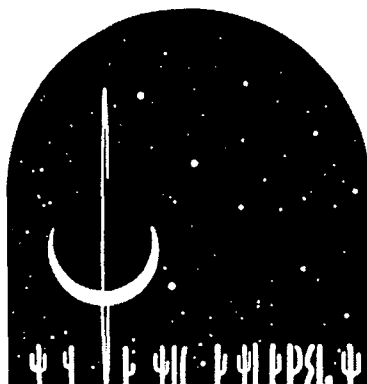**Planetary Science Institute**

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July 29, 2005

Dr. David Lindstrom
Solar System Exploration Division
Code SE
NASA Headquarters
Washington, D. C. 20046

Re: Origins of Solar Systems Program Final Report

Dear Dr. Lindstrom:

This letter and the enclosed attachments constitute the final administrative report for the research program entitled "Fractionation and Accretion of Meteorite Parent Bodies," Grant Number NAG5-11965, on which I was the Principal Investigator. This report covers the period 1 May 2002 - 30 April 2005. During this time, this research program resulted in the following publications:

Particle-gas dynamics and primary accretion. J. N. Cuzzi and S. J. Weidenschilling. To appear in Meteorites and the Early Solar System II (D. Lauretta et al., Eds.), Univ. Arizona Press, 2005.

Timescales of the solar protoplanetary disk. S. Russell, L. Hartmann, J. N. Cuzzi, A. Krot, M. Gounelle and S. J. Weidenschilling. To appear in Meteorites and the Early Solar System II (D. Lauretta et al., Eds.), Univ. Arizona Press, 2005.

Nebula evolution of thermally processed solids: Reconciling astrophysical models and chondritic meteorites. J. N. Cuzzi, F. J. Ciesla, M. I. Petaev, A. N. Krot, E. R. D. Scott and S. J. Weidenschilling. To appear in Chondrites and the Protoplanetary Disk (A. Krot et al., Eds.), ASP Conference Series, 2005.

Possible chondrule formation in planetesimal bow shocks: Physical processes in the near vicinity of the planetesimal. L. L. Hood, F. J. Ciesla and S. J. Weidenschilling. To appear in Chondrites and the Protoplanetary Disk (A. Krot et al., Eds.), ASP Conference Series, 2005.
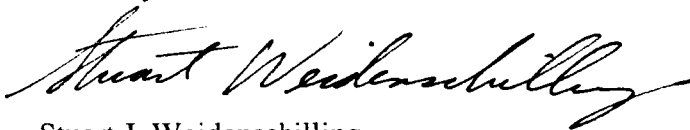
From icy grains to comets. In Comets II (M. Festou et al., Eds.), Univ. Arizona Press, pp. 97-104, 2005.

Evaluating planetesimal bow shocks as sites for chondrule formation. F. J. Ciesla, L. L. Hood and S. J. Weidenschilling. Meteoritics & Planetary Science 39, 1809-1821, 2004.

Radial drift of particles in the solar nebula: Implications for planetesimal formation. Icarus 165, 438-442, 2003.

Abstracts of these publications are enclosed. I hope that this will satisfy the reporting requirements. Please feel free to contact me if you require any additional information.

Sincerely,

Stuart J. Weidenschilling
Senior Scientist

Enclosures

Particle-Gas Dynamics and Primary Accretion

Jeffrey N. Cuzzi; Ames Research Center
Stuart J. Weidenschilling; Planetary Science Institute

A chapter for "Meteorites and the Early Solar System - II"
in press; June 13 2005

Final version
6/14/05

Summary

We review the basic physics of particle-gas interactions, and describe the various nebula epochs and regimes where these interactions are important. The potential role of turbulence is of special interest in a number of ways. Processes discussed include growth by sticking and incremental accretion, enhancement of abundance due to radial drift across evaporation boundaries, outward transport of small particles by diffusion and stellar winds, various midplane instabilities, and size-selective aerodynamic concentration of chondrule-sized particles. We provide examples of the structure and/or composition of primitive meteorites where these processes might have played a defining role, or where their signatures might be diagnostic.

