AGB-star dust from AGB stars that were moving through it prior to solar birth. Those AGB stars were more metal-rich than the Sun because they had formed interior to the solar birthplace at 6.6 kpc and have overwhelmingly diffused outward rather than inward. After its subsequent birth the Sun diffused outward from 6.6 kpc to its present 8.5 kpc, accounting for its own metal richness with respect to the local ISM. These features are illustrated in Fig. 1.

Shown in Fig. 1 are the radial metallicity (Fe/H or O/H) gradients today, at the time of solar birth, and at 6 G.y. ago. From chemical evolution theory, larger values of Fe/H contain isotopically heavier Si, in roughly direct proportion. The ordinate is either quantity therefore, and is normalized to solar composition. The diffusion of three stars that happened upon the solar cloud just as they reached their terminal C-star phases are shown by star symbols. They lie above solar Si in the three-isotope plot. Their outward drift may be likened to mankind's "gravity assist" from Jupiter when visiting Pluto. The strongly negative radial gradients in both the numbers of presolar AGB stars and the molecular clouds that scatter them produce the large ratio for internally born AGB stars to externally born ones. A rich astronomical future is to be found in the density profile of SiC grains along the mainstream.

OXYGEN ISOTOPES IN LABORATORY-HEATED CI AND CM CHONDRITES.

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Thermal metamorphism of CI- and CM-like chondrites was first recognized in the Antarctic meteorites B 7904, Y 82162, and Y 86720 [1–3]. These meteorites have O isotopic compositions very similar to one another, but quite distinct from other meteorites. It has not been established whether there is a direct causal relationship between the metamorphism and the isotopic composition. A new O isotope measurement of Y 86789 ($\delta^{18}O = 21.4$, $\delta^{17}O = 11.1$) falls in the narrow range of the "unusual CI-CM" listed above, so that this meteorite also belongs in this category. It is not known whether Y 86789 is paired with one of the other Yamato meteorites. Reflectance spectra of C-type asteroids are best matched by the spectra of the "unusual" CI and CM chondrites, implying that metamorphosed CI and CM material may be much more common in the asteroid belt than would be inferred from known meteorites [4].

More recently another group of CM-like chondrites has been recognized that shows evidence of partial dehydration, to a smaller extent than the "unusual CI-CM" described above [5]. These have O isotopic compositions close to common CM chondrites, but displaced toward lower $\Delta^{17}O$ [6].

Oxygen isotopic compositions of meteorites are useful for identification of source materials, and for determination of conditions of chemical processes occurring in the nebula or within parent bodies [7]. In particular, hydration reactions, in which ferromagnesian silicates are altered to clay minerals, produce large heavy-isotope enrichments due to the mass-dependent fractionations at low temperatures [8]. These processes are also well known on Earth in the low-temperature alteration of seafloor basalts [9]. However, the isotope effects associated with dehydration reactions are less well studied, and may be complicated by kinetic effects as well as isotopic partitioning between vapor and residual solids.

Laboratory studies of thermal metamorphism of CI and CM chondrites have previously been conducted in order to observe trace-level mobilization [10] and mineralogical effects on reflectance spectra [5]. In the present work, we have used samples from these previous studies to investigate the effects of dehydration reactions on the bulk O isotopic compositions of the residues. The Murchison samples were heated in closed tubes, initially containing 10^{-5} atm of H_2, for periods of one week at temperatures from 400° to 1000°C. The Ivuna samples were heated under vacuum for one week at temperatures from 300° to 700°C. Oxygen isotopic compositions of the residues are given in Table 1.

Oxygen isotope effects on the residues of dehydration reactions are expected to be small, since a relatively small fraction of O is lost, and fractionation factors are small at high temperatures. The effects observed in the Murchison experiments are consistent with these expectations: a small initial increase in δ values, due to loss of low-$\delta^{18}O$ H_2O, with no further significant change above 500°C. The change occurs along a mass-dependent fractionation trend, i.e., at constant $\Delta^{17}O$, indicating negligible interaction with terrestrial O (such as the walls of the apparatus). The isotopic variations in the Ivuna residues are much larger, and in the direction opposite to that seen in Murchison: heavy-isotope depletion in the residues. Most of this effect occurs between 100° and 500°C. These results appear to indicate the progressive removal of a component significantly enriched in ^{18}O and ^{17}O with respect to the bulk meteorite. No detailed study has been done of O isotope variability among the fine-grained minerals in CI chondrites. The results presented here suggest that such a search may produce interesting results.

