Reports

High Temperatures in the Early Solar Nebula

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One fundamental controversy about terrestrial planet and asteroid formation is the discrepancy between meteoritical evidence for high temperatures (1500 K to 2000 K) in the inner solar nebula, and much lower theoretical temperature predictions on the basis of models of viscous accretion disks that neglect compressional heating of infalling gas. It is shown here that rigorous numerical calculations of the collapse of a rotating, three-dimensional presolar nebula are capable of producing temperatures on the order of 1500 K in the asteroid region (2.5 astronomical units), in either nearly axisymmetric or strongly nonaxisymmetric nebula models. The latter models may permit significant thermal cycling of solid components in the early inner solar nebula.

THE CENTRAL PARADIGM OF PLANETARY cosmogony is that the sun and planets formed out of a rotating, flattened disk of gas and dust, which is termed the solar nebula. Early work on the thermal structure of the solar nebula implied that temperatures in excess of 1800 K were achieved (*1*), and this work helped to motivate studies of the equilibrium condensation sequence of elements in a nebula cooling from initially high (1700 K to 2000 K) temperatures (*2*). Highly refractory Ca-Al-rich inclusions (CAIs) in the primitive Allende meteorite appear to be consistent with cooling of an initially hot, vaporized nebula (*3*), and the presence of previously molten chondrules in the majority of meteorites also appears to require high temperatures within the solar nebula (*4*). However, subsequent work based on the thermodynamics of spherically symmetric models of protostellar collapse (*5*) implied much lower temperatures (500 K) for solar nebula material destined to be incorporated into the terrestrial planets and asteroids (*6*). I show here that when the collapse of the presolar nebula is rigorously calculated, including three-dimensional hydrodynamics, self-gravitation, and radiative transfer, it is possible to construct plausible early solar nebula models with relatively high (1500 K) temperatures in the region of the nebula (2.5 AU) from which the bulk of the meteorites are thought to originate.

For the last decade solar nebula models have concentrated on accretion disks driven by turbulent viscosity, with the turbulence usually being generated by convective instability (*7*). Compressional heating associated with the interstellar cloud collapse that formed the nebula is neglected. A nebula heated only by turbulent viscosity does not become very hot, however, except for extreme assumptions (for example, an effective turbulent viscosity parameter $\alpha = 0.24$ and a nebula dissipation time of 2.5×10^4 years). Typical temperatures at 2.5 AU are 160 K to 280 K for more reasonable model assumptions, too low to account for any significant thermal processing. Furthermore, the basic assumption of a continuous, smoothly evolving viscous accretion disk has been shaken by a recent study indicating such disks should be unstable to a diffusive instability that breaks disks up into a series of rings (*8*). Attempts to produce high temperatures by estimating the shock heating of dust grains entering the solar nebula have also been less than completely satisfactory (*9*).

The most promising alternative to turbulent viscosity for driving accretion disk evolution is angular momentum transport by gravitational torques (*10*). In order to assess the efficiency of gravitational torques, a series of models of presolar nebula collapse has been calculated (*11*). One by-product of this study is a self-consistent prediction of the thermal structure of a variety of solar nebula models.

The models involve a finite-difference solution of the equations of hydrodynamics, self-gravitation, and radiative transfer in the diffusion approximation on a spherical coordinate grid (*12*). The equations are solved in conservation law form, allowing global conservation of mass and angular momentum. The equations of state and for the specific internal energy include all relevant processes, such as dissociation of molecular hydrogen, and the dust grain opacity has been updated (*13*). The spatial grid is fully three dimensional, with effectively $N_r = 41$, $N_\theta = 23$, and $N_\phi = 32$ grid points, given the assumed symmetry through the midplane and through the rotational axis. The θ grid is compressed to provide increased spatial resolution for the thin disks that typically form ($\Delta\theta \approx 2°$ at midplane). The innermost Δr is 1 AU in model A and 1/3 AU in model B. A sink cell at the center of the models represents the gravitational attraction of the initial mass in the protosun and of any nebula matter falling onto the protosun. The temperature near the center of the models is averaged over all directions (for numerical stability of the energy equation), which tends to underestimate midplane temperatures in the inner solar nebula. Temperatures are also occasionally averaged at isolated grid points when incipient numerical instabilities become obvious.