Timescales of the Solar Protoplanetary Disk

Sara S. Russell

The Natural History Museum

Lee Hartmann

Harvard-Smithsonian Center for Astrophysics

Jeff Cuzzi

NASA Ames Research Center

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Hawai'i Institute of Geophysics and Planetology

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We summarize geochemical, astronomical, and theoretical constraints on the lifetime of the protoplanetary disk. Absolute Pb-Pb isotope dating of CAIs in CV chondrites (4567.2 ± 0.7 Myr) and chondrules in CV (4566.7 ± 1 Myr), CR (4564.7 ± 0.6 Myr), and CB (4562.7 ± 0.5 Myr) chondrites, and relative Al-Mg chronology of CAIs and chondrules in primitive chondrites suggest that high temperature nebular processes, such as CAI and chondrule formation, lasted for about 3-5 Myr. Astronomical observations of the disks of low-mass, pre-main sequence stars suggest that disk lifetimes are about 3-5 Myr; there are only few young stellar objects that survive with strong dust emission and gas accretion to ages of 10 Myr. These constraints are generally consistent with dynamical modeling of solid particles in the protoplanetary disk, if rapid accretion of solids into bodies large enough to resist orbital decay and turbulent diffusion are taken into account.

Nebula Evolution of Thermally Processed Solids: Reconciling Models and Meteorites

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We relate current protoplanetary nebula process models to the observed properties of chondrites and their individual constituents. Important nebula properties and processes that affect the evolution of small solid particles include the nebula temperature and pressure, the generally inward radial drift of particles under gas drag, and nebula gas turbulence. We review these nebula properties and describe how they affect particle evolution, emphasizing the primary accretion stage whereby the first primitive meteorite parent bodies are accumulated. We then turn to chondrite properties and discuss how they constrain the models. We treat physical properties (chondrule and refractory inclusion size distributions, fine-grained and coarse-grained accretionary rims, coarse-grained igneous rims), chemical and mineralogical properties (Wark-Lovering rims, redox state, and elemental fractionations), and isotopic compositions (primarily oxygen). We note how currently inferred accretion and melting ages of asteroidal bodies seem to imply that primary accretion of existing 100-km-sized objects was delayed by 1 Myr or more relative to Ca,Al-rich inclusions, and sketch scenarios for primary accretion in a temporally evolving protoplanetary nebula which allows for this hiatus. We advance a new perspective on explaining non-equilibrium mineralogy in terms of evolutionary timescales for small particles across nebula radial thermal gradients, which should be testable using meteoritical data, and present a specific application to Wark-Lovering rims.

1. Introduction

Understanding any geological formation requires understanding context, and meteorites are no exception. Context leads to insights into current puzzles, and to testable hypotheses. It is widely accepted that meteorite parent bodies formed in the protoplanetary nebula, at least tens

1

Possible Chondrule Formation in Planetesimal Bow Shocks: Physical Processes in the Near Vicinity of the Planetesimal

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Abstract. Planetesimal bow shocks would have existed during the chondrule formation epoch if proto-Jupiter formed within a few Myr of CAI formation and if the protoplanetary nebula persisted for a few Myr afterwards. As planetesimal orbits evolved inward under the influence of gas drag, they would have passed through Jovian resonances that temporarily increased eccentricities leading to supersonic velocities relative to the nebular gas. Previous studies have demonstrated that chondrule precursors passing through such shocks would have been heated to melting temperatures. Passage through more than one bow shock would have resulted in repetitive heating events. Outside of ~ 1 planetesimal radius from the symmetry axis, passage of formed chondrules through bow shocks with scale sizes < 1000 km would have led to cooling rates that are too rapid to be consistent with experimental constraints on chondrule formation. Inside of this distance, formed chondrules with aerodynamically suitable sizes would have been decelerated to low velocities, effectively accreting to the planetesimal. This would likely have led to reduced cooling rates and increased solids-to-gas mass ratios even for relatively small few km radius planetesimals. A near-surface boundary layer of denser gas may also have been present, further decelerating incident particles. If asteroid 6 Hebe is the parent body of the H chondrites (mean diameter 200 km; mean chondrule size ~ 0.3 mm), then numerical simulations and analytic calculations indicate that formation of these chondrules in a strong planetesimal bow shock would have resulted in accretion if the ambient nebula mass density was ~ 4×10^{-9} gm/cm³. An approximate calculation of the efficiency of planetesimal bow shocks in producing the large number of chondrules observed in some chondrites indicates that, within observational uncertainties, the bow shock mechanism can not easily be excluded as a possible chondrule formation model.

