THE ASTROPHYSICAL JOURNAL, 529:L57–L60, 2000 January 20

AN EXPERIMENTAL STUDY ON THE STRUCTURE OF COSMIC DUST AGGREGATES AND THEIR ALIGNMENT BY MOTION RELATIVE TO GAS

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Received 1999 September 24; accepted 1999 November 19; published 1999 December 22

ABSTRACT

We experimentally studied the shape of dust grains grown in a cluster-cluster type of aggregation (CCA) and derived characteristic axial ratios to describe the nonsphericity. CCAs might be described by an axial ratio $\rho_{\mathrm{CCA}} = r_{g,\,\mathrm{max}}/r_{g,\,\mathrm{min}} \approx 2.0$ in the limit of large aggregates, where $r_{g,\,\mathrm{min}}$ and $r_{g,\,\mathrm{max}}$ describe the minimum and maximum radius of gyration, while small aggregates show a somewhat larger value in their mean axial ratio up to $\rho_{\mathrm{CCA}} \approx 3.0$ but rapidly decrease to the limit $\rho_{\mathrm{CCA}} \approx 2.0$. The axial ratios for large aggregates are in agreement with the general findings of different authors for axial ratios of interstellar dust grains that are generally described by rods or spheroids. Beyond this kind of agreement, our approach does not necessarily require a special shape for individual dust grains but rather offers a physical process to generate nonsphericity. Although the simple shapes might be sufficient for first-order applications and are easier to handle analytically, our results offer a firm ground of special axial ratios for rods or spheroids on a more physical basis apart from any ad hoc assumptions. We also find an alignment of the aggregates during sedimentation in a gas along the drift axis leading to an axial ratio of $\rho_{\mathrm{CCA,\,align}} = 1.21 \pm 0.02$ with respect to the drift axis and an axis perpendicular to this drift. This result is directly applicable to dust grains in protoplanetary disks and planetary atmospheres.

Subject headings: dust, extinction — methods: laboratory — solar system: formation

1. INTRODUCTION

Cosmic dust particles play a major role in a variety of quite different astrophysical scenarios, ranging from the seeding process of planetary formation to interstellar extinction and polarization. In any case, it is crucial to obtain a detailed understanding of how the dust particles interact with their ambient gaseous environment, with surrounding electromagnetic fields, and with other dust particles in mutual collisions. These interactions are not independent of each other and might vary considerably in special astrophysical environments, but certain aspects are most probably valid in a wide range of scenarios. Knowledge of the general features of dust aggregates might improve the analysis of astronomical data since it reduces the number of unknown parameters.

In this Letter, we will focus on (1) the internal structure of dust aggregates which we assume to have grown by coagulation and (2) the immediate implications of the noncompact particle morphology on grain asymmetry and on grain alignment. Until recently, the general basic assumption considering the morphology of dust particles was that the small solid grains had spherical shape. A sphere is the most simple shape and allows one to describe the interactions of the dust particle with its environment quite reasonably. Models offer a way to calculate light scattering (Mie theory) as well as a way to treat the frictional coupling between dust particles and the ambient gas in a direct and noncomplex way (Epstein drag law). While this simplifying assumption is a natural approach for describing solid particles that have formed by gas-phase condensation, it might be doubted for special environments such as R CrB stars, in which dust-envelope formation takes place and shows clear evidence for nonspherical particles (Efimov 1989), and it is certainly an oversimplification for grains that have aggregated while in molecular clouds (Ossenkopf 1993) or in circumstellar disks, e.g., in protoplanetary environments (Weidenschilling & Cuzzi 1993). In the latter case, the particle shape will have a significant influence on the relative motion between dust and gas and hence on the aggregation process that leads to the formation of planetesimals (Weidenschilling & Cuzzi 1993; Wurm & Blum 1998; Blum & Wurm 1999).

