have electric dipole moments. But Purcell and Ramsey[11] realized at the time that such arguments were based on untested assumptions, and declared: "The question of the possible existence of an electric dipole moment of a nucleus or of an elementary particle in view of the above becomes a purely experimental matter."

Today, typical theories predict electric dipole moments for many fundamental particles, including the electron, but the predictions span a wide range of values. Therefore, despite the complete reversal of opinion on the theoretical front, the essence of Purcell and Ramsey's claim endures. Establishing the existence of an electric dipole moment of a fundamental particle is an exclusively experimental endeavour. Hudson *et al.*[1] are the latest to attempt such a feat. Experiments of this genre reach far beyond the realm of atomic, molecular and optical physics: they can be viewed as low-energy windows on the high-energy soul of the cosmos. ■

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PLANETARY SCIENCE

Building a planet in record time

It seems that Mars had grown to near its present size by 2 million to 4 million years after the Solar System began to form. Such rapid growth explains why the planet is much smaller than Earth and Venus. SEE LETTER P.489

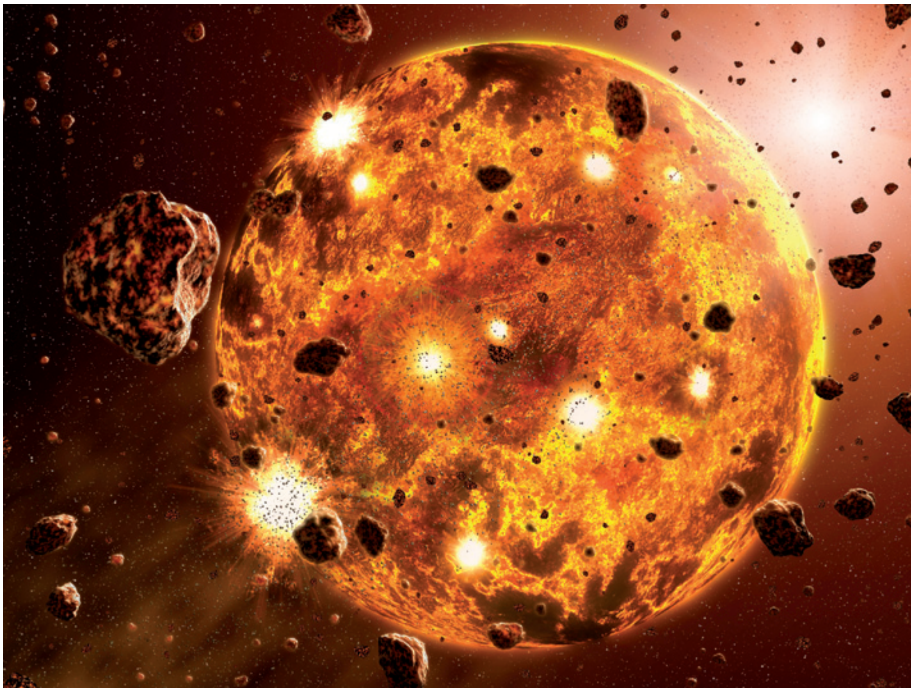
ALAN BRANDON

How long did the rocky planets Mercury, Venus, Earth and Mars take to form? Answering this question will tell us why our planets look the way they do today. Previous estimates[1,2] place the formation of Mars at up to 15 million years from the time the Solar System began to form. On page 489 of this issue, Dauphas and Pourmand[3] derive even tighter constraints on the planet's formation age by determining Mars's abundance ratio of hafnium to tungsten (Hf/W) and then re-evaluating the age obtained using a chronometer based on the decay of ^{182}Hf to ^{182}W.

The amount of ^{182}W in meteorites from Mars can be used to place constraints on its age of formation. The isotope ^{182}Hf decays to ^{182}W with a half-life of 9 million years, and can date events that occurred in the first 60 million years or so of Solar System history, before most ^{182}Hf decayed away. During their early history, rocky planets differentiate into iron-rich metal cores and silicate-rich mantles. Tungsten is siderophile (it likes to bond with iron) and so partitions into the iron-rich cores. Hafnium remains in silicate and oxide minerals (it is lithophile) in the newly formed mantles. Hence, the age of core formation of a planet is recorded in the tungsten isotopic compositions of planetary materials. Core formation is thought to occur at or near the time that planets reach their final mass.

The tungsten isotope compositions of Martian meteorites have been accurately determined. But calculating the age of Mars's core formation also depends on knowing its bulk silicate Hf/W ratio. These meteorites are igneous rocks that were produced by the melting of rock deep within Mars, and that subsequently migrated and cooled near or at its surface. This migration probably resulted in fractionation of Hf and W in the magmas relative to their sources. To better determine the Hf/W ratio of bulk silicate Mars, Dauphas and Pourmand[3] used the fact that the ratio of thorium to tungsten (Th/W) in Martian meteorites is constant, and recognized that the Th/Hf ratio of Mars should not differ from the average bulk Solar System value because of the similar chemical behaviours of Th and Hf in Mars during igneous processing.

Armed with this information, the authors[3] accurately determined the Th/Hf ratio of stony meteorites (chondrites), which represent the average bulk Solar System ratio, and used this as a proxy for the Th/Hf ratio of Mars, from which they calculated its bulk silicate Hf/W ratio. By combining their calculated bulk silicate Mars Hf/W ratio with the W isotopic compositions of Martian meteorites, the authors were able to determine an age of core formation for the planet — a maximum of around 2 million to 4 million years after the Solar System began to form. This rapid formation time explains why Mars is



TAKE 27/SPL

Figure 1 | Planetary accretion. This illustration shows small rocky bodies accreting to a larger body, a protoplanet. Such accretion is thought to be the way in which protoplanets grow to become planets.

much smaller than Earth and Venus, which took tens of millions of years to form[1].

Mars has about 11% of the mass of Earth. It has a diameter of 6,800 kilometres and fits within the size distribution of rocky bodies called oligarchs[4]. Oligarchs were formed during a period of runaway growth that occurred by the accretion of up to hundreds of kilometre-sized objects known as planetesimals, and then proceeded to collide with each other to form the planets we have today[1] (Fig. 1). The authors' finding[3] that rocky bodies the size of Mars accreted within 2 million to 4 million years has ramifications for models of early planetary history.

First, oligarchs largely formed during the time when the short-lived aluminium radionuclide ^{26}Al was active (the first 2.5 million years). Aluminium concentrations in rocky bodies are typically a few per cent, and ^{26}Al can provide heat from decay. Thus, this nuclide could have provided enough heat to melt the interiors of oligarchs such that these bodies had already differentiated into core, mantle and crust before they collided with each other to form large planets. This could explain why the samarium (Sm) and neodymium (Nd) isotopic compositions of rocks from Earth and Mars indicate that these planets do not have bulk Solar System values[5–8]. During the final growth stage of planets, the collisions between Mars- to Moon-sized oligarchs were very energetic and resulted in the preferential loss of their outer shells. If these shells were made of crust formed by melting of the oligarchs' mantles during earlier differentiation, they probably contained lithophilic elements such as Sm and Nd that were not present at average Solar System proportions in the planets[9]. Hence, this formation time for oligarchs[3] predicts that the material that makes the planets would have been depleted in the elements that made the crusts — a prediction that fits the Sm–Nd isotopic compositions observed.

Second, bodies smaller than Mars, such as the Moon, should have formed at the same stage of planetary accretion as Mars, or even earlier. However, recent findings using W isotopes show that the Moon formed much later than this — as much as 60 million to 100 million years after the Solar System began to form[10]. This later time of formation strongly supports the hypothesis that the Moon formed by accretion of molten and vaporized ejecta that were produced by a collision between proto-Earth and a Mars-sized impactor very late in the formation history of the Solar System.

Third, questions remain about the accretion times of the Solar System's planets. The W isotope age calculation assumes that W and Hf were in complete or nearly complete equilibrium between silicates and iron metal during core formation in Mars as it accreted from planetesimals. If much less equilibration had occurred, then the age calculated from the W isotopes represents the prehistory of the materials that make up Mars, rather than Mars formation itself. If this is the case, the true accretion age of Mars could be more recent, and beyond the time of ^{26}Al decay as a heat source for differentiation. If so, it may well be that not all oligarchs were differentiated when they collided to grow into larger planets such as Earth. This hypothesis has its own set of compositional consequences for planetary evolution.

With such an early time for Mars accretion, which probably led to the formation of a global magma ocean[3], how do we explain the times for magma-ocean solidification of around 100 million years after the Solar System began to form that are obtained from measurements[7,8,11,12] of Lu (lutetium)–Hf and Sm–Nd chronometers in Martian meteorites? Magma oceans are not supposed to take that long to solidify[13]. This suggests that, although Dauphas and Pourmand[3] have provided us with a key constraint on the early formation and evolution of our planets, we still have much to learn. ■

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PROTEIN–PROTEIN INTERACTIONS

Pull-down for single molecules

An innovative marriage of techniques, combining the principles of common protein pull-down assays with single-molecule fluorescence microscopy, opens up new ways of visualizing cellular protein complexes. SEE ARTICLE P.484

PHILIP TINNEFELD

Single-molecule detection has become an essential part of such technologies as DNA sequencing and certain realizations of super-resolution fluorescence microscopy. On page 484 of this issue, Jain *et al.*[1] now present a short cut to studying protein–protein interactions at the single-molecule level.

Most biological processes are governed by assemblies of dynamically interacting proteins. Identifying all the physiological permutations of protein–protein interactions is a crucial step in unravelling the complex molecular relationships that are characteristic of living systems. Historically, protein–protein interactions have been studied using a technique called co-immunoprecipitation[2,3]. In this approach, a protein of interest (the bait) is captured from cell lysate using an appropriate antibody or a protein tag. When the bait protein is isolated, proteins that interact with it (the prey) are simultaneously captured. The captured complexes are purified and subsequently analysed using western blotting or mass spectrometry.

Jain *et al.*[1] make a short cut by immobilizing the protein complexes from a comparatively small number of lysed cells directly on a coverslip, which is then studied under the single-molecule fluorescence microscope (Fig. 1). After a washing step, the microscopic analysis can be carried out without the further laborious separation steps necessary for western blotting or mass spectrometry. Co-immobilized proteins in the complexes (the prey) are visualized using a fluorescent fusion protein or by immunofluorescence detection. Prey proteins are quantified simply by counting the number of fluorescent spots, each representing an individual protein complex, in the fluorescence images.

This scheme can thus save several hours of sample preparation. In regard to the actual measurements, the short time between cell lysis, pull-down and readout minimizes the uncertainties about whether *in vivo* interactions are maintained. As a result of the high sensitivity of the method, the amounts of proteins needed are greatly reduced. Potentially, the method might even be applied to single cells, thereby avoiding