1. Introduction

Currently, gas dynamic shock waves in a low-temperature (< 650 K) nebula are considered to be a leading candidate mechanism for providing the repetitive, short-duration heating events that are believed to have been responsible for the formation of chondrules in chondrites (for reviews, see, e.g., Boss 1996; Hood and Kring 1996; Jones et al. 2000). It can be shown, for example, that shocks in such a low-temperature nebula with sonic Mach numbers greater than 4 or 5 (corresponding to shock velocities greater than 7 km s⁻¹) would be capable of thermally processing and melting 0.1-1 mm sized precursor aggregates as required by meteoritic data (Hood and Horanyi 1991; 1993; Iida et al. 2001; Desch and

From Icy Grains to Comets

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Comets formed from icy grains in the outer region of the solar nebula. Their coagulation into macroscopic bodies was driven by differential motions induced by nebular gas drag. The hierarchical growth by collisions produced "rubble pile" structures with sizes up to ~100 km on timescales on the order of 1 m.y. Two-dimensional models of this growth, including orbital decay due to drag, show radial mixing that lessens the tendency seen in one-dimensional models for components of a single characteristic size. Radial migration causes redistribution of condensed matter in the outer nebula, and produces a sharp outer edge to the Kuiper belt.

1. INTRODUCTION

Cometary nuclei are planetesimals that formed in the outer reaches of the solar nebula. Presumably, they were produced by the same process that formed planetesimals in the region of the terrestrial planets and the asteroid belt, but incorporated volatiles (notably water ice) that were in solid form in the cold outer nebula. While comets may not be pristine, they are probably the least-altered objects surviving from the origin of the solar system. While much can be learned about their formation from their chemistry, they may also provide a unique record of the physical processes involved in their accretion. The material now present in any comet originally existed in the solar nebula as microscopic grains, probably a mixture of surviving interstellar grains and nebular condensates. Somehow, these submicrometer-sized particles were assembled into bodies of sizes at least tens to hundreds of kilometers. It is clear that comets are not uniform aggregates of grains, but have structure on larger scales. They display complex behavior that varies both temporally and spatially (outbursts and jetting), and implies inhomogeneities on scales of tens to hundreds of meters (*Mumma et al.*, 1993; *Weissman et al.*, 2004). On the other hand, imaging of the nuclei of Comets Halley and Borrelly at comparable resolution did not reveal obvious larger structural units; although both bodies were irregular in shape, they did not appear to be lumpy on kilometer scales. Comets are structurally weak, as demonstrated by shedding of fragments, occasional splitting, tidal disruption of Shoemaker-Levy 9 during its encounter with Jupiter (*Asphaug and Benz*, 1996), and the spontaneous disruption of Comet LINEAR (*Weaver et al.*, 2001). The observed properties of nuclei are consistent with "rubble pile" structures with components ~100 m in size that are very weakly bonded, or perhaps held together only by gravity. These properties are the expected result of formation by accretion in the solar nebula.

