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Invited review

K–Ar ages of meteorites: Clues to parent-body thermal histories

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A R T I C L E I N F O

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Whereas most radiometric chronometers give formation ages of individual meteorites >4.5 Ga ago, the K–Ar chronometer rarely gives times of meteorite formation. Instead, K–Ar ages obtained by the ^{39}Ar–^{40}Ar technique span the entire age of the solar system and typically measure the diverse thermal histories of meteorites or their parent objects, as produced by internal parent body metamorphism or impact heating. This paper briefly explains the Ar–Ar dating technique. It then reviews Ar–Ar ages of several different types of meteorites, representing at least 16 different parent bodies, and discusses the likely thermal histories these ages represent. Ar–Ar ages of ordinary (H, L, and LL) chondrites, R chondrites, and enstatite meteorites yield cooling times following internal parent body metamorphism extending over ~200 Ma after parent body formation, consistent with parent bodies of ~100 km diameter. For a suite of H-chondrites, Ar–Ar and U–Pb ages anti-correlate with the degree of metamorphism, consistent with increasing metamorphic temperatures and longer cooling times at greater depths within the parent body. In contrast, acapulcoites–lodranites, although metamorphosed to higher temperatures than chondrites, give Ar–Ar ages which cluster tightly at ~4.51 Ga. Ar–Ar ages of silicate from IAB iron meteorites give a continual distribution across ~4.53–4.32 Ga, whereas silicate from IIE iron meteorites give Ar–Ar ages of either ~4.5 Ga or ~3.7 Ga. Both of these parent bodies suffered early, intense collisional heating and mixing. Comparison of Ar–Ar and I–Xe ages for silicate from three other iron meteorites also suggests very early collisional heating and mixing. Most mesosiderites show Ar–Ar ages of ~3.9 Ga, and their significantly sloped age spectra and Ar diffusion properties, as well as Ni diffusion profiles in metal, indicate very deep burial after collisional mixing and cooling at a very slow rate of ~0.2 °C/Ma. Ar–Ar ages of a large number of brecciated eucrites range over ~3.4–4.1 Ga, similar to ages of many lunar highland rocks. These ages on both bodies were reset by large impact heating events, possibly initiated by movements of the giant planets. Many impact-heated chondrites show impact-reset Ar–Ar ages of either >3.5 Ga or <1.0 Ga, and generally only chondrites show these younger ages. The younger ages may represent orbital evolution times in the asteroid belt prior to ejection into Earth-crossing orbits. Among martian meteorites, Ar–Ar ages of nakhlites are similar to ages obtained from other radiometric chronometers, but apparent Ar–Ar ages of younger shergottites are almost always older than igneous crystallization ages, because of the presence of excess (parentless) ^{40}Ar. This excess ^{40}Ar derives from shock-implanted martian atmosphere or from radiogenic ^{40}Ar inherited from the melt. Differences between meteorite ages obtained from other chronometers (e.g., I–Xe and U–Pb) and the oldest measured Ar–Ar ages are consistent with previous suggestions that the ^{40}K decay parameters in common use are incorrect and that the K–Ar age of a 4500 Ma meteorite should be possibly increased, but by no more than ~20 Ma.

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1. Introduction

Most ages of meteorites measured by various radiometric chronometers correspond to times of condensation of solid material in the early solar nebula, the formation time of the meteorite parent body, or formation of the meteorite itself, for example, by igneous processes. Chronometer systems used in such measurements include those based on long-lived parent nuclides (e.g., U–Th–Pb, Sm–Nd, and Rb–Sr) and short-lived, extinct nuclides (e.g., ^{53}Mn–^{53}Cr, ^{26}Al–^{26}Mg, ^{107}Pd–^{107}Ag, ^{182}Hf–^{182}W, ^{146}Sm–^{142}Nd, and ^{129}I–^{129}Xe). These chronologic data indicate that early condensates in our solar system formed ~4.565 Ga ago (1 Ga = 10^9 years), and that most meteorite parent bodies formed a few million years afterward, or about 4.56 Ga ago. Reviews of such meteorite ages are given in Carlson and Lugmair (2000), Gilmour (2000), Krot et al. (2009), Wadhwa et al. (2009), Nyquist et al. (2009a), and Kleine et al. (2009).

In contrast to most other isotopic chronometers, few K–Ar ages of meteorites represent their formation times as solid objects or formation times of the parent bodies. This situation exists because the K–Ar chronometer is easily reset by moderate heating and because most meteorites have experienced thermal events, produced either by internal metamorphism or impacts on the parent body. These thermal events span essentially the entire history of the solar system. The ease with which the thermal environment resets K–Ar ages permits this chronometer to be quite useful for determining the times of meteorite heating. In some cases, the K–Ar data obtained give additional information about these thermal events, such as heating temperature and post-heating cooling rate. These latter data derive from detailed characteristics of Ar diffusion in meteorite samples, and are acquired during the process of measuring the K–Ar age.

