number of times a chondrule is heated must be between 1 and ~3, based on observations of chondrule rims (Rubin and Krot, 1996; Hewins, 1996). The proposal for the origin of shock waves by Desch and Connolly may run aground on this point—if the massive bodies at ~5 AU are present for the lifetime of the nebula, $T \approx 10^6$ years, then shock fronts will have processed material along the entire circumference of the asteroid belt $T/T_{con} \approx 3 \times 10^4$ times, where $T_{con} \approx 30$ years is the time between conjunctions of a body at 5 AU and a body at 2.5 AU. While Desch and Connolly provide useful, state-of-the-art computations of the thermal histories of particles traversing shock fronts, until a convincing source of shock waves is identified, the problem of chondrule formation will remain unsolved at the zeroth order level.

Eugene I. Chiang
Departments of Astronomy/Earth and Planetary Sciences
University of California at Berkeley
Berkeley, California 94720, USA

REFERENCES

BOSS A. P. (1996) A concise guide to chondrule formation models. In *Chondrules and the Protoplanetary Disk* (eds. R. H. Hewins, R. H. Jones and E. R. D. Scott), pp. 257–263. Cambridge Univ. Press, Cambridge, U.K.

CONNOLLY H. C., JR. AND LOVE S. G. (1998) The formation of chondrules: Petrologic tests of the shock wave model. *Science* **280**, 62–67.

HEWINS R. H. (1996) Chondrules and the protoplanetary disk: An overview. In *Chondrules and the Protoplanetary Disk* (eds. R. H. Hewins, R. H. Jones and E. R. D. Scott), pp. 3–9. Cambridge Univ. Press, Cambridge, U.K.

HOOD L. L. AND HORANYI M. (1993) The nebula shock wave model for chondrule formation—One-dimensional calculations. *Icarus* **106**, 179–189.

RUBIN A. E. AND KROT A. N. (1996) Multiple heating of chondrules. In *Chondrules and the Protoplanetary Disk* (eds. R. H. Hewins, R. H. Jones and E. R. D. Scott), pp. 173–180. Cambridge Univ. Press, Cambridge, U.K.

SHU F. H. *ET AL.* (2000) The origin of chondrules and refractory inclusions in chondritic meteorites. *Astrophys. J.* **548**, 1029–1050.

WEIDENSCHILLING S. J. (1977) The distribution of mass in the planetary system and solar nebula. *Astrophys. Space Sci.* **51**, 153–158.

Heavy noble gases in solar system matter

The Sun, which contains 99.8% of solar system matter, is the major reservoir of solar system noble gases. The elemental abundances and their isotopic signatures are currently only approximately known as these properties were indirectly obtained from measurements of implanted solar corpuscular radiations in lunar and asteroidal regoliths. More direct information can be expected from the isotopic abundance determinations of directly collected solar wind noble gases by the GENESIS mission, which is currently in progress. The timing of solar particle implantation has to be inferred from detailed studies of the regolith histories. The primitive chondritic meteorites, which serve as reference materials for solar elemental and isotopic abundances, can not be used for noble gases since the relative elemental abundances are strongly depleted relative to those in the Sun (see Fig. 1), and their isotopic signatures are at variation with solar wind data. How were these gases incorporated into planetary materials?

The largest planets incorporated and retained noble gases in nearly solar proportions in their atmospheres, as verified by spacecraft on Jupiter. The atmospheres of Venus, Earth and Mars, as well as primitive chondritic meteorites show depletion factors of about a million and more for the lighter noble gases (see Fig. 1). In the case of Mars major differences are found between atmospheric signatures and those of the solid planet for both elemental and isotopic abundances (*e.g.*, Bogard *et al.*, 2001). While a solar-type xenon isotopic signature was observed for Xe in the interior of Mars (Mathew and Marti, 2001), this signature has not (or not yet?) been observed for solid Earth. On the other hand, the atmospheric xenon isotopic signatures of both planets were rather similarly fractionated (by ~3.7% per mass unit relative to solar Xe) in favor of the heavy isotopes. The chondritic meteorites in turn show a rather uniform xenon component (OC-Xe) which can not be related to the solar signature by a mass-dependent fractionation mechanism (Lavielle and Marti, 1992). Heavy noble gases in

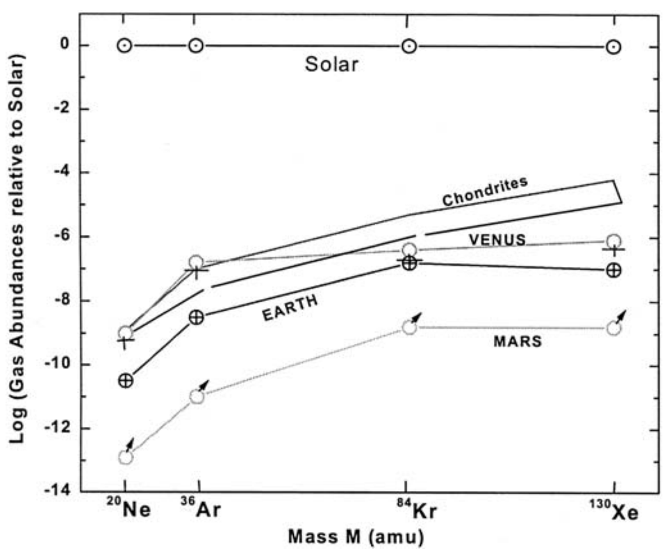

FIG. 1. The (logarithmic) abundances of Ne, Ar, Kr and Xe in the atmospheres of Venus, Earth and Mars are plotted relative to those in the Sun, when normalized to the Si abundances of each object; the abundances in the atmosphere of Jupiter are not shown, but are close to solar. For comparison, the range of abundances (relative to Si) in primitive chondrites (type 3 to CI) is also shown. This figure is adapted from Marti and Mathew (1998), where references can be found.

chondrites are found concentrated in a carbonaceous phase (Q-gas, Wieler *et al.*, 1992). Apparently, xenon may have been modified by a component associated with interstellar diamonds (Lewis *et al.*, 1987).

