



Invited Review

Planetary and pre-solar noble gases in meteorites

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ABSTRACT

Noble gases are not rare in the Universe, but they are rare in rocks. As a consequence, it has been possible to identify in detailed analyses a variety of components whose existence is barely visible in other elements: radiogenic and cosmogenic gases produced *in situ*, as well as a variety of “trapped” components – both of solar (solar wind) origin and the “planetary” noble gases. The latter are most abundant in the most primitive chondritic meteorites and are distinct in elemental and isotopic abundance patterns from planetary noble gases *sensu strictu*, e.g., those in the atmospheres of Earth and Mars, having in common only the strong relative depletion of light relative to heavy elements when compared to the solar abundance pattern. In themselves, the “planetary” noble gases in meteorites constitute again a complex mixture of components including such hosted by pre-solar stardust grains.

The pre-solar components bear witness of the processes of nucleosynthesis in stars. In particular, krypton and xenon isotopes in pre-solar silicon carbide and graphite grains keep a record of physical conditions of the slow-neutron capture process (s-process) in asymptotic giant branch (AGB) stars. The more abundant Kr and Xe in the nanodiamonds, on the other hand, show a more enigmatic pattern, which, however, may be related to variants of the other two processes of heavy element nucleosynthesis, the rapid neutron capture process (r-process) and the p-process producing the proton-rich isotopes.

“Q-type” noble gases of probably “local” origin dominate the inventory of the heavy noble gases (Ar, Kr, Xe). They are hosted by “phase Q”, a still ill-characterized carbonaceous phase that is concentrated in the acid-insoluble residue left after digestion of the main meteorite minerals in HF and HCl acids. While negligible in planetary-gas-rich primitive meteorites, the fraction carried by “solubles” becomes more important in chondrites of higher petrologic type. While apparently isotopically similar to Q gas, the elemental abundances are somewhat less fractionated relative to the solar pattern, and they deserve further study. Similar “planetary” gases occur in high abundance in the ureilite achondrites, while small amounts of Q-type noble gases may be present in some other achondrites. A “subsolar” component, possibly a mixture of Q and solar noble gases, is found in enstatite chondrites. While no definite mechanism has been identified for the introduction of the planetary noble gases into their meteoritic host phases, there are strong indications that ion implantation has played a major role.

The planetary noble gases are concentrated in the meteorite matrix. Ca-Al-rich inclusions (CAIs) are largely planetary-gas-free, however, some trapped gases have been found in chondrules. Micrometeorites (MMs) and interplanetary dust particles (IDPs) often contain abundant solar wind He and Ne, but they are challenging objects for the analysis of the heavier noble gases that are characteristic for the planetary component. The few existing data for Xe point to a Q-like isotopic composition. Isotopically Q-Kr and Q-Xe show a mass dependent fractionation relative to solar wind, with small radiogenic/nuclear additions. They may be closer to “bulk solar” Kr and Xe than Kr and Xe in the solar wind, but for a firm conclusion it is necessary to gain a better understanding of mass fractionation during solar wind acceleration.

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1. Introduction

Noble gases are not rare in the Universe, e.g., helium is the second most abundant element in the Solar System (Lodders et al., 2009). They are rare, however, in solids, since – being noble – they hardly take any part in chemical interactions, are among the most incompatible elements and generally prefer the gas phase. As an example, a typical abundance in even the most primitive carbonaceous chondrites for Xe of (in the units commonly used in noble gas geo- and cosmochemistry) 2×10^{-8} cm³ STP/g (Marti, 1967; Mazor et al., 1970) corresponds to no more than about 0.1 ppb by weight (1 cm³ STP/g = 1 cc/g = 2.668×10^{19} atoms per g).

In spite or (more likely) just because of that, fundamental insights in the field of cosmochemistry have come from the study of the abundances and isotopic compositions of noble gases. Being so low in abundance, their isotopic compositions are easily influenced by “foreign” or “exotic” additions. More often than not these show up even in the analysis of bulk materials, in particular in stepwise heating analyses that tend to partially separate gases carried by different minerals according to their thermal stability. A case in point is the discovery of presolar grains in primitive meteorites: isotope abundance anomalies in noble gases were known long before the discovery of presolar grains per se, such as nanodiamonds, silicon carbide and graphite, and it was the search for the carrier phases of these anomalies that ultimately led to the identification and isolation of these types of grains (e.g., Anders and Zinner, 1993; Ott, 1993). Note, in this context, that recent work (Stroud et al., 2011) has shown that nanodiamond separates contain also

abundant glassy carbon (see Section 3.2.3); for simplicity in the following I will use the term “nanodiamonds” or just “diamonds” to describe real samples containing both.

Usually noble gases in meteorites occur as a number of discrete “components”, where a component is defined by having a certain isotopic/elemental composition or a certain origin, but need not be restricted to a certain mineral (“carrier phase”). This includes components that are of *in situ* origin, which means those produced from radioactive decay (e.g. ⁴He, ⁴⁰Ar), and also those produced by nuclear spallation reactions induced by cosmic rays. *In situ* components are often dominant in meteorites of higher petrologic type, which tend to have low abundances of the “trapped” (also called “primordial”) noble gases. While cosmogenic contributions have traditionally played a significant role in the study of noble gases and can be used to determine cosmic ray exposure (CRE) ages, they have generally been negligible in the study of the isotopic systems of “solid” elements. This is changing now due to the increased precision with which these elements can be analyzed nowadays. An important example is the Hf-W decay system used to study core formation of early planetesimals in the early Solar System via extinct ¹⁸²Hf, where it is essential to take into account the cosmic ray induced effects (e.g., Kruijer et al., 2013; and references therein).

Coming to the trapped noble gases, starting with the work of John Reynolds at Berkeley, much of the work has centered on xenon, so much that an own term “xenology” was coined to describe this field of noble gas cosmochemistry (Reynolds, 1963). The first of the so-called “gas-rich meteorites” were discovered by Gerling and Levskii (1956), in the same year that Reynolds (1956) published

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