TABLE 1. Oxygen isotopic compositions of heated meteorites.

Meteorite	Heating Temperature (°C)	$\delta^{18}O$	$\delta^{17}O$	$\Delta^{17}O$
Murchison	unheated	5.15	−0.83	−3.51
	400	6.78	0.45	−3.08
	500	7.72	1.05	−2.96
	600	7.14	0.47	−3.24
	700	7.51	0.68	−3.23
	800	7.52	0.58	−3.33
	1000	7.41	0.41	−3.44
Ivuna	unheated	18.04	9.82	+0.44
	100	18.14	9.82	+0.39
	300	14.63	7.90	+0.29
	500	11.61	6.28	+0.24
	600	11.32	5.84	−0.05
	700	11.45	5.78	−0.17

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EUROPIUM VALENCE STATE DISTRIBUTIONS IN EQUILIBRATED ORDINARY CHONDRITES.

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It has been recognized for 30 years that the presence of Eu anomalies in REE patterns is due to the presence of divalent Eu, unique among the REE. However, it has not previously been possible to infer quantitative Eu^{+2}/Eu^{+3} ratios in natural samples. We have used ion probe data for lithophile trace elements for the phases in equilibrated ordinary chondrites [Guareña (H6), Marion (L6) and St. Séverin (LL6)] to perform mass-balance calculations that yield relatively precise Eu^{+2}/Eu^{+3} ratios.

The required input data are (1) relative Eu concentrations in two reference phases [plagioclase (plag) and merrillite (merr) in our case]; (2) Eu^{+3} crystal-crystal partition coefficients (interpolated from REE patterns) for merr, plag, and clinopyroxene (cpx); and (3) modal abundances for plag, merr, and cpx. Apatite appears not to be important because its modal abundance is too low. Olivine and orthopyroxene Eu concentrations are measured to be too low to be significant. We assume (1) unmeasured phases are

TABLE 1.

Meteorite	Eu^{+2}/Eu^{+3}	Fa
Guareña	7.5	18
Marion	7.0	24
St. Séverin	4.1	29

negligible, and (2) crystal-crystal partition coefficients for Sr are the same as Eu^{+2}. Partitioning systematics indicate that (2) is a good assumption. As the only issue is material balance, the assumption of equilibrium partitioning is not necessary. For given locations in individual meteorites, REE and Sr concentrations are sufficiently uniform. The fact that Eu/Sr ratios vary among phases shows that Eu^{+3} is not negligible. For St. Séverin the percentages of Eu in plag, merr, and cpx are 77, 22, and 6. The corresponding percentages for Sr are 94, 2, and 4. Results for the other meteorites are similar. Modal abundances are obtained from normative calculations using literature data, but with actual measurements for the proportions of apatite and merrillite.

The nominal mass-balance calculations give Eu^{+2}/Eu^{+3} between 3 and 5. However, a complication is that total-rock Eu concentrations calculated from our ion probe and modal data fall short of measured literature total-rock Eu concentrations by 21% (St. Séverin), 32% (Marion), and 51% (Guareña). Total rock concentrations for most lithophile elements in ordinary chondrites are accurately measured and exceptionally uniform down to the hundred-milligram scale. When the same material balance calculations are done for Yb and La, good agreement is obtained with literature whole-rock data. The calculated total-rock Sr concentration falls short, but the percentage shortfalls for each meteorite are the same within errors as Eu, suggesting that the missing Eu is Eu^{+2}. Using this conclusion and literature total-rock Eu concentrations, we can correct the observed Eu^{+2}/Eu^{+3} ratios. The corrected Eu^{+2}/Eu^{+3} ratios are shown in Table 1. These correlate with the relative oxidation states based on Fa contents of olivines in the major ordinary chondrite groups.

It is possible that our inability to achieve material balance for Eu and Sr reflects the fact that the largest grains (greater than 30 μm in all dimensions) are selected for ion probe analysis and that smaller plagioclase grains have higher concentrations of Sr and Eu. If this hypothesis can be confirmed, it would indicate a disequilibrium distribution for these elements in equilibrated chondrites.