In this issue of MAPS, Hohenberg, Thonnard and Meshik report data on a new efficient heavy noble gas capture mechanism, which they term "active capture". Active capture refers to a process for the incorporation of heavy noble gases which depends upon anomalous adsorption to retain gases long enough to be captured by deposited surface material. The authors use the term "anomalous adsorption" for a poorly understood process that involves a form of bonding which was observed under conditions of fracture, or involving ionizing radiation. Energy released by adsorption on metal surfaces is usually expected to be dissipated by surface vibrations, but surface reactions with energy transfer by nonadiabatic processes producing excited electronic states are also known. On a silver surface, electronic excitations were found to increase with increasing adsorption energy (Gergen *et al.*, 2001). Hohenberg *et al.* (2002) consider that active capture may help to further our understanding of the origin and incorporation of heavy noble gases in the solar system and suggest that a mechanism of this type may account for the large observed Q-gas enrichment in an ill-defined Q-phase in chondrites.

Mechanisms of noble gas trapping which cause elemental but little isotopic fractionation were identified in the condensation of carbon (Niemeyer and Marti, 1981) and in the adsorption of heavy noble gases (Bernatowicz and Podosek, 1986). Isotopic fractionation was observed in low energy ion implantation (*e.g.*, Bernatowicz and Hagee, 1987; Ponganis *et al.*, 1997) and predicted for hydrodynamic escape (*e.g.*, Pepin, 1992), and for gravitational capture followed by hydrodynamic escape (*e.g.*, Ozima and Zahnle, 1993). Trapping mechanisms need to be considered not only for neutral gases, but also for plasmas. During the T Tauri phase of the proto-Sun the solar nebula presumably was being swept up by intense solar wind and strong flare activities. The penetration of the solar particles, however, was limited to the inner edge of the solar nebula. If the stagnation point between T Tauri wind and the inner edge of the solar nebula progressed outward, it may have reached the condensation zones of asteroidal matter and eventually of icy planetesimals. According to Hohenberg *et al.*, the simultaneous vapor deposition onto the gas-trapping surfaces could have substantially increased the efficiencies. Can the mechanism account for observed isotopic signatures? The authors report that the efficient trapping mechanism is associated with significant isotopic fractionation of both Xe and Kr, favoring the heavy isotopes, but that isotopic fractionation at higher energies is small. The data reported by Hohenberg *et al.* add a relevant step in the study of mechanisms of heavy noble gas incorporation into planetary materials.

Kurt Marti
University of California, San Diego
Department of Chemistry and Biochemistry
La Jolla, California 92093-0317, USA

REFERENCES

BERNATOWICZ T. AND HAGEE B. E. (1987) Isotopic fractionation of Kr and Xe implanted in solids at very low energies. *Geochim. Cosmochim. Acta* **51**, 1599–1611.

BERNATOWICZ T. J. AND PODOSEK F. A. (1986) Adsorption and isotopic fractionation of Xe. *Geochim. Cosmochim. Acta* **50**, 1503–1507.

BOGARD D. D., CLAYTON R. N., MARTI K., OWEN T. AND TURNER G. (2001) Chronology and evolution of Mars. *Space Sci. Rev.* **96**, 425–458.

GERGEN B., NIENHAUS H., WEINBERG W. H. AND MCFARLAND E. W. (2001) Chemically induced excitations at metal surfaces. *Science* **294**, 2521–2523.

HOHENBERG C. M., THONNARD N. AND MESHIK A. (2002) Active capture and anomalous adsorption: New mechanisms for the incorporation of heavy noble gases. *Meteorit. Planet. Sci.* **37**, 257–267.

LAVIELLE B. AND MARTI K. (1992) Trapped xenon in ordinary chondrites. *J. Geophys. Res.* **97**, 20 875–20 881.

LEWIS R. S., TANG M., WACKER J. F., ANDERS E. AND STEEL I. M. (1987) Interstellar diamonds in meteorites. *Nature* **326**, 160–162.

MARTI K. AND MATHEW K. J. (1998) Noble gas components in planetary atmospheres and interiors in relation to solar wind and meteorites. *Proc. Indian Acad. Sci. (Earth Planet. Sci.)* **107**, 425–431.

MATHEW K. J. AND MARTI K. (2001) Early evolution of Martian volatiles: Nitrogen and noble gas components in ALH 84001 and Chassiigny. *J. Geophys. Res.* **106**, 1401–1422.

NIEMEYER S. AND MARTI K. (1981) Noble gas trapping by laboratory carbon condensates. *Proc. Lunar Planet. Sci. Conf.* **12th**, 1177–1188.

OZIMA M. AND ZAHNLE K. (1993) Mantle degassing and atmospheric evolution—Noble gas view. *Geochem. J.* **27**, 185–200.

PEPIN R. O. (1991) On the origin and early evolution of terrestrial planet atmospheres and meteoritic volatiles. *Icarus* **92**, 2–79.

PONGANIS K., GRAF T. AND MARTI K. (1997) Isotopic fractionation in low-energy ion implantation. *J. Geophys. Res.* **102**, 19 335–19 343.

WIELER R., ANDERS E., BAUR H., LEWIS R. S. AND SIGNER P. (1992) Characterization of Q-gases and other noble gas components in the Murchison meteorite. *Geochim. Cosmochim. Acta* **56**, 2907–2921.