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Accretion and Early History of Planetesimals and Planets: The Noble Gas Record

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Abstract Some of the distinct noble gas "components" in meteorites represent a record of processes during and even before solar system formation. This record is difficult to interpret. Often, one of the major problems is to recognize whether a certain noble gas elemental and isotopic pattern has been established in a presolar epoch, later in the solar accretion disk, during meteorite parent body formation or finally as a result of metamorphism on a parent body. It would also appear that noble gases are a preferred tool to deduce the types of matter from which the Earth and other planets accreted—if the respective parent materials are present in our extraterrestrial sample collections at all. However, also this issue is unsettled. Noble gas isotopes originating from the decay of radioactive precursors allow us to study the early and later degassing history of terrestrial planets, although the interpretation often remains model-dependent. This contribution briefly reviews some of the fundamental aspects of the noble gas record in meteorites and planets.

Keywords Noble gases · Solar system formation · Planet formation · Planet degassing

1 "Exotic" Noble Gases in Presolar Grains

Small amounts of dust condensing in the outflows of stars found their way into meteorite parent bodies (Meyer and Zinner 2006; Ott 2007). These presolar dust grains (nanodiamonds, silicon carbide, graphite and others) contain a surprisingly large part of the noble gas inventory of primitive meteorites (Ott 2002). Some of these noble gas components have an "exotic" isotopic composition, widely different from that of the sun. The search for their host phases actually led to the discovery and first isolation of surviving circumstellar dust in meteorites. Xenon enriched in both the lightest and the heaviest isotopes by

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about a factor of two relative to solar Xe was discovered by Reynolds and Turner (1964), and it soon became clear that this composition could not have formed in the solar system. In 1987 the host phase of the anomalous Xe—representing several percent of the total Xe inventory in primitive meteorites—was identified as tiny presolar diamond grains of about a nanometer in size (Lewis et al. 1987). The Xe in the diamonds is likely of supernova origin, the light and heavy isotope excesses being due to p- and r-process nucleosynthesis, respectively (Ott 2002), but it remains unclear whether all nanodiamonds in primitive meteorites (up to several hundred ppm) are indeed presolar. Much larger grains of up to several μm were discovered later, the most important types being silicon carbide and graphite. They contain noble gases from, e. g., s-process nucleosynthesis, sometimes detectable even in single grains (Heck et al. 2007). Apart from exotic noble gases, almost every other element analysed in presolar grains is isotopically extremely anomalous (Meyer and Zinner 2006). Whereas differences in isotopic compositions in normal matter are usually on the order of permil or less, presolar grain data are often displayed on a logarithmic scale. The $^{18}O/^{16}O$ ratio in presolar oxide grains varies, for example, between a few times 10^{-5} and a few times 10^{-2} (Meyer and Zinner 2006). This is the best and unequivocal evidence that the grains indeed are intact condensates from other stars. The laboratory studies of presolar grains—sometimes called astrophysics in the laboratory—not only allow us to pinpoint stellar sources contributing material to the solar system but also to better understand stellar nucleosynthesis, the evolution of stars, stellar mixing, or galactic chemical evolution (cf. Ott 2007). Noble gases have been guiding us towards the fascinating finding that a small meteorite sample contains matter from many different stars older than the sun.

Noble gases produced by spallation of target atoms by galactic cosmic ray particles have allowed dating the presolar age of presolar grains (Heck et al. 2009). It appears that most grains have considerably shorter interstellar lifetimes than theoretical estimates of about half a billion years.

2 “Normal” Noble Gases in Meteorites

Unlike the “exotic” gases, some noble gas components in meteorites have an isotopic composition sufficiently close to that in the sun that a genetic relationship between meteoritic and solar reservoirs is indicated or at least possible. The most important of these components has been dubbed “Q” (for Quintessence). Its carrier “Phase Q” survives acid attack by HF and HCl but gets destroyed by strong oxidants. It is carbonaceous and almost massless, but has otherwise remained elusive (Wieler et al. 2006). Ne, Kr, and Xe in Q have a mass-fractionated isotopic composition relative to solar composition, favouring the heavy isotopes, and the lighter elements are heavily depleted in Q relative to solar composition. The He/Xe ratio in Q is about seven orders of magnitude lower than in the sun (Busemann et al. 2000).

