UNRAVELING THE THERMAL STRUCTURE OF THE ASTEROID BELT FROM METEORITIC AND ASTEROIDAL EVIDENCE. P. S. Hardersen[1] and M. J. Gaffey[2], [1]Rensselaer Polytechnic Institute, Planetary Sciences Laboratory, 2C01 Science Center, Troy, NY 12180, hardep@rpi.edu, [2]Rensselaer Polytechnic Institute, 2C04 Science Center, Troy, NY 12180, gaffem@rpi.edu.

Introduction: Abundant meteoritical evidence strongly suggests a heating event in the early solar system that caused many of the meteorite parent bodies (generally presumed to be asteroids) to be heated and/or melted to varying degrees [1]. Based on the ECAS survey of the main belt asteroids [2], researchers have found varying relative abundances of different asteroid taxonomic groups versus heliocentric distance [3-4]. The two main interpretations of these variations are that the asteroids are mostly primitive bodies that record the compositional gradients present in the solar nebula [3] and, alternatively, that the asteroids are an evolved population of objects that have experienced a significant, if short-lived, heating event that varied with heliocentric distance [5]. Detailed near-infrared spectroscopic and radar observations of asteroids also suggest that a substantial fraction of main belt asteroids have been heated to varying degrees [6-17]. The meteoritic record indicates that a large fraction (~80%) of the samples in the collection are igneous in nature and that at least 135 asteroidal parent bodies existed at the time of the early solar system [1]. Based upon the evidence available in the meteoritical and asteroidal communities, it is very likely that an early solar system heating event did occur.

Heating Patterns: Previous work has attempted to define the heating pattern and its large-scale structure in the main asteroid belt [5]. Igneous, metamorphic and primitive zones have been defined in the main asteroid belt that display the effects of a distinct radially dependent heating pattern. The igneous zone is in the inner belt, followed by a narrow metamorphic zone and a larger primitive zone that escaped significant heating [5]. However, no attempts have been made to learn about the heating pattern at higher spatial and geothermal resolutions besides that found at the largest of scales. The purpose of this research is to not only begin to understand the fine-scale thermal structure of the main asteroid belt, but also to relate the emerging thermal structure to the heating mechanisms that have been proposed to account for this radially dependent trend.

Heating Mechanisms: The two mechanisms that are usually invoked to explain the asteroid belt heating patterns are the decay of the short-lived radionuclide ^{26}Al and the effects of a transverse magnetic induction heating event caused by mass outflow produced by the Sun experiencing the T Tauri stage of its early evolution [18-19]. Both mechanisms satisfy the requirement to account for a short-duration heating event that produces a radially dependent pattern of heating among the asteroids. Both mechanisms, however, suffer from numerous and unresolved problems that prevent either from being accepted as the most probable source of heat that affected the asteroid parent bodies [20].

^{26}Al Heating: The main premise supporting the use of ^{26}Al as a heat source is the widespread presence of this radionuclide in Ca-Al inclusions (CAI) found in carbonaceous meteorites such as Allende with abundances up to ^{26}Al/^{27}Al ~ 5 x 10^{-5} [21]. The high abundances of ^{26}Al have also been found in a few ordinary chondrites and in one basaltic achondrite [22-23]. However, many samples show ^{26}Al abundance values well below 5 x 10^{-5}. A plot of ^{26}Al abundances in all analyzed samples shows a distinctly bimodal distribution that peaks at 5 x 10^{-5} and at 0, as well as abundances at intermediate values [21]. This brings into question whether or not the abundance of ^{26}Al was homogeneous in the solar nebula and whether there was enough ^{26}Al present to cause the melting of the meteorite parent bodies. There may also be a time problem because the time that elapsed between the formation of the CAIs and their incorporation into their respective parent bodies may be several half-lives of ^{26}Al, which would diminish the radionuclide's capacity as a heat source. It is also believed that ^{26}Al was not the heat source that melted the CAIs and that other nebular mechanisms are more likely [24]. Therefore, it is important to study related issues such as the time period between CAI formation and their incorporation into parent bodies, the amount of ^{26}Al needed to actually cause parent bodies to melt at various sizes and compositions and the likely consequences if ^{26}Al originated mostly from cosmic ray spallation or via an external mechanism such as a nearby supernova.