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REVISITING NEBULAR SHOCKS AS A CHONDRULE FORMATION MECHANISM. H. C. Connolly Jr.[1] and S. G. Love[2], [1]Mail Code 100-23, California Institute of Technology, Pasadena CA 91125, USA, [2]Mail Code 252-21, California Institute of Technology, Pasadena CA 91125, USA.

Experimental studies have provided numerous constraints on chondrule formation. The most important of these are: (1) chondrules were formed when cool (<650°K) precursors were heated to temperatures of 1700°–2000°C for seconds to minutes and cooled for minutes to hours, with shorter heating times demanding higher peak temperatures [1,2]; (2) chondrules experienced multiple generations of melting, reheating, shattering, and accretion (i.e., recycling), all in the presence of finer-grained "rim" dust [3,4]; (3) chondrules probably formed in regions of enhanced dust concentration and gas pressure [5,6] compared with the canonical protoplanetary nebula; and (4) dark-zoned (DZ) and agglomeratic olivine (AO) chondrules were less strongly heated than other chondrules in the same meteorite [2].

Many different mechanisms have been proposed to explain these observations [2,7]. One mechanism [8] calls for chondrules to be heated by gas drag and mutual radiation in strong (Mach 3–8) shock waves propagating through the protoplanetary disk. Shocks can produce heat pulses with temperatures and durations appropriate for chondrule formation [8]. Here we note some additional implications of shock heating that are consistent with the observations listed above, and that we believe strengthen the case for nebular shocks as a chondrule formation mechanism.

Shock waves imply high-speed collisions between particles, explaining the broken chondrules found in meteorites. Shocks also facilitate accretion of chondrule precursors by concentrating the particles they overrun [8,9], locally boosting the abundance of solids. This effect may also provide the locally enhanced dust-to-gas ratio suggested [2,5] to control the local f_{O_2} during chondrule melting. Shocks also size-sort solids [9]. Because small particles are entrained sooner than larger ones [9], the immediate postshock region is an ideal place for chondrules to accrete dust rims. In this model, finer rim grains would be accreted first.

The gas density and temperature increase across a shock front [8]. So does the pressure. The pre- to postshock pressure ratios for Mach 3, 5, and 8 shocks are 10, 29, and 74 respectively [10]. Thus, shocks coincidentally boost the pressure by 1–2 orders of magnitude, neatly explaining both chondrule heating and its apparent high-pressure environment [6].

Finally, shock-wave heating can explain different thermal histories among chondrules in the same meteorite. Gas drag heats particles of different sizes to the same temperature immediately behind the shock. The temperature then drops as particles match speed with the gas, which takes more time for larger particles [11]. Thus, shock heating is less severe for smaller particles. The smallest chondrule types (DZ and AO) are also the least heated [2], which is consistent with shock heating. Further information on the size dependence of chondrule heating would provide a powerful test of the shock formation model.

Although a specific source for strong nebular shocks is still in question (spiral density waves, unsteady disk accretion, and FU Orionis outbursts have been proposed recently) [2,6], we believe that shock heating is consistent with every important constraint on chondrule formation and that a strong case can be made for nebular shock waves as a chondrule formation mechanism.

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MODEL POROSITIES OF CHONDRITES AND THE NATURE OF ASTEROIDAL MATERIAL. G. J. Consolmagno SJ[1], D. T. Britt[2], and C. P. Stoll[3], [1]Specola Vaticana, V-00120, Vatican City State, [2]Lunar and Planetary Laboratory, University of Arizona, Tucson AZ, USA, [3]6270 Colby Street, Oakland CA 94618, USA.

Porosity offers clues to the nature and history of material in the asteroid belt. However, terrestrial weathering fills pore spaces, reducing the measured grain density and porosity of these samples. But filling pore space with weathering material will not significantly alter the bulk volume or mass, and so the bulk density is relatively unchanged (until the fabric of the sample is seriously degraded). For meteorites classified by mineralogical composition (e.g., ordinary chondrites), a single pristine grain density can be assumed for each class; from that and the measured bulk density, we can estimate an original model porosity representing the state of the meteorite before terrestrial weathering [cf. 1].

We have examined density and physical data of more than 600 chondrites representing more than 300 different meteorites. These include measurements taken at the Vatican collection, literature values, and a database compiled by M. Terho and colleagues at the Geological Survey of Finland (whose assistance we gratefully acknowledge). From these, we have deduced model porosities that can be compared against meteorite class and petro-