Two models are presented here, both involving the self-gravitational collapse of an initially uniform density and uniform rotation sphere of radius 40 AU. Each model is initially perturbed with a 1% $\cos\phi$ variation in the density; this level of nonaxisymmetry is approximately equal to the background noise level for the numerical code. Model A involves a sphere of mass 0.102 $M_\odot$ collapsing onto a protosun with initial mass 1.000 $M_\odot$, whereas model B involves a sphere of mass 1.025 $M_\odot$ collapsing onto a protosun with initially zero mass. Model A approximates the formation of a solar nebula through the accretion of the last vestiges of an interstellar cloud that has already largely led to solar formation, whereas model B approximates an earlier formation phase when much of the presolar matter is still

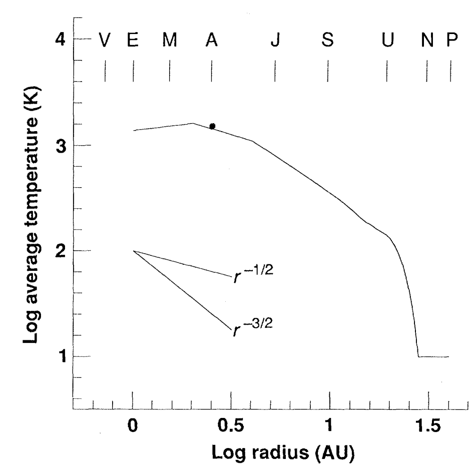

Fig. 1. Azimuthally averaged midplane temperature as a function of heliocentric radius for model A. The solid dot denotes a temperature of 1500 K at 2.5 AU. The dip in the average temperature inside ~2 AU is an artifice introduced for stability of the numerical solution method; in reality, temperatures should continue to increase toward the protosun. Orbital radii of major solar system bodies are also shown.

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collapsing. Models A and B apparently represent two end members of the range of possibilities. The specific angular momentum (J/M) of model A is 2.0×10^{19} cm^2 s^{-1} and for model B is 6.2×10^{18} cm^2 s^{-1}; these values of J/M are plausible for slowly rotating dense clouds. However, the initial densities of 2.22×10^{-13} g cm^{-3} for model A and 2.22×10^{-12} g cm^{-3} for model B are roughly 10^6 times higher than typical dark cloud maximum densities. The temperature is initially uniform at 10 K, which also leads to an underestimate of subsequent temperatures, if one considers the optically thick initial densities.

The assumption of relatively high initial nebula densities is crucial for these calculations; if the collapse is started from much lower densities, the calculation is stymied by the need to calculate the evolution past the first quasi-equilibrium phase. Because the first quasi-equilibrium core involves only a minor fraction of the mass of a solar mass–sized cloud, ignoring the earlier phases should not be detrimental to the dynamics. With respect to the thermodynamics, this artifice should also not be important, provided that the nebula cooling time is longer than the nebula collapse time, which is the free fall time. For typical models produced in this study, cooling times are on the order of 10^5 years or more, because dust grains in the outer nebula produce an effective blackbody temperature on the order of 20 K. Collapse times for dense clouds are on the order of 10^5 years or less, whereas the free fall times for models A and B are 140 and 45 years, respectively. Collapsing the presolar nebula on this shorter time scale should then have a marginal effect on the thermodynamics, but this approximation may tend to overestimate temperatures, contrary to the other approximations mentioned above.

The initial presolar nebula in model A collapsed to form a mildly nonaxisymmetric nebula (maximum deviation from axisymmetry of about 10% in density) containing 0.061 $M_\odot$ when the calculation was halted. The protosun has a mass of 1.041 $M_\odot$ at this time. The inner regions are beginning to settle into centrifugal equilibrium, and so this model is a reasonable approximation of a low mass, Safronov-type nebula model (*14*). Because of the nearly axisymmetric nature of model A, azimuthally averaged quantities suffice for its description. Figure 1 shows the temperature profile for model A. Note that the temperature gradient does not tend toward a single universal power law, contrary to some early expectations (*15*), but does vary within the range of previous predictions, for example, $T \propto r^{-1/2}$ to $r^{-3/2}$ (*16*). Perhaps most important is the fact that model A produces temperatures on the order of 1500 K at 2.5 AU; gas falling onto a disk inside the potential well of a solar mass object becomes significantly hot because of compressional heating.