So that the reader can better understand interpretations of K–Ar ages and other information derived from the Ar diffusion data, I first present some basics about measuring K–Ar ages and Ar diffusion. Following that, I summarize K–Ar ages for several classes of meteorites and review what these apparently tell us about the thermal histories of their parent bodies. In a paper with such a broad topic, it is not possible to reference all sources of data and discussion. Rather, I emphasize those papers that both present new data and review previously published age data or interpretations. Although sufficient data will be presented so as to establish obvious trends for a given meteorite class, some data on meteorites without a clear connection to a meteorite group will not be utilized. The major purpose of this paper is to summarize what K–Ar ages imply about thermal histories of some specific meteorite groups, and not to produce an exhaustive data complication. Hopefully, the many references given will serve to introduce the interested reader to the broader literature. Much of the data utilized were obtained in the author's laboratory at the NASA Johnson Space Center (JSC) in Houston, TX.

2. ^{39}Ar–^{40}Ar method

For the past few decades, K–Ar ages of meteorites have not been determined by the older method of independent measurements of K and ^{40}Ar, but rather by utilizing the superior ^{39}Ar–^{40}Ar technique (*cf.* McDougall and Harrison, 1999, and references therein). The ^{39}Ar–^{40}Ar method (hereafter called Ar–Ar) involves fast neutron irradiation of the sample to convert a portion of the stable isotope ^{39}K to ^{39}Ar (half-life 269 years), which is then located in the same K lattice sites as is ^{40}Ar resulting from the natural decay of ^{40}K over time. The irradiated sample is heated at increasing stepwise temperatures in a high vacuum furnace, using an internal resistance coil, induction heating or a laser. Infrared (e.g., CO_2) lasers are often used, or more rarely, a laser emitting at higher frequency, e.g., a UV laser. The ^{40}Ar/^{39}Ar ratio in the argon released in each step is measured on a mass spectrometer designed for this purpose. Because the ^{39}Ar serves as a proxy for ^{39}K, the measured ^{40}Ar/^{39}Ar ratio is a measure of the K–Ar age of the sample, without requiring a separate, absolute measurement of K abundance. With increasing extraction temperature, the Ar released may derive from different K-bearing phases and from different lattice sites, such as grain surfaces or grain interiors. An Ar–Ar age spectrum (Fig. 1) plots

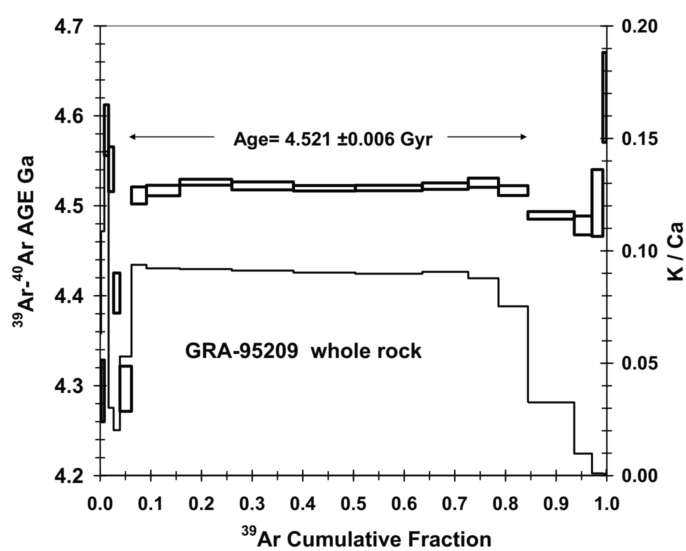

Fig. 1. Example of an Ar–Ar age spectrum, which plots age in Ga (rectangles, showing uncertainties) and the K/Ca ratio (stepped line) vs. the cumulative release of ^{39}Ar during stepwise temperature extractions of the GRA-95209 lodranite meteorite. Low temperature release of Ar shows effects of terrestrial weathering (loss of radiogenic ^{40}Ar and gain of atmospheric ^{40}Ar) and high temperature release shows effects of ^{39}Ar recoil in the reactor. An age of 4.521 ± 0.006 Ga is defined by the major K-bearing phase having a constant K/Ca ratio and releasing 6–84% of the total ^{39}Ar. Figure reproduced from McCoy et al. (2006).