

A TEST OF SOLAR SYSTEM ABUNDANCE SMOOTHNESS D. S. Burnett, Caltech, Pasadena, CA. 91125; D. S. Woolum, Calif. State Univ., Fullerton, CA. 92634; T. M. Benjamin, P. S. Z. Rogers, C. J. Duffy, C. J. Maggiore, Los Alamos National Lab, Los Alamos, N. M. 87545

The idea that carbonaceous chondrite (C1) elemental abundances represent the average primordial solar system composition rests basically on two empirical arguments (see, e.g. Anders and Ebihara (AE), [1]): (a) the agreement between C1 and photospheric abundances, and (b) the smoothness of heavy element (beyond Fe) abundances of odd mass nuclei when plotted as a function of mass number. Although nominal errors have decreased significantly in the past 15 years, it is still best to regard heavy element photospheric abundances as uncertain to about a factor of 2. Thus, the accuracy to which C1 concentrations can be identified as average solar system abundances is determined by the smoothness argument. Confidence in solar system abundances, e.g. to the 10% level, would permit better interpretations of inter-meteorite chemical differences.

We have initiated proton probe (PIXE) analyses of homogenized carbonaceous chondrites in order to test elemental smoothness in the range of elements from Ni to Mo, where PIXE analysis has good sensitivity. The K lines of these elements are well separated using a Si(Li) detector. All elements in this region can be analyzed in a single sample, obviating the need to compare analyses done at different times, in different laboratories, using different techniques. Most importantly, although the accuracy of PIXE at present is not higher than techniques previously used, we have the advantage that all corrections used to convert the intensity of a single X-ray line to absolute concentration are either constants or smooth functions of atomic number (Z). Any systematic errors in the corrections will not affect inherent abundance smoothness. The smoothness of the abundance curve should only be affected by the statistical precision of the X-ray intensities, to a good approximation. The only major correction not strictly a function of Z is the correction for the K beta peak of element Z on the K alpha peak of element Z+2.

Approximately one quarter gram samples of interior specimens of carbonaceous chondrites were crushed and homogenized, and 20-50 mg aliquots were then pressed into 5mm diameter pellets using a stainless steel pellet press. These were mounted in high purity, reactor-grade graphite target holders and irradiated at the Nuclear Microprobe in the Los Alamos Ion Beam Facility. Proton beams from the Van de Graaff accelerator were typically 3.0 MeV in energy and 2mm x 2mm in size, with currents of up to about 150 nanoamps on target.

Figure 1 shows a representative spectrum of Orgueil (3 hours counting time). A 14 mil Al absorber completely attenuates the major element X-rays and reduces the Fe counting rate by a factor of roughly 10^4 . Higher energy, trace element X-rays are less attenuated (e.g., Sr K alphas by about a factor of 2), and these losses in intensity can be compensated by increased beam currents. Current densities are low, and no sample damage could be observed. Detector deadtimes were kept low (roughly 6%), and sum peaks are negligible. Definite peaks of all trace elements from Zn through Zr are present; for clarity, only the positions of the K alpha peaks are labelled. For reference, the Sr peak corresponds to about 6 ppm, and the precision of the net Sr counts is about 2%.

To fit the experimental spectra, line intensities for each element in the particular sample are calculated from first principles [2]. Subshell cross sections, fluorescence yields, and transition probabilities are known. Corrections are made for variations of X-ray production with decreasing beam energy in the sample and for the effects of X-ray absorption in the Si(Li) absorber and in the sample. The correction for the overlap of the K beta line of element Z with the K alpha line of element Z+2 is tightly constrained, since the K alpha to K beta ratios for a given element are known. The background of a chosen energy range is typically fit with a first- or second-degree polynomial. Finally, the background and the individually-calculated elemental line intensities are added together to fit the experimental spectrum, using a linear least squares fitting routine. Once a detector calibration is established, peak positions and widths are set and are not free parameters; thus, the relative elemental concentrations are the only free parameters in the spectral analysis. Elemental concentrations have been determined relative to a known major element as an internal standard.