Although labelled “normal”, it is thus important to note that the noble gases acquired by meteorite parent bodies during their formation isotopically mostly differ from solar composition. This is a remarkable difference to the Earth and Mars, which contain Ne (and presumably He) of solar isotopic composition in their interior (see below). It should also be noted that a sizeable fraction of meteorites do actually contain noble gases of an elemental and isotopic composition close to that of the sun. These meteorites, however, were exposed to the solar wind while being fine dust at the surface of their parent asteroids, similar to the lunar regolith. Although some workers believe that the solar wind gases in most meteorites were trapped in the early solar system, they are generally not regarded as being "primordial". Hence, while the solar-gas-rich meteorites record processes on early or later asteroidal surface layers and are also important to determine to composition of the noble gases in the sun (as the lunar regolith and samples from the Genesis space mission), they are not regarded to reflect the solar system formation history. A few meteorites appear to contain primordial noble gases of solar-like composition though (e. g. Busemann et al. 2006; Ivanova et al. 2008), but the implications of this finding for noble gas inventories of planets are not yet clear.

While noble gases carried by phase Q are different from solar composition, it is nevertheless commonly assumed that they were derived from a parent reservoir of solar or solar-like composition by one of more processes preferentially depleting light elements and isotopes (e. g. Wieler et al. 2006). Unfortunately, we are far from a good understanding of these processes and where they happened, which hampers the usefulness of meteoritic noble gases to elucidate early solar system processes. One problem is the insufficient characterisation of the carrier. What is clear is that Q-like gases of more or less uniform composition were widespread in the early solar system, since they are found in many different meteorite types originating from different parent bodies. This favours a global process rather than one acting on a parent body, such as hydrodynamic escape upon blow-off of transient early atmospheres (Pepin 1991). Various workers prefer an origin of Q gases in the sun's parent molecular cloud, e. g. by trapping of (solar-like) noble gases in icy mantles around presolar grains (Huss and Alexander 1987), perhaps involving UV radiation (Sandford et al. 1998) or by active capture on growing surfaces (Hohenberg et al. 2002). Pepin (2003) studied fractionation due to hydrodynamic escape during the dissipation of the solar accretion disk. This process could reproduce to some extent the elemental but not the isotopic pattern of meteoritic Q gases. Other proposed mechanisms are not without problems either (Wieler et al. 2006), implying that the potential of the primordial noble gas record in meteorites to reveal accretionary processes in the early solar system has not been fully exploited yet.

3 Records of an Early Energetic Particle Irradiation in Meteorites?

Noble gases produced by interactions with high-energy particles in particular phases in meteorites ("cosmogenic" noble gases) may yield information about energetic particle fluxes in the early solar system or exposure durations of the respective phases to energetic particles prior to the compaction of the meteorite. Above we mentioned the example of presolar exposure ages of circumstellar SiC grains. Unequivocal precompaction effects in primitive meteorites have been reported by Caffee et al. (1987) and Woolum and Hohenberg (1993). Olivine grains which once had been exposed to heavy (iron group) energetic solar particles (as revealed by lattice defects, "solar flare tracks") contained much higher ^{21}Ne concentrations than the track-free grains. The authors suggested this to be evidence for a very high energetic particle flux emitted by the early sun. Very active young stars during their T-tauri stage are indeed common (Feigelson and Montmerle 1999). However, the correlation between solar flare tracks and excess ^{21}Ne could also be the result of mixing of material irradiated by both solar and galactic energetic particles in an asteroidal regolith with unirradiated material (Wieler et al. 2000). Only olivine crystals in the fine grained "matrix" of meteorites but not those in larger inclusions contain solar flare tracks (Metzler 2004), which would not be expected if the olivines had once been exposed in free space. Some chondrules (mm-sized spheroids in primitive meteorites) in two meteorites also acquired cosmogenic noble gases prior to compaction, but also these excesses are plausibly explained by an irradiation in an asteroidal regolith (Roth et al. 2008). Although no unequivocal evidence for an exposure of chondrules to an early energetic particle flux as individual objects has yet been found, the search for such effects should continue.

4 Noble Gases in Planets as Tracers of Their Accretionary History

An impressive data base is available on noble gases in the terrestrial atmosphere, crust and mantle (Ozima and Podosek 2002; Porcelli et al. 2002). In contrast, the data on the other terrestrial and the giant planets is very limited (Wieler 2002; Swindle 2002; Taylor et al. 2004), and mostly restricted to the respective atmospheres (except for Mars, where meteorites convey some information on the interior noble gases). Yet, these limited data may allow inferences on processes and timing of planetary accretion, early and late degassing of planets, as well as atmosphere formation and modification.

