REHEATED ORDINARY CHONDRITES: THE RECORD OF SMALL PERIHELIA AND IMPACTS OVER THE LAST MILLION YEARS. P.H. Benoit. Cosmochemistry Group, Dept. Chemistry and Biochemistry, University of Arkansas, Fayetteville, AR 72701 USA. E-mail: COSMO@uafsysb.uark.edu.

"Reheated" meteorites, *i.e.*, meteorites that have experienced some significant degree of heating after metamorphism often within the last 100 million years or so, are fairly common among ordinary chondrites and basaltic meteorites. Heating is inferred to be by impact or by close passage to the Sun. Here I use the ratios of cosmogenic helium and neon and the natural thermoluminescence (TL) of individual meteorites to examine the timing and nature of reheating of ordinary chondrites. The noble gases can reflect reheating at any time over the entire cosmic ray exposure age (typically millions of years), while natural TL reflects reheating events within the last hundred thousand years. Natural TL can reflect thermal events of smaller magnitude than can the noble gases. About 40% of H and L modern falls have been reheated to some extent over their cosmic ray exposure history, but only about 25% of LL chondrites have apparently been reheated. The TL data indicate that, while about 20% of H chondrites have been reheated within the last 10^5 years, only about 12% of L and LL chondrites have experienced recent reheating. Data for Antarctic meteorites suggest that reheated meteorites were less common or even absent >200,000 years ago.

"Reheating" is commonly observed among meteorites. Bogard *et al.* [1] noted that 9 out of 14 ordinary chondrites experienced significant degassing of ^{40}Ar that they attributed to impact processing. Different physical properties are more or less sensitive to thermal events, so that one analytical technique may detect a thermal event which had little or no effect on some other characteristic. Time is also a consideration, since some characteristics have saturation values (and hence reflect thermal resetting only until levels rebuild) whereas others may are essentially permanent (*e.g.*, $^{40}Ar/^{39}Ar$, [1]). In the present study I concentrate on two indicators of reheating for the last few tens of millions of years or for the last few hundred thousand years, cosmogenic noble gases and natural thermoluminescence.

Data. I use the cosmogenic noble gas compilation of Schultz and Kruse [2] and our previously published natural thermoluminescence (TL) data [3], with the addition of some recent unpublished data. Terrestrial age estimates for Antarctic meteorites are taken from Nishiizumi *et al.* and Michlovich *et al.* [4] and natural TL data for Antarctic meteorites are from [5]. I have natural TL and cosmogenic noble gas data for 51 H chondrites, 17 L chondrites, and 17 LL chondrites I have natural TL and terrestrial age estimates for 22 H and 25 L chondrites from Antarctica. Only equilibrated ordinary chondrites are considered here, these showing little variation in TL and noble gas properties [3,6].

Results and Discussion. The release of cosmogenic noble gases is by diffusion, and thus the rate of loss is largely determined by grain size and temperature. Light gases diffuse faster than heavier gases [7]. The $^3He/^{21}Ne$ ratio usually reflects reheating at any time throughout cosmic ray exposure because there are no equilibrium levels of cosmogenic He or Ne. An exception to this generalization is very extensive reheating, such that both He and Ne are entirely lost. Using experimentally determined diffusion parameters [7], I calculate the loss of cosmogenic noble gases from an ordinary chondrite as a function of temperature. In Fig. 1 I assume the heat source is solar heating and I convert temperatures to perihelion using a black body approximation [8]. I assume 10^5 years of heating but similar degrees of loss can be obtained in less time at higher temperatures or by longer periods of heating at lower temperatures.

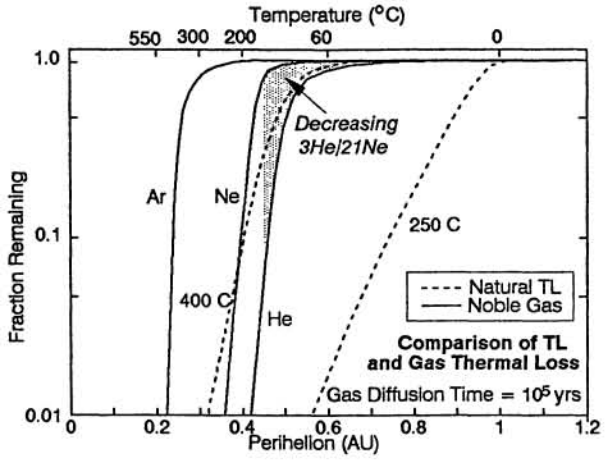

Fig. 1. Natural TL and noble gas loss as a function of perihelion (temperature) for ordinary chondrites.

A $^3He/^{21}Ne$ ratio between 4 to 8 is typical of nonreheated meteorites [6,9]. The $^3He/^{21}Ne$ ratio increases with $^{22}Ne/^{21}Ne$ due to shielding. I adopt the conservative criteria that reheated meteorites have $^3He/^{21}Ne$ values <4. Crabb and Schultz [10] used the even more conservative criteria of $^3He/^{21}Ne$ <2.5 but I use my own criteria in order to incorporate meteorites that may have experienced lesser degrees of reheating.