Figure 2 shows results to date for the C1 chondrites, Orgueil and Ivuna, plotted as atomic abundances ($S_i=10^6$) for odd A nuclei, normalized to the AE ^{61}Ni abundance [1]. Agreement is excellent for the abundant even Z elements, Zn-Se; comparing results in ppm for Orgueil (this work; AE): Zn (301; 308), Ge (30.9; 32.2), Se (17.4; 18.2). Significant spectral interference corrections are required for Cu and Ga, and we have not yet evaluated the appropriate relative errors. An As peak is present, but the interferences from Pb L lines require further analysis. Br has a statistical precision of a few percent. Our Orgueil result is close to AE, but the Ivuna Br is distinctly higher, which may reflect either sample heterogeneity or, possibly, contamination. In either case the "notch" in the abundance curve between Se and Br is confirmed in our data. Following convention, the entries in Figure 2 for mass 87 are the sum of ^{87}Rb and ^{87}Sr . Agreement with AE is good for Rb, as can be seen at mass 85; however, we are systematically lower by 20-30% for Sr, Zr and Mo. Statistical errors are significant for Zr and Mo but not for Sr; it is conceivable that this difference reflects a systematic error in the correction factors adopted at present, but following the arguments above, this does not affect our evaluation of abundance

smoothness. The greatest difference between our results and the AE compilation is for Y. (Our Nb results are upper limits.) Because of the Z to Z+2 interference corrections, the Y abundance is sensitive to errors in fitting the Br and Rb peaks, and we do not yet know the appropriate error to put on the Y abundance, but the sharp Y spike in the AE compilation may not be present. An average of the present, tentative, Y abundances would yield an odd-A abundance curve dropping relatively smoothly above mass 85.

The concept of abundance smoothness is somewhat ambiguous. There are well-defined heavy element abundance peaks, associated with magic neutron number nuclei, interpretable in terms of s- and r-process nucleosynthesis. The s- and r-process peaks are well-resolved for the N=82 and N=126 shells, but not for the N=50 (A=86-90) shell of concern here. In general, there could be (a) just an N=50 shoulder on the steeply dropping odd A abundance curve above ^{56}Fe , (b) unresolved s- and r-process peaks, or (c) a sharp ^{89}Y s-process peak and a broad ^{77}Se - ^{85}Rb r-process peak. Nucleosynthesis theory offers some clues both to the N=50 peaks and the overall issue of abundance smoothness. To the extent that odd A abundances above A=70 are the sum of s- and r-process contributions, a smooth total abundance curve can only reasonably occur if both processes separately give smooth abundance curves. We consider only the s-process, as it is the best defined, astrophysically. Although it is probably not valid to assume a simple s-process steady state ($\sigma N = \text{const}$), a plausible zeroth-order approximation is that this product should be a smooth function of mass number, in which case the issue is the smoothness of odd A neutron capture cross sections. The cross sections compiled by Ulrich [3] show +30% structure above A=70, some of which could represent experimental uncertainties; however, the most striking feature is a sharp negative " ^{89}Y anomaly" which would give some theoretical justification for a sharp ^{89}Y abundance peak. Theoretical s-process abundance curves are not entirely smooth in this region; e.g., those calculated for core He-burning [4] show irregularities of up to a factor of 2, but, interestingly, reproduce the Se-Br "notch" in the solar system abundance curves.

Summarizing, it is likely that elemental abundance smoothness is only approximate, with possible deviations of 30%, perhaps even 50%. However, lack of smoothness in Cl abundances does not necessarily imply chemical fractionation, because it is likely that the true solar system abundance curves are not smooth at this level. With the aid of general ideas of n-capture nucleosynthesis, even in the absence of detailed astrophysical understanding, explanations for non-smooth behavior might be possible, which, somewhat ironically, could provide the strongest argument for the identification of Cl with average solar system abundances.

Refs: [1] Anders and Ebihara (1982) *Geochim. Cosmochim. Acta* **46**, 2363-2380. [2] Rogers, et.al. (1984) *Nucl. Instrum. Meth.* **B3**, 671-676. [3] Ulrich (1982) In, *Essays in Nuclear Physics*, pp.301-324. Cambridge Univ. Press, Cambridge. [4] Lamb, et.al. (1977) *Ap.J.* **217**, 213-221.