Because model A started with a spherical, solar mass protosun, the collapse of its low mass nebula is expected to be largely axisymmetric. By not allowing for any nonaxisymmetry in the dominant object in the nebula (the protosun), model A errs on the side of axisymmetry. In order to see what might have happened when the protosun itself was forming, I turn to model B. The massive nebula of model B, unstabilized by a dominant central mass, collapses to form a strong bar in the inner solar nebula. The temperature contours in Fig. 2 for model B roughly trace the density contours; extreme nonaxisymmetry is evident. In model B, temperatures are a strong function of azimuthal location in the nebula.

Very little matter (0.008 $M_\odot$) reaches the sink cell in model B. Most of the nebula mass (about 0.75 $M_\odot$) lies within 2 AU, forming a transient binary system. Using a binary survival criterion (*17*), one can predict that this mini-binary should undergo rapid decay through loss of orbital angular momentum by gravitational torques to the rest of the nebula. Thus the binary should rapidly decay into a central protosun, leaving behind a low mass nebula.

Contrary to model A, model B did not reach centrifugal equilibrium, in part because of its much different initial J/M distribution. Model A starts off with its angular momentum problem already solved: its mass is largely in the protosun, and its angular momentum is in the nebula. Model B, however, has its mass in the nebula along with the angular momentum, and must undergo considerably more evolution before settling into equilibrium (such as the binary decay noted above). Gravitational torques appear to be quite adequate to account for this nebula evolution (*10, 11*). Model B illustrates clearly that strong nonaxisymmetry can arise in the early solar nebula; how robust and long-lived this nonaxisymmetry is remains to be seen. Possible means for exciting nonaxisymmetry include rotational

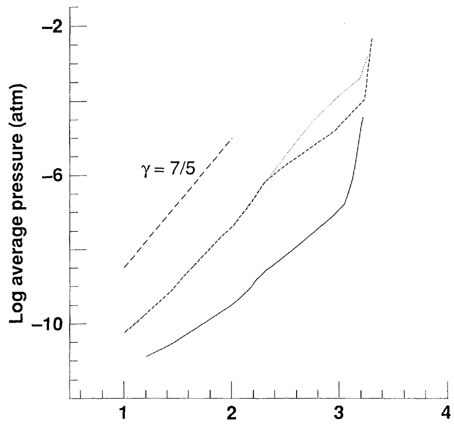

Fig. 3. Dependence of the azimuthally averaged pressure on the azimuthally averaged temperature for models A (solid line) and B (dotted line). Also shown for model B (short-dashed line) is the profile along the maximum density region of the bar in Fig. 2. At high temperatures, all three profiles converge. The long-dashed line is an arbitrary adiabat for a gas with $P \propto \rho^{7/5}$, where P is pressure and ρ is the density. This adiabat is appropriate for a cloud composed primarily of molecular hydrogen.

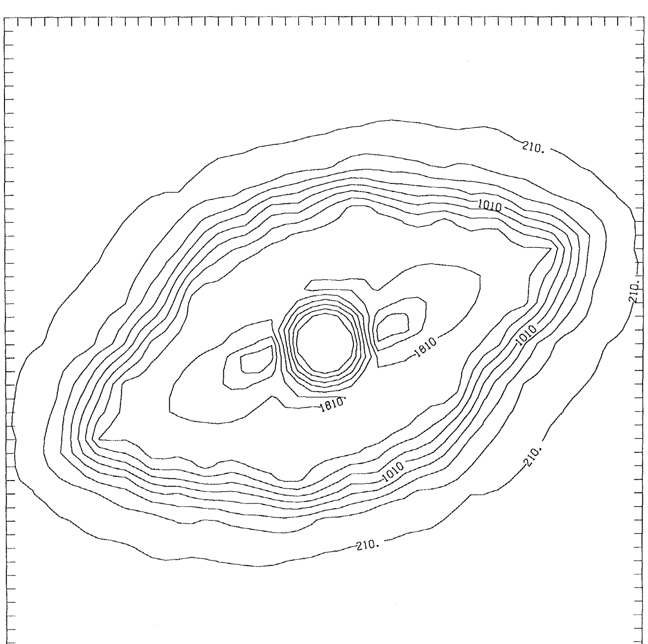

Fig. 2. Temperature contours in the midplane of model B. The rotational axis falls in the center of the plot. A region 8 AU in diameter is shown. Each temperature contour corresponds to a change in temperature by 200 K; several contours are labeled with temperatures in kelvins. At a given heliocentric radius, for example, 2.5 AU, the temperature varies from ≈1700 K to ≈200 K in azimuth. As in Fig. 1, the central decrease in temperature is a numerical artifice.