2. PARTICLE MOTIONS IN THE SOLAR NEBULA

The motions of solid particles in the solar nebula are dominated by drag forces due to gas; this is true even in the outermost region, where the density is low, and solids are relatively more abundant due to condensation of volatiles at low temperatures. The radial pressure gradient partially supports the gas against the Sun's gravity, causing it to rotate at slightly less than the local Kepler velocity (*Whipple*, 1972). The fractional deviation from Keplerian rotation is approximately the ratio of the thermal energy of the gas to its orbital kinetic energy. One can show that ΔV, the difference between the gas velocity and Kepler velocity V_k, is proportional to the temperature T and the square root of the heliocentric distance R (*Weidenschilling*, 1977). A typical magnitude for ΔV is ~50 m s^{-1} for plausible nebular models. As T decreases with R, ΔV does not vary strongly; for a plausible temperature gradient of T $\propto$ R$^{-1/2}$, ΔV is independent of R. Thus, the deviation from Keplerian motion is larger in proportion to the orbital velocity at larger heliocentric distances. Typically, $\Delta V/V_k$ is a few times 10^{-3} in the region of the terrestrial planets, but can exceed 10^{-2} beyond Neptune's distance.

Solid particles are not supported by pressure forces. As a consequence, no particle can be at rest with respect to the gas, but always has some components of radial and transverse velocity. Their magnitudes depend on the particle size (more precisely, area/mass ratio) and drag law (*Adachi et al.*, 1976; *Weidenschilling*, 1977). A small particle moves with the angular velocity of the gas (negligible transverse component), but drifts radially inward at a rate that increases with size. A large body pursues a Kepler orbit, experiencing a transverse "headwind" that causes its orbit to decay; the rate of decay decreases with size. The peak radial velocity, equal to ΔV, occurs at the transition between these regimes. The size at which this peak velocity is reached
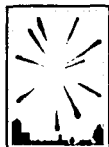
Evaluating planetesimal bow shocks as sites for chondrule formation

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Abstract–We investigate the possible formation of chondrules by planetesimal bow shocks. The formation of such shocks is modeled using a piecewise parabolic method (PPM) code under a variety of conditions. The results of this modeling are used as a guide to study chondrule formation in a one-dimensional, finite shock wave. This model considers a mixture of chondrule-sized particles and micron-sized dust and models the kinetic vaporization of the solids. We found that only planetesimals with a radius of ~1000 km and moving at least ~8 km/s with respect to the nebular gas can generate shocks that would allow chondrule-sized particles to have peak temperatures and cooling rates that are generally consistent with what has been inferred for chondrules. Planetesimals with smaller radii tend to produce lower peak temperatures and cooling rates that are too high. However, the peak temperatures of chondrules are only matched for low values of chondrule wavelength-averaged emissivity. Very slow cooling (<~100s of K/hr) can only be achieved if the nebular opacity is low, which may result after a significant amount of material has been accreted into objects that are chondrule-sized or larger, or if chondrules formed in regions of the nebula with small dust concentrations. Large shock waves of approximately the same scale as those formed by gravitational instabilities or tidal interactions between the nebula and a young Jupiter do not require this to match the inferred thermal histories of chondrules.

INTRODUCTION

Chondrules are millimeter-sized, silicate spheres that are abundant in most chondritic meteorites. The textures of these objects suggest that they formed before being incorporated into their respective meteorite parent bodies (for a detailed review of our current understanding of chondrules and their formation, see Jones et al. [2000]). The exact method by which these chondrule melts were formed and kept warm as crystals grew has not yet been identified.

Recently, shock waves within the solar nebula have been shown to be capable of explaining the complex thermal histories that have been inferred for chondrules and possibly allow for the formation of other meteoritic components (Iida et al. 2001; Desch and Connolly 2002; Ciesla and Hood 2002; Ciesla et al. 2003). While such work supports the hypothesis that shock waves were the dominant chondrule forming mechanism in the solar nebula, the source of the shocks still remains to be determined. In the studies mentioned above, large scale shock waves (>10^5 km) were modeled, suggesting that shocks due to gravitational instabilities (Boss 2002) or tidal interactions of Jupiter with

the nebula (Bryden et al. 1999; Rafikov 2002) may have been where chondrules formed. Other possible sources are planetesimals, the orbits of which caused them to attain supersonic velocities with respect to the nebular gas (Hood 1998; Weidenschilling et al. 1998). Such velocities could be attained if the planetesimals were in highly eccentric or inclined orbits around the Sun.

