

**Pb-Pb DATING OF THE D'ORBIGNY AND ASUKA 881371 ANGRITES AND A SECOND  
ABSOLUTE TIME CALIBRATION OF THE Mn-Cr CHRONOMETER**

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A number of short-lived radioactive isotopes, which existed in the early solar system but are now extinct (e.g., <sup>26</sup>Al ( $t_{1/2} = 0.74$  Ma)  $\rightarrow$  <sup>26</sup>Mg, <sup>53</sup>Mn ( $t_{1/2} = 3.7$  Ma)  $\rightarrow$  <sup>53</sup>Cr, <sup>182</sup>Hf ( $t_{1/2} = 9$  Ma)  $\rightarrow$  <sup>182</sup>W, <sup>146</sup>Sm ( $t_{1/2} = 103$  Ma)  $\rightarrow$  <sup>142</sup>Nd), have proven useful for dating the relative ages of meteorites. Based on the ratio of the stable daughter isotope to a proxy isotope for the parent element, this method only provides relative ages, and then only if a number of conditions are met. For example, a direct temporal relationship between daughter and proxy parent ratios requires that the original isotopic composition of the parent element where the meteorites formed was homogeneous. The discovery of an initially variable <sup>53</sup>Cr/<sup>52</sup>Cr among meteorites could reflect a radial inhomogeneous distribution of Mn/Cr and <sup>53</sup>Mn/<sup>55</sup>Mn in the early solar system [1].

The importance of establishing an absolute time calibration for the extinct, short-lived chronometers has long been recognized. However, only the coupled <sup>207</sup>Pb-<sup>206</sup>Pb system has so far demonstrated sufficient temporal resolution to provide a precise enough 'golden spike' for this purpose. The two angrites, Angra dos Reis and Lewis Cliff 86010, for which the <sup>53</sup>Mn/<sup>55</sup>Mn has been determined to be  $1.25 \pm 0.07 \times 10^{-6}$  [2], have identical Pb-Pb ages of  $4557.8 \pm 0.5$  Ma [3]. We have repeated this age measurement on a split of Angra dos Reis pyroxene provided by G. W. Lugmair--yielding a Pb-Pb age of  $4558.6 \pm 0.6$  Ma (with close to concordant U-Pb ages and a measured <sup>206</sup>Pb/<sup>204</sup>Pb = 7300), in good agreement with the earlier results.

Subsequent to the determination of this first golden spike, a number of new angrites were found and petrologically described. We report here on the U-Th-Pb study of two important additional angrites--D'Orbigny and Asuka 881371--that have a very primitive texture and are extremely depleted in incompatible elements compared to Angra dos Reis or Lewis Cliff 86010 (the concentrations of 2.4-5.9 ppb U and 7.3-17.7 ppb Pb in the D'Orbigny, and 1.5-7.2 ppb U and 4.8-27.9 ppb Pb in Asuka pyroxenes are 10-50 times lower than in Angra dos Reis pyroxene). A study of the Mn-Cr systematics in D'Orbigny shows this angrite to have had a considerably higher <sup>53</sup>Mn/<sup>55</sup>Mn of

$3.24 \pm 0.04 \times 10^{-6}$  than Angra dos Reis at the time of crystallization, which suggests a  $\sim 5$  Ma older age of 4563 Ma for it [4].

Because adequate delineation of the crystallization history of early solar system objects at the  $\sim 1$  Ma level requires that the <sup>207</sup>Pb/<sup>206</sup>Pb ratio be measured with a precision of  $\pm 0.05\%$ , extreme care must be exercised in sample chemistry and mass spectrometry. The results reported here were obtained in two laboratories (MPI and MIT) that are especially designed to maintain very low Pb procedural blanks and control the mass fractionation of both Faraday and electron multiplier ion collection systems. We are encouraged by the demonstrable reproducibility in isotopic measurements within and between laboratories, and believe that the necessary analytical precision is indeed achievable, even at these low concentration levels. If true, it may allow us to speculate on whether incongruities of just a few million years in calculated ages might be due not to quality of analysis but violations in the assumptions of the radioactive dating equation.

