compound, fragmented and rimmed chondrules show distinct hysteresis properties, related to mineral composition and microstructures. The remanent magnetization record and paleointensity estimates derived from the Allende and other chondrites support remanent acquisition under influence of internal magnetic fields within parent planetesimals. Results support that rapid differentiation following formation of calcium-aluminum inclusions and chondrules gave rise to differentiated planetesimals with iron cores, capable of generating and sustaining dynamo action for million year periods. The Allende chondrite may have derived from a partly differentiated planetesimal which sustained an internal magnetic field.

Key words: Paleomagnetism, meteorites, magnetic fields, dynamos, Solar System.

Introduction

Studies of meteorites provide the earliest records concerning the conditions and evolution of the planetary system (Wood, 1988; Cameron, 1988; Lauretta and McSween, 2006). Meteorites constitute the oldest rocks preserved from the initial stages of planetary accretion. Information on the age of the solar system, conditions and chronology for formation of first solids, planetesimals and early differentiated bodies is based on studies of chondrites and other primitive meteorites (Wood, 1988; Hewins *et al*., 1996; Scott, 2007; Connelly *et al*., 2012). Chondrites are composed by millimeter sized silicate spherules named chondrules and calcium-aluminum rich inclusions (CAIs) embedded in a fine grained silicate matrix. In recent years research on the origin and evolution of the solar system has expanded, with developments from planetary missions, astronomical observations, discovery of exoplanets and theoretical and numerical simulation models. The multi-and interdisciplinary approaches and new data are providing fresh insights on the origin of planetary systems. Major questions on fundamental aspects still remain open, including conditions and chronology in the early phases.

Many studies on meteorites focused on the petrography and geochemistry, which permitted to distinguish and characterize distinct classes of meteorites. Meteorites are divided into primitive and differentiated classes, which include ordinary and carbonaceous chondrites and achondrites and iron meteorites, respectively (Weisberg *et al*., 2006). Chondrules represent molted droplets of aggregated fine silicate dust, recording transient heating events in the solar nebula (Hewins, 1997; Zanda, 2004; Scott, 2007). They show different textures and mineral assemblages, with some containing fragments of other chondrules and rare CAIs. Preservation of chondrules indicates that chondrites were not melted through their subsequent history after formation. In contrast, differentiated meteorites, which include iron and iron-silicate meteorites, were subject to various degrees of melting and metamorphism, and interpreted as derived from planetesimals later fragmented by collisions.

Understanding the early stages of planetary system evolution has remained a complex difficult task. Considerable effort is spent in characterizing the distinct classes of meteorites, which are investigated with a wide range of analytical techniques. Studies have documented new minerals and unraveled evidence on the formation and alteration histories of meteorites and parent planetesimals with increasing detail (Taylor *et al*., 1987; Nyquist *et al*., 2009; Weiss and Elkins-Tanton, 2013). The conditions and nature of processes involved in the formation of the proto-Sun, chondrules, CAIs, and early accreted planetesimals remain poorly constrained.