In order to explain the observed (interstellar) polarization by the application of different alignment mechanisms, spheroidal, rod-, or disk-shaped dust grains were postulated (Gold 1952; Davis & Greenstein 1951; Lazarian, Goodman & Myers 1997; Li & Greenberg 1997). For example, Li & Greenberg (1997) determine a length-to-diameter ratio of 2 for rod-shaped particles to fit the interstellar polarization curve. Other authors infer magnetic fields from polarization measurements by assuming spheroidal particle shapes and various alignment mechanisms (Lazarian et al. 1997; Roberge, Hanany, & Messinger 1995; Hildebrand & Dragovan 1995). In general, such assumptions can only serve as crude estimates of the interstellar extinction and polarization curves, since the particle morphologies will inevitably influence the optical properties of the dust grains (Henning & Stognienko 1993; Wolff, Clayton, & Gibson 1998; Fogel & Leung 1998). This might explain why models are sometimes hardly able to predict observed polarimetric data (Lazarian et al. 1997). There are only few approaches for basing the topic of grain alignment on experimental results; e.g., Chihara et al. (1998) studied the magnetic ordering of graphite grains in an ethanol suspension which, nevertheless, itself does not directly match astrophysical parameters concerning the underlying process of generating grain nonsphericity.

In this Letter, we will present experimental evidence that shows that, even when starting from spherical grains (but not necessarily), a cluster-cluster type of aggregation, which is supposed to be present in the interstellar medium as well as in protoplanetary disks, is a straightforward and natural way to generate "elongated" particles. The mean value of the ratio

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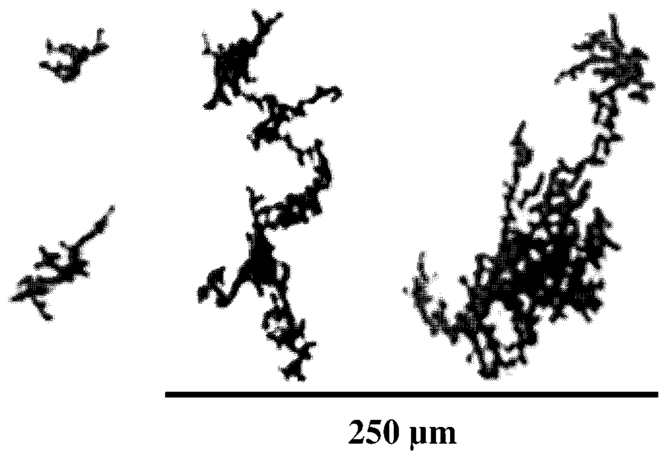

FIG. 1.—Sample images of the sedimentating aggregates

between maximum and minimum extension is, within the investigated size range, in perfect agreement with often-assumed axial ratios of rods and spheroids and converges to a single limiting value for large aggregates. We will further present results of alignment measurements of dust aggregates during sedimentation in a gas, which might be especially applicable to protoplanetary disks and planetary atmospheres (in which the gas-grain interaction dominates all other alignment sources) and might have a lasting effect on the polarization of electromagnetic radiation in such environments as well as on the collision cross sections and, thus, on the formation of larger dust grains.

2. EXPERIMENTAL APPROACH

In our laboratory experiments, we produced open-structured dust conglomerates by rapid aggregation in a turbulent, rarefied gas environment. We injected dust samples consisting of monodispersed, spherical SiO_2 grains of 0.95 μm radius into a pre-evacuated turbomolecular pump ($p < 0.1$ mbar) in which the dust sample is deagglomerated and homogeneously distributed within a small volume of gas of pressure $p = 1.7$ mbar (for details of the deagglomeration process, refer to Blum et al. 1996a). Due to a turbulent gas motion, dust grains collide frequently at moderate velocities ($\sim$0.1 m s^{-1}), stick to each other with a sticking probability of $\beta = 1$ (Wurm & Blum 1998), and thus form dust aggregates before they leave the volume of turbulent gas through a nozzle. This continuous extraction of dust aggregates at subsonic velocities allows further studies with these particles in an adjacent vacuum tube of $\sim$1 m length and $\sim$4 cm diameter. In this experiment partition, the dust aggregates sediment with constant velocity $v_s = g_0 \tau_f$, where g_0 and τ_f are the gravitational acceleration of the Earth and the dust aggregate's response time to the gas, respectively. In a free molecular flow, the latter is given by