4.1 Giant Planets

The helium abundance in Jupiter's atmosphere has been precisely determined by the Galileo probe, and much less accurate values are also available from Voyager data for the three other giant planets. The first order observation is that the He/H ratio in the atmospheres all giant planets is close to the value in the sun. Hence, with an atmospheric mass fraction of ~20–30%, He is not at all a "rare gas" in giant planets, very much unlike in the terrestrial planets. The giant planets thus have primary atmospheres, accreted from the solar nebula and not produced by later degassing. The Jupiter data are precise enough to confirm earlier suspicions that He in the outer atmosphere is somewhat depleted relative to the protosolar abundance (von Zahn et al. 1998; Taylor et al. 2004), indicating a downward migration of He droplets, which form because He and H become immiscible at high pressures. A similar He migration presumably ocurred in Saturn but probably not in Uranus and Neptune (Taylor et al. 2004).

The Galileo probe also revealed distinctly non-solar elemental abundances of the four heaver noble gases relative to hydrogen. Ne is depleted by an order of magnitude, presumably because it is preferentially incorporated into segregating He droplets (Niemann et al. 1998). Ar, Kr, and Xe are all enriched by about a factor of 2.5 relative to solar composition, and similar enrichment factors are observed for other volatile elements: carbon, sulphur, and probably nitrogen (Atreya et al. 2003; Taylor et al. 2004). Owen et al. (1999) proposed that this uniform enrichment indicates that all these elements—and presumably others—were brought to the planet in very cold (<30 K) icy planetesimals. This is different from other models which postulate that heavy elements in giant planets were mainly delivered by much warmer planetesimals, condensed just beyond the "snowline" in the solar nebula. It has also been proposed, however, that trapping of Ar, Kr, and Xe in icy planetesimals may have largely been inhibited because the heavy noble gases may have formed complexes with H_3^+ ions and thus remained in the gas phase, a process that might explain the scarcity of noble gases in Titan's atmosphere (Mousis et al. 2008).

The ^{3}He/^{4}He ratio in Jupiter of 1.66×10^{-4} (Taylor et al. 2004) is widely accepted as the best value for the isotopic composition of protosolar He. The reported ^{20}Ne/^{22}Ne ratio of 13 is close to the solar wind value (though with a large uncertainty), which further supports the idea that the noble gases in the giant planets reflect solar nebula composition.

Similarly, data from the Genesis mission (Marty et al. 2010) confirm that the nitrogen isotopic composition in Jupiter and the solar wind are similar.

4.2 Terrestrial planets

Noble gas concentrations in the atmosphere of Venus (expressed per g planet) are about an order of magnitude higher than in the terrestrial atmosphere, which in turn has about two orders of magnitude higher concentrations than the martian atmosphere. All three atmospheres show strongly fractionated elemental abundances of Ne–Xe relative to solar abundances (He is not retained in the atmospheres of terrestrial planets). Essentially, lighter gases are progressively depleted, with Ne/Xe in the terrestrial atmosphere being almost four orders of magnitude lower than in the sun (e. g. Pepin 1991). However, despite the highly variable gas concentrations, the Ne:Ar:Kr:Xe ratios are strikingly similar in all three atmospheres. Moreover, they are also similar to noble gas abundances in primitive bulk meteorites.

A seemingly obvious conclusion from these facts is that the noble gases in the terrestrial planets have been acquired by accreting material similar to—or with similar noble gas abundances as—known present day meteorite classes. In fact, such "gas-poor" noble gas acquisition scenarios have once been popular (see reviews by Donahue and Pollack 1983; Pepin and Porcelli 2002). These models explained the different gas concentrations in the various planets by mechanisms such as a less efficient incorporation of noble gases into accreting matter further from the sun due to decreasing nebular pressures with increasing heliocentric distance. However, when isotopic compositions are also considered, the straightforward picture of similar noble gas patterns in Venus, Earth, Mars, and meteorites cannot easily be upheld. Ratios of (nonradiogenic) Ne, Ar, and Xe isotopes in the three atmospheres (where known), mostly differ from each other (Wieler 2002; Swindle 2002), hence an identical source is unlikely. For Earth and Mars, there are also important differences between the isotopic compositions of atmospheric and interior noble gases.

Because "gas-poor" models have intrinsic problems to account for the isotopic variability of planetary noble gas reservoirs, "gas-rich" models have gained popularity. These models assume that the planets initially accreted large noble gas amounts of perhaps solar-like composition. The primordial atmospheres would subsequently have been largely lost, allowing modellers to chose among a wide variety of processes potentially able to fractionate isotopic ratios. Pepin and Porcelli (2002) summarize acquisition and loss scenarios. One popular model postulates that the Earth captured noble gases from dust grains that were irradiated by an early solar wind (similar to dust grains irradiated today on the lunar surface). Another popular model postulates gravitational capture of nebular gases by a protoplanet, followed, e. g., by dissolution into a magma ocean. The most widely studied atmospheric loss process is hydrodynamic escape, where hot hydrogen-rich primary atmospheres escape efficiently enough to drag heavier elements along (e. g. Zahnle et al. 1990; Pepin 2000).