Transverse Magnetic Induction Heating: This mechanism proposes to heat meteorite parent bodies through the interaction of the solar magnetic field with an elevated mass outflow from the young Sun [25-26]. Although this mechanism has been found to occur in the present-day solar system at low levels [26], there are serious questions as to whether this mechanism is a viable source of heat for the very earliest of solar system bodies. Theoretical and observational work on young stellar objects (YSOs) suggests that mass outflow from T Tauri stars is probably coupled with mass accretion from the solar nebula [27]. The elimination of the mass outflow at the onset of the weak T Tauri stage (WTTS) may prevent induction heating from being a significant factor in heating the meteorite parent bodies. In addition, the model proposed for induction heating often uses input parameters that are not considered realistic based on the more recent observational data [20]. Theoretical and observational astronomers need to determine if a large plasma outflow, compared to today, is likely to occur in a WTTS and if this event can be detected. Models for induction heating also need to be refined to use the best available astronomical data.

Asteroid Data: Several asteroids have been observed using near-infrared reflectance spectroscopic and radar techniques that indicate that many of these bodies have experienced significant heating. Radar observations of 16 Psyche and 216 Kleopatra have produced relatively high radar albedos (0.31 and 0.44, respectively) that are interpreted to represent large abundances of NiFe metal on the asteroids' surfaces [12]. Kleopatra has been delay-Doppler imaged and has a minimum estimated surface bulk density of 3.5 g/cm^3, which is consistent with a largely metallic object [14].

Near-infrared measurements of 4 Vesta, 6 Hebe, 8 Flora, 15 Eunomia, 113 Amalthea, 289 Nenetta, 349 Dembowska, and 446 Aeternitas suggest various levels of thermal heating of these objects [8,9,10,11,13,15,16]. Observations of 1 Ceres, 2 Pallas, 55 Pandora and 92 Undina show the presence of H_2O features that indicate the presence of structurally bound water in phyllosilicate minerals that indicate mild heating sufficient to melt ice and form hydrous silicates [6,7,17]. These asteroids will serve as the initial data points that will be used to test two models: 1) the Grimm and McSween model for ^{26}Al heating [18] and 2) the Herbert and Sonett model for induction heating [19,26]. These two models predict different heating trends will occur and it should be possible to determine if one, both, or neither of the models accurately fits the thermal histories inferred from asteroid observations. A long-term program of observations of main belt asteroids using both radar and near-infrared techniques is underway to characterize the thermal histories of additional asteroids.

Model Testing: The maximum temperatures inferred to have been experienced by the initial set of 15 asteroids listed below is being used to test the two models. Temperatures are divided into four bins: 0-300ºC (I), 300-950ºC (II), 950-1200ºC (III) and >1200ºC (IV). 1 Ceres, 2 Pallas, 55 Pandora and 92 Undina are in group I; 6 Hebe is in group II; 113 Amalthea and 349 Dembowska in group III; and 4 Vesta, 8 Flora, 15 Eunomia, 16 Psyche, 44 Nysa, 216 Kleopatra, 289 Nenetta and 446 Aeternitas are in group IV.

Parent body diameters of the asteroids are estimated by using their likely original chondritic bulk compositions, and placing additional limits based on their current diameters and compositions.

Data points (diameter vs. heliocentric distance and inferred maximum temperatures) from the asteroids above will be superimposed on the graphical models of Grimm and McSween [18] and of Herbert and Sonett [19,26] to determine how well the models match the inferred asteroid thermal histories.

Model Results: The 15 asteroid data points were superimposed on five variations of the Herbert and Sonett model and on the Grimm and McSween model. The Grimm and McSween model predict the correct temperatures for 6 asteroids; the number of correct predictions for the five variations of the Herbert and Sonett model are as follows: a) 8, b) 9, c) 1, d) 4, and for the preferred model, 2.

The results indicate that none of the models performed particularly well. The most accurate predictor (Herbert variation c) was correct for ~60% of the sample. An additional problem with this particular variation is that the input parameters are not considered to be astronomically realistic [20].

Future Work: This is only an initial attempt to define the actual thermal structure of the asteroid belt. Additional data points will be added as detailed near-infrared spectroscopic and radar data become available. Plans include extensive use of the SpeX instrument at the NASA Infrared Telescope Facility [28] and the Arecibo Observatory to gather this important data.

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