An initial attempt to date the matrix pyroxene from D'Orbigny resulted in highly discordant ages, which we attribute to impurity of the mineral separate or contamination by terrestrial(?) Pb, and are not further considered. Next a 4-step dissolution isochron was performed on the D'Orbigny whole-rock resulting in a Pb-Pb age of  $4563 \pm 2.5$  Ma. Our greatest success, however, lay in the careful extraction of euhedral pyroxenes lining late-stage drusy cavities of the meteorite. These pyroxene crystals were found to have higher <sup>206</sup>Pb/<sup>204</sup>Pb ratios and to yield essentially concordant ages.

Five hand-picked fractions of druse pyroxenes weighing 11 to 47 mg were recovered from a crushed fragment of D'Orbigny, subjected to several acid leaching steps, and analyzed in either the MPI or MIT laboratories. The U-Pb ages for all these analyses are, allowing for the uncertainties of the correction parameters, within 2 percent of concordant, as are the Th-Pb ages for 2 out of 3 fractions for which Th was determined. Three of the fractions subjected to intermediate severity leaches yielded Pb-Pb ages of  $4563.2 \pm$

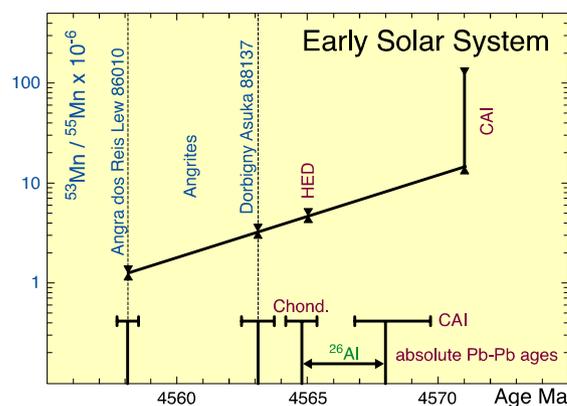
1.1, 4564.3  $\pm$  0.8, and 4563.8  $\pm$  0.8 Ma. A fraction given a milder leach yielded a 4569.4  $\pm$  2.8 Ma age, and another given a more severe leach yielded a 4558.5  $\pm$  3.3 Ma age. Also correlating with the leaching severity and decreasing Pb-Pb age was an increase in  $^{206}\text{Pb}/^{204}\text{Pb}$  ratio and a decrease in U and Pb content. Although not vigorously proven, we speculate that the mildest leach may not have entirely removed surface contamination, and the severest leach may have attacked lattice-bound Pb in the pyroxene. The relatively large errors of the two aberrant Pb-Pb ages reflect, in the first case, the low  $^{206}\text{Pb}/^{204}\text{Pb}$  ratio and, in the second case, the small amount of Pb available for analysis.

In a similar manner three hand-picked fractions of pyroxenes from a crushed fragment of Asuka 881371 and weighing 2.7 to 5.5 mg were analyzed. The Asuka pyroxenes, however, were recovered from only the matrix of the meteorite, and given leaches of intermediate severity. Because of the smaller sample size and lower Pb content, isotopic measurements could only be made by ion counting with an electron multiplier, thus yielding somewhat less precise Pb-Pb ages of 4562.7  $\pm$  2.4, 4564.8  $\pm$  2.6, and 4561.2  $\pm$  1.4 Ma.

Omitting the two aberrant D'Orbigny analyses, we calculated the weighted mean age of D'Orbigny to be 4563.9  $\pm$  0.6 Ma, and of Asuka 881371 to be 4562.4  $\pm$  1.6 Ma. Not included in our error treatment are allowances for variations in the initial Pb or U isotopic composition or post-crystallization disturbance in the isotopic systematics. Preliminary investigation of a glass phase found in D'Orbigny, which may have been included in the pyroxene and not removed by the mildest leach, appears to contain an anomalously Pb that could presage a curium contributed  $^{207}\text{Pb}$  [5]. Accepting our confirmation of the age of Angra dos Reis at  $\sim$ 4558 Ma and the new determination of a 4562-4564 Ma age for D'Orbigny and Asuka 881371, we do support the Mn-Cr relative chronology. These results strongly imply that there were at least two formational events for the angrites. Kurat et al. [6] give convincing evidence that D'Orbigny might actually have directly condensed from the solar nebular. The Mn-Cr dating method, previously calibrated with only one absolute age, has now been calibrated with two absolute ages. Thus, it would appear that the assumption of uniformity in Mn isotopic composition at the sites of angrite formation is valid.

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Absolute and relative ages in the early solar system (Pb ages from Chondrules and CAIs [7])