instability of a flattened disk, and nonlinear coupling with the large infall velocities associated with the accretion of the residual interstellar cloud.

Figure 3 shows the dependence of the pressure on the temperature in models A and B, compared to an arbitrary adiabat for a nebula composed of molecular hydrogen. The matter in model B is generally colder than that in A at a given pressure, because of the absence of the initial 1.000 $M_{\odot}$ protosun. The bar in model B is clearly hotter than the azimuthal average. Both models converge at high temperatures (late times), because at temperatures above $\approx$1500 K the dust opacity vanishes, molecular and atomic opacities are factors of $\sim$100 lower than dust opacities, and the nebula midplane becomes less optically thick locally, which acts as a thermostat on the midplane temperature.

These models have shown that compressional heating of infalling nebula gas may be sufficient to produce temperatures on the order of 1500 K in the inner solar nebula. Temperatures this high are intriguing, in light of meteoritical evidence for temperatures of 1500 K to 2000 K in the inner solar nebula. Peak temperatures of 1700 K are needed to melt Type B CAIs (*18*), and peak temperatures of 1700 K to 1900 K are required to melt chondrules (*4*). The evidence for rapid cooling of chondrules and Type B CAIs (time scales on the order of hours to days) may be difficult to reconcile with a globally hot inner solar nebula (*4*). However, because temperatures decrease quickly away from the midplane (falling to $\sim$600 K within 0.1 AU above or below the midplane), particles transported by convection to the nebula photosphere might be rapidly cooled (*19*). Also, the extra degree of freedom in a strongly nonaxisymmetric solar nebula may allow even more flexibility in scenarios for understanding meteorite formation. For example, if solid bodies in the nebula move relative to the gas at $\sim 10^4$ cm s^{-1} (*20*), and thus move relative to the nonaxisymmetric temperature distribution, it would be possible for particles to pass in or out of high temperature regions within a few hours if shocks of spatial extent no more than 1000 km exist. The present solar nebula models are quite incapable of resolving shock structure on such a small scale; deciding whether or not this scenario is possible must await future work.

REFERENCES AND NOTES

1. A. G. W. Cameron, *Icarus* **1**, 13 (1962).
2. H. C. Lord III, *ibid.* **4**, 279 (1965); J. W. Larimer, *Geochim. Cosmochim. Acta* **31**, 1215 (1967); L. Grossman, *ibid.* **36**, 597 (1972).
3. U. B. Marvin, J. A. Wood, J. S. Dickey, Jr., *Earth Planet. Sci. Lett.* **7**, 346 (1970).
4. R. H. Hewins, in *Chondrules and Their Origin*, E. A. King, Ed. (Lunar and Planetary Institute, Houston, 1983), pp. 122–133.
5. R. B. Larson, *Mon. Not. R. Astron. Soc.* **145**, 271 (1969).
6. A. G. W. Cameron and M. R. Pine, *Icarus* **18**, 377 (1973).
7. A. G. W. Cameron, *Moon Planets* **18**, 5 (1978); G. E. Morfill, in *Birth and Infancy of Stars*, R. Lucas, A. Omont, Eds. (North-Holland, Amsterdam, 1985), pp. 693–794; D. N. C. Lin and J. Papaloizou, in *Protostars and Planets II*, D. C. Black, M. S. Matthews, Eds. (Univ. of Arizona, Tucson, 1985), pp. 981–1072; A. G. W. Cameron, in *ibid.*, pp. 1073–1099.
8. W. Cabot *et al.*, *Icarus* **69**, 423 (1987).
9. J. A. Wood, *Earth Planet. Sci. Lett.* **70**, 11 (1984); J. A. Wood, *Lunar Planet. Sci. Conf.* **XVII**, 956 (1986).
10. R. B. Larson, *Mon. Not. R. Astron. Soc.* **206**, 197 (1984); A. P. Boss, *ibid.* **209**, 543 (1984).
11. A. P. Boss, *Lunar Planet. Sci. Conf.* **XIX**, 122 (1988).
12. ——, *Astrophys. J.* **236**, 619 (1980); *ibid.* **277**, 768 (1984).
13. J. B. Pollack, C. P. McKay, B. M. Christofferson, *Icarus* **64**, 471 (1985).
14. V. S. Safronov, *Evolution of the Protoplanetary Cloud and Formation of the Earth and Planets* (Nauka, Moscow, 1969) (translation NASA TTF-677, 1972).
15. J. S. Lewis, *Science* **186**, 440 (1974).
16. A. P. Boss, G. E. Morfill, W. M. Tscharnuter, in *Planetary and Satellite Atmospheres: Origin and Evolution*, J. B. Pollack and S. K. Atreya, Eds. (Univ. of Arizona, Tucson, in press).
17. A. P. Boss, *Astrophys. J. Suppl.* **62**, 519 (1986).
18. E. Stolper and J. M. Paque, *Geochim. Cosmochim. Acta* **50**, 1785 (1986).
19. A. G. W. Cameron and M. B. Fegley, *Icarus* **52**, 1 (1982).
20. S. J. Weidenschilling, *Mon. Not. R. Astron. Soc.* **180**, 57 (1977).