Portions of the natural TL glow curve are more sensitive to thermal loss than others. In Fig. 1 I show calculated equilibrium TL levels as a function of perihelion (temperature) for 250 and 400 °C in the natural TL glow curve, using the TL parameters of an equilibrated ordinary chondrite [11]. Unlike the

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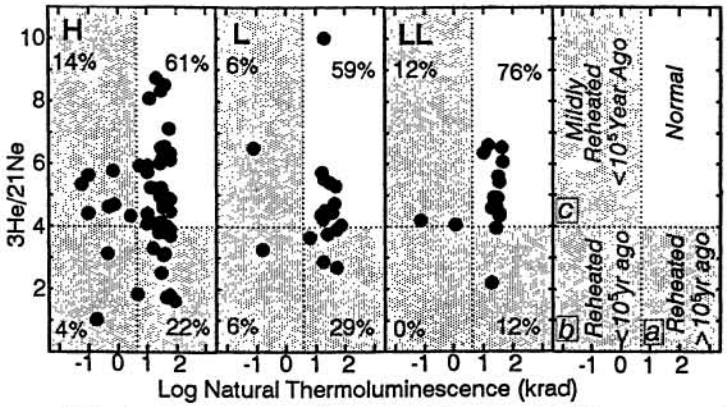

Fig. 2. $^3He/^{21}Ne$ *vs.* natural TL for equilibrated modern falls. Regimes of reheating are stippled and are defined at far right. In regime *a*, reheating occurred $>10^5$ years ago; in *b*, $<10^5$ years ago, while in regime *c* reheating was mild and occurred $<10^5$ years ago. Percent (by number) of meteorites in each regime are indicated.

noble gases, however, the loss of TL is essentially instantaneous and natural TL can rebuild to saturation levels after reheating in about 10^5 years [3]. In the present study I use the 250 °C portion of the natural TL glow curve, taking values of <5 krad as indicative of reheating [3].

In Fig. 2 I show $^3He/^{21}Ne$ and natural TL data for modern falls and a schematic showing three regimes of reheating (labelled *a*, *b*, and *c*). About 40% of H and L chondrites experienced reheating to some degree during their CRE age. Most of these reheating events (20 to 30% of H and L chondrites) occurred $>10^5$ years ago, and are thus not reflected in natural TL (category *a*). About 15% of H chondrites have experienced mild heating within the last 10^5 years, reflected in the TL but not in the noble gases (category *c*), and this proportion may or may not be lower for L chondrites in consideration of the small number analyzed. The LL chondrites differ from H and L chondrites in the low proportion of reheated samples, only about 25% of these meteorites having apparently been reheated during their cosmic ray exposure history. Again considering the small number of samples, reheated LL chondrites are about evenly divided between those that were reheated $>10^5$ and $<10^5$ years ago. Few equilibrated chondrites have experienced large degrees of heating within the last 10^5 years (category *b*).

Reheated samples are also commonly found among Antarctic meteorites. About 15% of Antarctic ordinary chondrites (after pairing) were reheated $<10^5$ years prior to fall (categories *b* and *c*) [12], similar to modern falls (Fig. 2). Reheated Antarctic meteorites generally have apparent terrestrial ages <200 ka (Fig. 3). Impact would not increase abundances of ^{14}C and ^{36}Cl, but the higher solar cosmic ray flux near the Sun might result in significantly higher radionuclide production. Most of these meteorites are, however, relatively large, comparable to non-Antarctic meteorites, and thus their interiors were shielded from the low energy solar cosmic rays. It thus seems likely that reheated ordinary chondrites of categories *b* and *c* rarely fell to Earth prior to 200 ka.

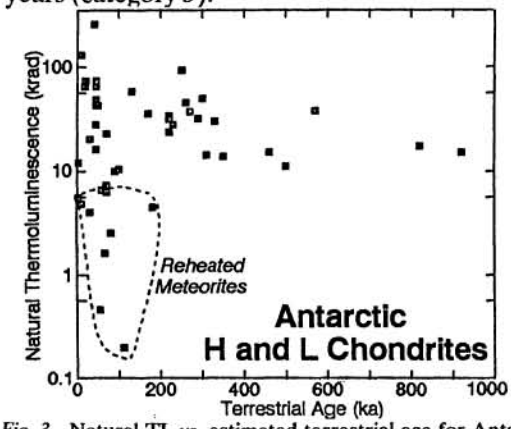

Fig. 3. Natural TL *vs.* estimated terrestrial age for Antarctic ordinary chondrites. Reheated meteorites have terrestrial ages <200 ka.

Conclusions. Reheating is a common phenomena among ordinary chondrites, having been experienced by about 40% of H and L chondrites and about 25% of LL chondrites to some degree over their cosmic ray exposure history. Shock heating may be a major factor for many reheated meteorites of category *a* and possibly *b*, but close approach to the Sun is probably more important for category *c*. The low proportion of recently reheated meteorites (*b* and *c*) is in agreement with the observed proportion of meteorites with perihelion <0.8 AU [13]. However, the apparent lack of reheated meteorites of categories *b* and *c* in meteorites falling to Earth >200 ka suggests that this is not an equilibrium situation, instead reflecting changes in the orbital distributions of these major chondrite groups as a function of time.

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