Another important observation also strongly supports scenarios implying a solar-like composition of the primordial planetary noble gases. Some of the noble gases trapped in the interior of Earth and Mars have a solar-like composition—modified by additions of other components (Graham 2002; Swindle 2002). A possibly crucial observation is that the isotopic composition of terrestrial mantle Ne is close to that of isotopically fractionated SW Ne as, e. g., retained in the lunar regolith (Trieloff et al. 2000; Ballentine and Holland 2008) rather than the pure solar Ne as measured, e. g., in targets from the Genesis solar wind mission. This is interpreted as evidence that the Earth trapped its mantle Ne from material irradiated by the solar wind and not from the solar nebula. Note that related inferences about the nature of Earth's parent planetesimals based on comparisons between the noble gas inventories of the Earth's mantle and different meteorite classes, respectively (Trieloff et al. 2002) should be viewed with caution, since meteorites rich in solar noble gases may have acquired them in a regolith on an asteroid much after the Earth had finished accreting.

Summarizing this section, we need to admit that the statement by Pepin (1992) still largely holds today: "Most workers agree that atmospheric mass distributions of the nonradiogenic noble gases were probably established very early, through the action of processes operating before, during or shortly after planetary accretion, but beyond this there is no consensus as yet on the specifics of sources or mechanisms".

5 The Early and Later Degassing of Planets Traced with Radiogenic Noble Gases

Noble gas isotopes produced by radioactive decay are very useful to constrain the extent and in some cases also the timing of noble gas loss—and hence probably also losses of other volatile elements—from a planetary atmosphere or its interior (Porcelli and Ballentine 2002). The most important nuclides are ^{4}He and ^{21}Ne from decay of U and Th (^{21}Ne produced through ^{24}Mg(α,n)^{21}Ne), ^{40}Ar from ^{40}K, ^{129}Xe from ^{129}I and ^{136}Xe from fission of ^{244}Pu (and ^{238}U). The latter two noble gas nuclides are particularly important to constrain the timing of early degassing of the Earth, due to the short half-lives of their parents of ~16 and 80 Ma, respectively.

5.1 Xe closure age of the Earth

Only about 0.8% of the ^{129}Xe ever produced in the Earth or its building blocks is now present in the Earth's atmosphere, and it is hardly possible that most of the rest still resides in the Earth's interior (Porcelli and Ballentine 2002). Wetherill (1975) calculated from this a "closure" age of the Earth for Xe of ~110 Ma after the formation of the first meteorites, assuming complete loss of Xe before 110 Ma and complete retention thereafter. Modern estimates—also considering fission Xe from ^{244}Pu—yield a similar single stage closure age of ~80 Ma (Porcelli and Ballentine 2002). The radiogenic Xe isotopes thus indicate a thorough early degassing of the Earth. It remains unclear, however, whether this degassing can be attributed to a specific event (the moon-forming giant impact and fast core formation have been proposed), or whether the degassing actually was more continuous. Since the formation of the Earth itself lasted some 100 Ma, a large part of the Xe loss might have occurred in the planetesimals already.

A few lunar regolith samples also contain radiogenic and fissiogenic ^{129}Xe and ^{136}Xe, respectively, trapped on grain surfaces and very likely testifying of an early outgassing of the Moon. A formal age of 63 ± 42 Ma after the first meteorites has been calculated from the ratio ^{129}Xe/^{136}Xe (Swindle et al. 1986). These authors suggest that this age might represent the onset of retention of radiogenic Xe in the Moon and thus may provide a lower limit to the age of formation of the Moon, but they also critically discuss the assumptions on which this interpretation is based. Wieler and Heber (2003) also note problems with this straightforward chronological interpretation.

5.2 Later degassing of Earth and Venus

Radiogenic ^{40}Ar in the Earth's atmosphere corresponds to perhaps ~40% or even considerably more of all ^{40}Ar produced throughout Earth's history (Porcelli and Ballentine 2002). Because only a small fraction of this has been produced before retention of radiogenic Xe started, it is clear that the Earth also experienced considerable later degassing. A reconstruction of the temporal evolution of the atmospheric ^{40}Ar/^{36}Ar ratio would yield more quantitative constraints on the degassing history of the Earth. Unfortunately, insufficient data are available so far (Porcelli and Ballentine 2002).

Venus' atmosphere contains about four times less ^{40}Ar than the terrestrial atmosphere, although Venus has about 80% of the Earth's mass and the two planets presumably have a similar K abundance. This suggests that Venus is less well degassed than the Earth (Krasnopolsky et al. 1994). This may well be the result of the lack of—or only sporadic episodes of—plate tectonics.

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