EXPERIMENTAL TESTS OF THE INDUCTION HEATING HYPOTHESIS FOR PLANETESIMALS.
C. A. Marsh, D. N. Della-Giustina, J. Giacalone, D. S. Lauretta, University of Arizona, Lunar and Planetary Laboratory, Tucson, AZ 85721, USA (celinda@lpl.arizona.edu)

Introduction: Induction heating is the release of thermal energy within a body due to the resistance of that material to a current passing through it. This mechanism is also called Joule heating or Ohmic dissipation. Induction heating has been proposed as a process that could have caused metamorphism and melting in planetesimals in the early solar system [1]. Although other theories are more widely studied, this hypothesis is still considered a viable source of asteroid heating [2, 3].

Induction heating requires a magnetic field of sufficient strength to induce a current in the materials present. When Sonnet and co-workers proposed induction heating in the early solar system they assumed that a magnetic field originated in the protostar and was carried outward by the expanding solar wind. Subsequent observations and models resulted in a reduction in the estimated intensity of T-Tauri stage solar winds, especially in the mid-plane [4, 5]. Some authors have used these observations to argue against induction heating of planetesimals [6].

Recent observations of the Orion cluster made with Chandra have provided new measurements of magnetic field intensities around Young Stellar Objects (YSOs) which are similar to our early Sun. Twenty-eight of these analogs were identified in the COUP field, and found to have an average x-ray flare luminosity of $10^{33}$ ergs/s [7]. Flares occurred an average of 1.5 times for each young solar analog over the 9 day observing period [8]. Characteristics of the brightest flares were used to calculate magnetic field strengths of 10s to 1000s of Gauss [8]. The same authors interpreted the Chandra flare measurements as indicating large magnetic structures are present that would connect the stellar photosphere with the inner rim of the circumstellar disk [8]. While these measurements of magnetic fields around YSOs do not provide a direct measurement of field strengths in the regions we expect planetesimals to form, they do show that the intense field strengths presumed in induction heating models are feasible [i.e. 1].

Meteoritic Constraints: The available meteoritic and asteroidal evidence indicates the presence of an intense, selective, and short-lived heat source in the very early solar system. The chronology of meteoritic heating events, indicators of parent-body size derived from cooling histories, and the spatial distribution of asteroid types provide constraints for the analysis of proposed heating mechanisms.

Experimental Methods: We seek an upper limit to the intensity of the magnetic field experienced by chondritic materials in the early solar system by measuring the field strength required to heat chondritic materials in the lab.

The materials used in our experiments are pellets of cutting dust from the Fukang pallasite [10], controlled mixtures of olivine and metal, and pure metal reference materials. Grain sizes and composition are measured in control samples in all cases through optical microscopy and electron microprobe analysis.

Our procedure is similar to that of previous work [9]. However, samples are placed in vacuum-sealed silica tubes and heated by an Ameritherm HotShot radio frequency (RF) induction heating station. This device is designed to heat small objects using frequencies from 150 to 400 kHz with up to 2 kW of power. The RF radiation is generated using a water-cooled copper induction heating coil. The geometry of the coil can be varied to accommodate a variety of sample sizes, currently we are using a 5 cm diameter coil, 2 cm in height, which is wrapped four times. Heating is achieved through Joule heating resulting from Eddy currents in electrically conductive material. Temperatures up to 2000 °C can be achieved within seconds in highly conductive materials. The length of the heating cycle can be varied from 10 milliseconds up to 3 hours. Magnetic field strength ($B$) is calculated using:

$$B = \frac{\mu * n * I}{2} \left( \frac{L/2 + d}{\sqrt{R^2 + (L/2 + d)^2}} + \frac{L/2 - d}{\sqrt{R^2 + (L/2 - d)^2}} \right)$$

where $\mu$ is the permeability, $N$ is the number of turns of the coil divided by coil length, $I$ is the current, $L$ is the length of the coil, $R$ is the radius, and $d$ is the distance from the center of the coil along the z axis. The RF furnace is producing magnetic fields from 0.1 to 24 Gauss. Temperature is monitored throughout the experiment using an Omega OS37-10-K pyrometer and DPi32 temperature logging system.

Once a sample has undergone Joule heating and returned to room temperature, it is removed from the furnace and weighed to determine the mass difference. The surface of the sample is characterized by optical microscopy, scanning-electron microscopy, and energy dispersive spectroscopy. The sample is then be mounted in epoxy and polished for electron microprobe analysis (EMPA). EMPA provides information on the main mineral phases and
the distribution of major elements between the metal and silicates, and the compositional variation with distance from the interface. We apply our newly-developed quantitative X-ray mapping technique[10] to determine the amount of elemental mobilization that occurs during each experiment.

Results: Table 1. shows results of experiments conducted thus far. Several metal standards have been heated as well as two samples derived from the Fukang meteorite. We have not been able to melt iron samples with our present configuration. However, we have found that grain size of the samples affects the temperature to which they are heated. We heated a 5 micron diameter Fe powder to 510 °C. This powder responded to the magnetic field by forming filaments of material up the side of the silica rod secured above the sample while still at low temperatures. It glowed dimly at the highest temperature. The iron foil samples reached about 570 °C at peak temperature and glowed brightly (see Figure 1.)

Discussion: There are several additional factors that need to be considered before an upper limit on field strength in the solar nebula can be calculated. The frequencies at which our induction furnace operates are higher than those expected in the early solar system. In addition, chondritic parent bodies were likely 10s of kilometers in diameter. Therefore, current density with depth will be quantitatively modeled before the difference between magnetic field strength at the surface and the location of various thermal metamorphic zones in the parent body can be assessed.

Our preliminary results show that grain size effects the extent of heating and that mixtures of silicate and metal are less efficiently heated than metal alone. Variations in frequency will impact what grain sizes are optimal and to what extent mixtures are resistant to heating.

Even the strongest flares observed around YSOs [8] are unlikely to produce magnetic fields in the 10s of Guass in the region of planetesimal formation for extended periods. The maximum temperature to which we could heat pure metal samples in a 24 Gauss magnetic field was well below their melting temperature. This indicates that induction heating is unlikely to be the sole source of thermal processing in planetesimals.

Further induction experiments and modeling will allow us to determine constraints on the extent to which induction heating may have affected planetesimals in our early solar system.

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<table>
<thead>
<tr>
<th>Sample</th>
<th>Amps</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fukang 1</td>
<td>243 (max)</td>
<td>~230 °C</td>
</tr>
<tr>
<td>Fukang 2</td>
<td>243 (max)</td>
<td>~220 °C</td>
</tr>
<tr>
<td>Fe Powder</td>
<td>243 (max)</td>
<td>~510 °C</td>
</tr>
<tr>
<td>Fe Foil</td>
<td>243 (max)</td>
<td>~570 °C</td>
</tr>
<tr>
<td>Zn Shot</td>
<td>160</td>
<td>420 °C (melt)</td>
</tr>
<tr>
<td>Al Shot</td>
<td>170</td>
<td>660 °C (melt)</td>
</tr>
<tr>
<td>Ag Shot</td>
<td>200</td>
<td>960 °C (melt)</td>
</tr>
</tbody>
</table>

Table 1. Results of induction furnace experiments. Refinement of pyrometer calibrations will permit better accuracy in temperatures. Amps represent the current used to heat those samples to the listed temperature. In the case of the standard metals, the experiments were halted when melting began.

Figure 1. Metal foil sections inside an evacuated sealed silica tube respond to the application of a magnetic field. Temperatures of 570 °C are reached with the maximum current our induction furnace is capable of producing. The pictured induction coil is 2” in diameter.