The isotopic signatures of the noble gases found in planetary atmospheres compared to those in the solar wind have been considered diagnostically early and ongoing solar system processes. Model explanations for the evolution of terrestrial planets' atmospheres have been numerous, but largely ignored until recently has been the process of low-energy ion implantation. Although low-energy ion implantation was suggested as a factor influencing the evolution of solar system inventories, [1,2] little work has been carried out regarding the magnitude and relevance of the process, and none was done for Ne or Ar. We confirmed observations by Bernatowicz and Hagee [2] that Kr and Xe implanted in W are isotopically fractionated by 1% to 2% per amu.[3,4] We further demonstrated that argon is fractionated > 3% per amu [3]; here we report large fractionations for Ne and Ar. The identification of suitable conditions for changing isotopic and elemental signatures of noble gases is a first step in a search for natural environments where low-energy implantation may have occurred.

Some recently published work has considered dusty plasma environments where low-energy ions may be available. Horányi et al.,[5] have considered buildup of potentials by large scale charge separations and found that it is limited by the breakdown of the nebular gas. They considered grain potentials of $\Delta \phi = kT_e = 30$eV. In such an environment the bulk of the heat flux will come from ions accelerated toward the grains. In planetary atmospheres lightning discharge does occur when the ambient electric field grows strong enough that a significant fraction of the electrons acquire enough energy in a mean free path [$\lambda_e$] to ionize a molecule or atom. Cascades form for energies $\gg 30$eV/$\lambda_e$, where $\lambda_e$ depends, approximately linearly, on the inverse of the gas pressure. [6]

Pepin [7] has discussed in much detail the expected fractionation and evolution of atmospheres affected by hydrodynamic escape processes. Recent models on Mars' atmospheric evolution have considered ionization processes and Jakosky et al. [8] discuss atmospheric loss processes and isotopic fractionation, caused by solar wind sputtering and photochemical escape. Thermally-driven escape from the upper atmospheres will alter the elemental and isotopic signatures, as well. Owen and Bar-Nun [9] consider atmospheric evolution of the inner planets as having been influenced with delivery of gases by icy planetesimals. Laboratory studies of the trapping of gases in ice have shown this to be a reasonable way to elementally fractionate the noble gases depending upon the temperature that the ice forms. [10] It is less clear, however, whether isotopic fractionation can be achieved.

To study the isotopic fractionation under controlled conditions we built an implanter cell with an approximately cylindrical field configuration and a W wire collector at the center. We report first data on the fractionation of implanted Ne up to 4.6% per amu. The trapping efficiency for Ne is approximately four to six times lower than for Ar onto a W target. Furthermore, the implanted gases resulting from low-energy ion implantation appear to be held more firmly than has been previously considered. Experimental conditions of the implanter have been previously described. [3,4] Briefly, the chamber, grid and shield are at 0 V, the electron filament at -34 V and a set of ion collector's voltages from -40 V to -100 V are used. All implantation times are for two hours. The electron beam is focussed by the shield onto an electron trap, the resulting current is monitored (shield to grid) for the entire implantation time and kept at (500 ±10)µA.

Neon measurements are corrected for Ar$^+$, CO$_2$$^+$ and other interferences. These peaks are resolved using the procedures described by Niedermann et al. [11] The non-linearity of the ion source in our VG-5400 mass spectrometer, although small, is corrected for all measurements. Procedural blanks were run before every experiment and blank corrections were applied for all experiments. We find that degassing the ion collector at 1000 °C for 20 hours did not release all the trapped gas. The current temperature limit of ~1500 °C minimizes the problem, although small amounts of gas are still missing. Komelsoe [12] who measured the trapping efficiencies of noble gases concluded that the W collector needs to go to 2400 °C for rapid degassing. No subsequent implantations were run until blanks verified that the system will not add significant amounts of residual gases from a previous experiment. Since gases retained in the collector may be isotopically heavy, this makes all our reported trapped phase fractionations a lower limit. Although low-energy ion implantation causes at least some portion of the heavier trapped gases to be tightly held, this is not observed for Ne.
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The characteristic and reproducible isotopic fractionation effects on a W collector are shown in Fig. 1. Implantations were carried out in a closed system over two-hour periods using Ne and Ar mixtures (2 x 10⁷ cc STP of Ar and 2 x 10⁸ cc STP of Ne) at a temperature of ~80°C (due to the hot filament.) All implanted gases are fractionated, favoring the heavy isotopes. We note a maximum in the Ar fractionation for the trapped phase with the collector voltage of -50 V, confirming our previously reported systematics.[3] The Ne fractionation is nearly linearly dependent on the collector voltage. In these runs the extent of trapping varies for Ar from 11% at -40 V to 63% at -100 V, and for Ne from 1.7% at -40 V to 15% at -100 V. If the implantation of argon is allowed to proceed until only approximately one-third of the gas remains in the free phase, the resulting free phase of argon is highly fractionated, > 4% per amu. At -40 V collector voltage the trapped phase of Ar is 21% with a fractionation of (+2.97% ± 0.10%) per amu. Yet, for -100 V the free phase of Ar is now 20% and the isotopic fractionation is now (-0.05% ± 0.60%) per amu, favoring the light isotopes. Obviously, there is not exactly a symmetry in this type of implantation, but we have not considered effects due to sputtering, diffusion losses and saturation. At this time we have not tested the trapping characteristics in other collectors, but the work of Filleux et al. [13] shows that the He trapping efficiencies on Pt foils are considerably different from those on low-mass films (BeO, Al₂O₃). This dependence on target projectile mass ratio may effect isotopic discrimination.

We conclude that in a natural environment where low-energy ion implantation processes are possible, isotopic fractionation of noble and by extrapolation of other gases has to be expected. Low-energy ion implantation provides a mechanism for considerable gas loading as Filleux et al. [13] found a range 10⁴ to 10⁵ for collection efficiencies of He at 10-100 eV. The implications of this process in the origin of the planetary atmospheres and meteoritic gases needs to be considered.

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References: