ON THE ABUNDANCES OF MODERATELY VOLATILE ELEMENTS IN METEORITES; P. Cassen, NASA-Ames Research Center, Moffett Field, CA 94035.

The abundances of the moderately volatile elements (those which condense or evaporate in the temperature range 650 - 1350 K) in chondritic meteorites deviate from solar (or "cosmic", as defined by CI meteorite composition) in a manner that strongly suggests that they were determined primarily by volatility, independent of chemical affinity [1]. Wasson and collaborators [2,3] have long argued that the observed correlation of relative abundance with condensation temperature reflects a systematically selective process which favored the accretion of refractory material over volatile material from a nebula cooling from a hot initial state.This view is supported by the detailed examination of chondrules and matrix in carbonaceous meteorites [4] and the contrast between meteorite trace element abundance patterns with those produced in heating experiments [5]. However, the idea that the moderately volatile abundances reflect global condensation has not previously been quantitatively tested or used as a constraint on nebula evolution. We have therefore constructed models of the solar nebula designed specifically for addressing meteoritic data. Calculations so far indicate that the abundance patterns of the moderately volatile elements in chondritic meteorites can be produced naturally in an evolving nebula that cools with the reduction in opacity associated with the accumulation of meteoritic bodies.

The models include prescriptions for the evolution of nebula surface density, temperature, and accumulated solid material. In view of the current lack of a predictive theory of angular momentum transport, the surface density is simply assumed to have a guassian distribution, governed by time-dependent parameters that enforce global conservation of mass and angular momentum. The total mass of the nebula is assumed to decay algebraically, in a manner consistent with the ages and accretion rates of T Tauri stars and their disks, and isotopic chronology. The temperature is governed by the disk accretion rate and opacity [6,7]. We generalize the results of coagulation calculations [8,9,10] to specify the rate of conversion of fine-grained material to preserved meteoritic components to be $\varepsilon\Omega\Sigma_i$ gm/cm^{2}sec, where: Ω is the local orbital frequency; Σ_i is the local surface density of elemental species i; and ε is an efficiency factor taken to be the same for all elemental species, or zero for any species for which the midplane temperature exceeds its condensation temperature. Thus the conservation of mass equation for each species i is:

$$\frac{\partial \Sigma_i}{dt} = \frac{1}{r}\frac{\partial}{\partial r}(rV_r\Sigma_i) = -\varepsilon\Omega\Sigma_i,$$

where V_r, the radial velocity, is determined by the evolution of total surface density. This equation is solved for Σ_i, and the right-hand side is integrated to obtain the mass of each species "deposited" in surviving meteoritic material.

Several parameters, variously constrained by observations, govern the models: the total angular momentum and maximum mass of the nebula; the initial mass accretion rate through the nebula; the characteristic evolution time; and the characteristic coagulation time and efficiency. (In the models calculated so far, it is assumed that all solid material is either *fine-grained*, in which case it follows the gas and contributes to the opacity, or *coagulated,* in which case it is retained in the solar system.) Our general procedure is to specify values of the above parameters and calculate the total mass deposited and thermal evolution. We restrict attention to the moderately volatile elements by lumping all elements with condensation temperatures above that of silicon (taken to be 1311 K) as "rock", which contribute most of the mass and all of the opacity, and by ignoring evolution below 650 K. Models that reproduce to a satisfactory degree the surface density of deposited rock required to form the planets are then examined for their predicted abundances of the moderately volatile elements.

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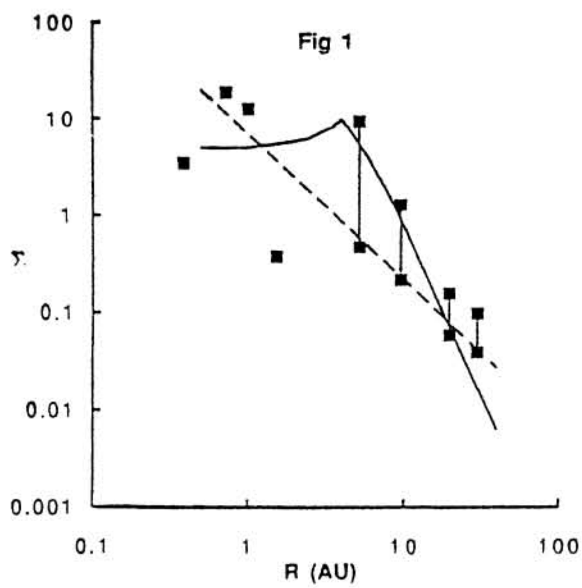
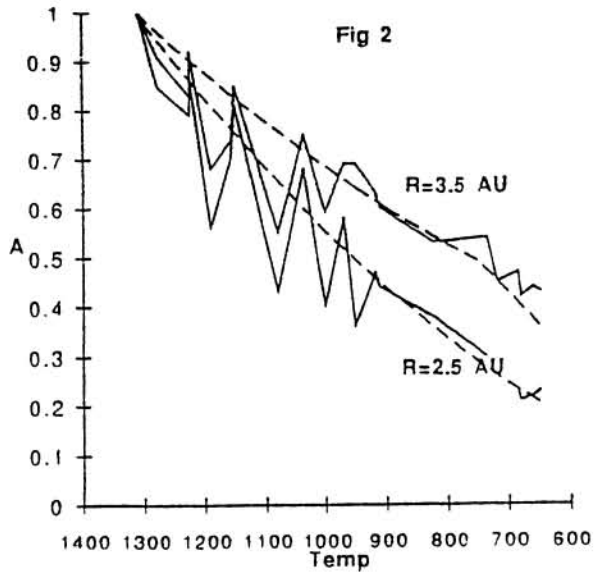
Results from a preliminary set of calculations that yield plausible nebula evolutions are shown below. Figure 1 shows the distribution of surface density of deposited rock (solid line) for a nebula with total angular momentum 4×10^{52} gm-cm^2/sec, initial mass .23 $M_\odot$, initial accretion rate 10^{-5} $M_\odot$/year, and characteristic coagulation time at 1 AU of 5×10^3 years. In this model, the high initial accretion rate and nebular mass were sufficient to cause the evaporation of silicate material out to about 4 AU. The squares are the surface densities inferred from planetary masses by Weidenschilling [11], and the dashed line is that derived by Hayashi [12]. Figure 2 shows the predictions for the abundances (normalized to CI silicon) deposited at 2.5 and 3.5 AU (dashed lines), as a function of condensation temperature, along with measured abundances for CM (upper solid) and CO (lower solid) meteorites (taken from [1] and [4]).





In these models, the abundances of elements are determined by the superimposed thermal and surface density evolutions of the nebula, as originally proposed by Wasson and Chou [2]. However, the history of depletion carried by nebular gas from one place to another can be important. Even if the local surface density of the nebula is not decreasing, condensation and accretion of solids from radially inflowing gas in a cooling nebula can result in depletions of volatiles like those observed. Also, although the reduction in opacity naturally couples the deposition and cooling time scales, the dynamical history of the nebula is important in controlling the total mass density and energy input, through accretion. For these reasons, it seems likely that a thorough exploration of the effects of all parameters on moderately volatile element abundances (and other meteorite properties) will yield useful constraints on general aspects of nebula evolution.

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