21. I thank R. W. Carlson, D. D. Clayton, M. B. Fegley, L. Grossman, R. O. Pepin, F. Tera, J. T. Wasson, S. J. Weidenschilling, G. W. Wetherill, and J. A. Wood for encouraging discussions, J. A. Wood and G. E. Morfill for an instructive preprint, and A. G. W. Cameron and M. B. Fegley for comments on the manuscript. The calculations were performed on the Numerix NMX-432 array processor of the Carnegie Institution of Washington. Supported by the Innovative Research Program and the Planetary Geology and Geophysics Program of the National Aeronautics and Space Administration.

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A Tsunami Deposit at the Cretaceous-Tertiary Boundary in Texas

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At sites near the Brazos River, Texas, an iridium anomaly and the paleontologic Cretaceous-Tertiary boundary directly overlie a sandstone bed in which coarse-grained sandstone with large clasts of mudstone and reworked carbonate nodules grades upward to wave ripple–laminated, very fine grained sandstone. This bed is the only sandstone bed in a sequence of uppermost Cretaceous to lowermost Paleocene mudstone that records about 1 million years of quiet water deposition in midshelf to outer shelf depths. Conditions for depositing such a sandstone layer at these depths are most consistent with the occurrence of a tsunami about 50 to 100 meters high. The most likely source for such a tsunami at the Cretaceous-Tertiary boundary is a bolide-water impact.

THERE IS CONSIDERABLE EVIDENCE for terrestrial impact by bolides throughout the Phanerozoic, including evidence for at least one at the Cretaceous-Tertiary (K-T) boundary [for counterarguments and references see (*1*)]. If the locations of such impacts were random, three to four tsunami-generating impacts in water should occur for every impact on land. Diagnostic evidence for these tsunamis is most likely to be preserved in strata deposited on the continental margin. Conformable sections of Upper Cretaceous to Paleocene continental-margin deposits around the Gulf of Mexico and in the western Atlantic contain coarse-grained beds at or close to the K-T boundary, and some unconformable sections contain breccias at the boundary (*2–13*, Fig. 1). We suggest that these coarse-grained beds may be tsunami deposits (*14*).

Some of these occurrences (Fig. 1) have been attributed to the effects of a latest Cretaceous sea-level excursion (*6–8, 15*). Estimates for the magnitude of sea-level change near the K-T boundary range from negligible (*3, 16*) to more than 100 m (*5, 17, 18*); the age assigned to the postulated maximum low stand varies by several million years, from Late Cretaceous to early Paleocene (*8, 17, 19*). Many workers have suggested that sea level was high at the K-T boundary (*2, 3, 18, 20*), whereas others have suggested that a low stand coincided with the boundary (*21*).

We studied an unusual sandstone bed in midshelf to outer shelf mudstone at five

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