ON NOBLE GAS PROCESSING IN THE SOLAR ACCRETION DISK

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Abstract. Two fractionation models are applied to the problem of generating the widely distributed “Q-component” noble gases in meteorites from the solar-like isotopic and elemental compositions that presumably characterized the early solar accretion disk. Noble gas fractionation by mass-dependent dissipation of the solar nebula, as suggested by Ozima et al. (1998), is examined in the context of a model developed by Johnstone et al. (1998) for accretion disk photoevaporation driven by intense UV radiation from a neighboring giant star. Hydrodynamic escape of heavier species entrained in hydrogen outflow from the UV-heated outer regions of the disk can generate substantial noble gas fractionations, but they do not match the observed Q-component isotopic pattern and moreover require the physically unrealistic assumption that the fractionated gases are confined to the heated disk boundary zone, without mixing with the interior nebula, for long periods of time. It seems more likely that hydrodynamic outflow is actually established below this zone, in the body of the disk. In this case fractionations are governed by Rayleigh distillation of the entire remaining nebula, and are negligible at the time when disk erosion is halted by the gravitational potential of the young sun embedded in the disk.

A “local” model of noble gas fractionation by hydrodynamic blowoff of transient, methane-rich atmospheres outgassed from the interiors of large primitive planetesimals (Pepin, 1991) is updated and assessed against current data. Degassed atmospheres are assumed to contain isotopically solar noble gases except for an additional nucloegenic Xe component that contributes primarily to the two heaviest isotopes; there is evidence that this same component is present at varying levels in other solar-system volatile reservoirs, possibly reflecting a compositional change with time in the solar nebula. Single fixed values for the two free parameters in the blowoff modeling equations can generate fractionated Xe, Kr, Ar and Ne compositions in the residual atmosphere that closely match observed meteoritic isotopic distributions, and Q-gas elemental ratios are approximated by adsorption of fractionated gases on planetesimal surface grains using plausible values of relative Henry Law constants. Additional requirements for adsorption of sufficient absolute amounts of Q-gases on carrier grains, and their subsequent ejection to space, mixing in the nebula, and dispersal into meteorite bodies, are examined in the context of current models for body sizes and dynamical evolution in an early mass-rich asteroid belt (Chambers and Wetherill, 2001). Despite its ability to replicate isotopic compositions, uncertainties about the environments in which the blowoff model can successfully operate suggest that there is, as yet, no entirely satisfactory understanding of how the Q-component noble gases might have evolved from solar-like precursor compositions.

1. Introduction

The astrophysical environments and mechanisms responsible for generating trapped meteoritic noble gas distributions from more primitive compositions are not well understood. These “primordial” gases are dominated by a widely distributed and,
for the most part, an isotopically invariant component called Q-gases. Although they could be associated with a separate and so far unidentified minor carrier phase, current evidence suggests that they occupy adsorption sites on the surfaces of carbonaceous materials. Relative to solar compositions (Figure 1), these Q-gases display isotopically heavier isotope ratios and increasingly severe elemental depletions with decreasing atomic mass (e.g. Wieler, 1994; Busemann et al., 2000; Ott, 2002), strongly suggesting that processes favoring loss of lighter species – for example, Rayleigh fractionation – have played a role in generating them from solar-like parental compositions (Pepin, 1991; Ozima et al., 1998).

A “local” fractionation model based on hydrodynamic blowoff of compositionally solar-like degassed planetesimal atmospheres (Pepin, 1991) can generate isotopic distributions in the residual atmospheres that closely resemble meteoritic isotope ratios for Xe, Kr, Ar and Ne. “Local” models of this kind, however, face the intrinsic difficulty that carrier grains loaded with Q-gases on individual planetesimals must later be ejected, mixed, and widely distributed throughout meteorite-forming regions of the accretion disk. Ozima et al. (1998) propose a quite different scenario – that Q-gas compositions were established by a “global” Rayleigh distillation of an initially solar-composition gaseous nebula, presumably during its separation and loss from condensed solar-system matter. In this view there is no dispersal and mixing problem; ambient Q-gases pervade the dissipating nebula and are adsorbed or otherwise occluded into carbonaceous phases later incorporated into meteorites. But there are difficulties here as well. There is no known astrophysical mechanism that leads naturally to the required Rayleigh fractionation of the entire gas-phase nebula. Moreover the particular fractionation model utilized by Ozima et al. fails to generate the characteristic Q pattern for all noble gas isotopes and elements (Pepin and Porcelli, 2002).