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Dr. R. Stephen Saunders
NASA Headquarters
Solar System Exploration Division
Code SE
Washington DC 20046

Dear Dr. Saunders:

As requested, I am submitting this letter and the enclosed attachments as a final administrative report for the research program entitled "Aerodynamic and Gasdynamic Effects in Cosmogony," Grant Number NAG5-13156, on which I was Principal Investigator. This report covers the period April 1, 2003 - March 31, 2005. During this time, this research program produced the following publications:

Particle-gas dynamics and primary accretion. J. N. Cuzzi and S. J. Weidenschilling. In Meteorites and the Early Solar System II (D. Lauretta and H. Y. McSween, Eds.), Univ. Arizona Press, in press, 2005.

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

From icy grains to comets. In Comets II (M. Festou et al., Eds.), Univ. Arizona Press, pp. 97-104, 2004.

Gravitational instability and clustering in a disk of planetesimals. P. Tanga, S. J. Weidenschilling, P. Michel and D. C. Richardson. Astron. Astrophys. 427, 1105-1115, 2004.

Abstracts of these publications are attached. Please feel free to contact me if you require any additional information.

Sincerely,

S. J. Weidenschilling
Senior Scientist

pc: Ms. Renee Luna (ONR); no attachments
Ms. Stephanie Jackson (GSFC); no attachments

From Icy Grains to Comets

S. J. Weidenschilling
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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 of order 1 Myr. Two-dimensional models of this growth, including orbital decay due to drag, show radial mixing that lessens the tendency seen in 1-D 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 sub-micrometer-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 with sizes ~ 100 m 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;

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(DOI: will be inserted by hand later)

Gravitational instability and clustering in a disk of planetesimals

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Abstract. For a long time, the gravitational instability in the sub-disk of planetesimals has been suspected to be the main engine responsible for the beginning of dust growth, its advantage being a rapid growth. Its real importance in planetary formation is still debated, mainly because the potential presence of turbulence can prevent the settling of particles into a gravitationnally unstable layer. However, several mechanisms could yield strongly inhomogeneous distributions of solids in the disk: radial drift, trapping in vortices, perturbations by other massive bodies, etc. In this paper we present a numerical study of a gravitationally unstable layer. This allows us to go beyond the classical analytical study of linear perturbations, exploring a highly non-linear regime. A hierarchical growth of structure in presence of dissipation (gas drag) can yield large, virialized clusters of planetesimals, that are observed for the first time in the context of planetesimal disks.

Key words. Planetary systems: formation, protoplanetary disks; gravitation

1. Introduction

The planetesimal growth – from dust to planetary sizes – is a complex process containing several obscure details. In particular, time scales, dust–gas interactions and collective effects are matters of intense research.

Several years ago, K.E. Edgeworth, better known for having postulated the existence of a huge reservoir of quiescent cometary nuclei beyond Neptune's orbit, already offered some interesting speculations about the fact that planetesimal growth could be an highly non-homogeneous process. More precisely, he qualitatively inferred that self-gravitating clusters of solid bodies could form (Edgeworth, 1949). In order for this scenario to be possible, some regions of the disk of planetesimals have to overcome both the tidal distortion due to the central star and the "internal heat" associated to their velocity dispersion. Those formed clusters could have coalesced in larger and larger structures before giving birth to more dense regions where the planets eventually formed.

A first mathematical analysis of this qualitative picture was established later (Safronov, 1969, Goldreich and Ward, 1973), suggesting that self-gravitating regions could become gravitationally unstable. The collapse of clusters of planetesimals could have been responsible for the rapid formation of large planetesimals. Nevertheless, as we will further clarify, in order to be effective the velocity dispersion of the unstable layer has to remain very low. Conversely, several mechanisms can induce the "heating" of the disk of planetesimals. Most notably, during the first phases of evolution, when the gas-dust coupling plays an important role, the gas flow can strongly influence the behavior of solids. For example, **a laminar nebula having a slightly sub-keplerian profile (due to the presence of the radial component of pressure) could induce a size–dependent radial velocity dispersion high enough to prevent the instability onset, at least until the bodies grow large enough for the drag-induced radial velocity dispersion to be sufficienty reduced (see e.g. Weidenschilling 1995).**

In presence of any kind of turbulent motion, whose existence is generally accepted as an unavoidable source of viscosity in accretion disks, the situation could even be more unfavorable. The sedimentation itself of a dense layer of planetesimals in the disk midplane could be responsible for the creation of turbulence, given the strong shear that can be generated between the layer of solids, moving at keplerian speed, and its sub-keplerian surroundings. However, the efficiency of this process is under debate (Youdin & Shu 2002, Weidenschilling 2003) and an enhancement of the dust/gas ratio of several times the Solar abundances could again favor the instability.

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Timescales of the Solar Protoplanetary Disk

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The Natural History Museum

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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 on 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 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.

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

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.