While the existence of planetesimals before the formation of the very primitive chondrules (and thus the chondrite parent bodies) seems paradoxical, it may have been possible given the inferred extended lifetime of the nebula before chondrule formation. Amelin et al. (2002) used Pb-Pb dating to show that chondrules formed 2.5 ± 1.2 Myr after the formation of calcium-aluminum-rich inclusions (CAIs), the first objects to have formed in the solar nebula. This time is much longer than the expected time needed to accrete large bodies in a laminar solar nebula (~10^4 yr), and possibly long enough to accrete these same bodies in a weakly turbulent nebula (Weidenschilling 1988; Weidenschilling and Cuzzi 1993). In fact, it is possible that this age of chondrules overlapped the global differentiation of the parent body of the HED meteorites, thought to be the 500 km-diameter asteroid

ICARUS

Radial drift of particles in the solar nebula: implications for planetesimal formation

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Received 7 March 2003; revised 21 May 2003

Abstract

For standard cosmic abundances of heavy elements, a layer of small particles in the central plane of the solar nebula cannot attain the critical density for gravitational instability. Youdin and Shu (2002, Astrophys. J. 580, 494–505) suggest that the local surface density of solids can be enhanced by radial migration of particles due to gas drag. However, they consider only motions of individual particles. Collective motion due to turbulent stress on the particle layer acts to inhibit such enhancement and may prevent gravitational instability.
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Keywords: Planetesimals; Solar nebula

1. Introduction

Two principal mechanisms have been suggested for the formation of planetesimals in the solar nebula: gravitational instability and collisional coagulation. In the "classical" model for gravitational instability (Safronov, 1969; Goldreich and Ward, 1973), particles settle to the central plane of the nebula, forming a dense layer. When its density reaches a critical value it becomes unstable with respect to density perturbations, and spontaneously breaks up into self-gravitating condensations that collapse into solid bodies of a characteristic size. This scenario is attractive, as it does not depend on any sticking mechanism or mechanical properties of the particles. However, it has one serious problem. The nebular gas is supported by a radial pressure gradient, and rotates at slightly less than the local Kepler velocity. Particles lack this support, and a dense layer tends to rotate faster than the gas. The resulting shear produces turbulence that inhibits settling, and prevents the layer from attaining the critical density (Weidenschilling, 1995). This phenomenon argues in favor of particle growth by collisions due to motions produced by turbulence and differential drift induced by gas drag.

Youdin and Shu (2002; hereafter YS02) have shown that the particle layer can attain the critical density for instabil-

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ity if its surface density is enhanced relative to the gas by a factor of 2–10 over normal solar abundance. They suggest that this could be accomplished by radial drift of particles due to gas drag. In their model, chondrule-sized particles migrate from the outer part of the nebula and are concentrated in the inner region on timescales of 10^6–10^7 years. However, they considered only the drift behavior of individual particles. The purpose of the present paper is to consider collective effects of gas drag on an ensemble of particles. It will be shown that while radial migration may redistribute solid matter in the solar nebula, collective effects may produce outcomes that are quite different from those inferred from motions of individual particles.

2. Nebular structure and drift rates

For a nebula with a radial pressure gradient, the velocity of the gas V_g deviates from the Kepler velocity V_k such that

$$V_g = (1 - \eta)V_k, \qquad (1)$$

where

$$\eta = \frac{-dP/dr}{2\rho_g \Omega^2 r} \qquad (2)$$

and P, ρ_g are the gas pressure and density, r is the heliocentric distance, and Ω is the local Kepler frequency (Adachi et al., 1976). Equation (1) is valid when the particle mass loading is negligible compared with the gas density. When the