$$\tau_f = \epsilon \frac{m}{\sigma_a} \frac{1}{\rho_{\rm gas} v_m} \qquad (1)$$

(Blum et al. 1996b), where m, σ_a, $\rho_{\rm gas}$, v_m, and $\epsilon \approx 0.6$ are the aggregate mass and aerodynamic cross section, the gas density, the mean molecular gas velocity, and an empiric factor for aggregates, respectively. For the gas and dust parameters in our experiment, the typical gas-grain friction time is $\tau_f = 1.5 \times 10^{-3}$ s. For an easier microscopical observation of the sedimenting dust aggregates, we move the whole experimental setup vertically upwards at a velocity v_s so that the sedimentation is compensated and the dust grains appear to be (almost) at rest with respect to the nonmoving long-distance microscope. A detailed description of the experimental apparatus can be found in Wurm & Blum (1998).

In a previous paper (Wurm & Blum 1998), we have shown that the turbulent aggregation process leads to fractal aggregate structures and can be modeled by Smoluchowski's equation, in which the sticking probability is unity (for the given collision velocities), relative velocities are basically only dependent on the aggregates' response times τ_f, and the collision cross sections can be formulated according to the analysis by Ossenkopf (1993).

To a good approximation, the turbulent aggregation in a rarefied gas environment can be treated as a ballistic cluster-cluster aggregation process (see, e.g., Meakin 1991) in which the mean mass of an aggregate m is related to its radius of gyration r by a power law $m \propto r^{D_f}$. Here, D_f and r are the fractal (mass) dimension and the radius of gyration which is defined by $r = (\sum_{i=1}^{N} d_i^2/N)^{1/2}$, with d_i being the three-dimensional distance of monomer i to the center of mass of the aggregate. In agreement with theoretical predictions, our experiments show $D_f \approx 1.9$ (Wurm & Blum 1998). While our earlier experiments (Wurm & Blum 1998; Blum & Wurm 1999) were intended to study the aggregation process and, therefore, aimed to determine mean values for D_f as well as to describe the temporal evolution of the aggregate mass distribution, the fractal aggregates from these experiments might also be analyzed concerning their morphological anisotropy, e.g., their maximum and minimum dimensions.

For this purpose, we determined the one-dimensional radius of gyration of fractal dust aggregates with respect to different axes rather than its mean value. We chose a sample of 245 aggregates from two aggregation experiments in which the gas pressure was set to 1.7 mbar. The dust aggregates were selected randomly under the condition that their microscopical images had to be well focused. Due to a limited focal depth of the long-distance microscopes of $\sim$80 μm, this condition limits the number of monomer grains in the aggregates to $N \leq 1000$. A selection of aggregates is shown in Figure 1.

We used the data reduction algorithm described in Wurm & Blum (1998) to binarize the digital microscopical images and to derive the number of visible monomers. With the projected positions of each visible monomer, we derived the one-dimensional radius of gyration with respect to an arbitrarily oriented reference axis through the center of gravity of the aggregate by

$$r_g = \sqrt{\frac{\sum_{i=1}^{N} \delta_i^2}{N}}, \qquad (2)$$

in which δ_i is the distance of monomer i to the reference axis. By rotation of the reference axis in steps of 1°, we determined a set of 360 one-dimensional radii of gyration for each aggregate in the sample. Since there are only four axes of interest, we restrict the discussion on the one-dimensional radius of gyration to those which were taken (1) in the direction of the gravitational vector $r_{g,v}$ and (2) in the direction perpendicular to the gravitational vector $r_{g,h}$, as well as (3) those which gave the maximum one-dimensional radii of gyration $r_{g,\max}$ and (4) those perpendicular to the latter axis, resulting in $r_{g,\min}$.

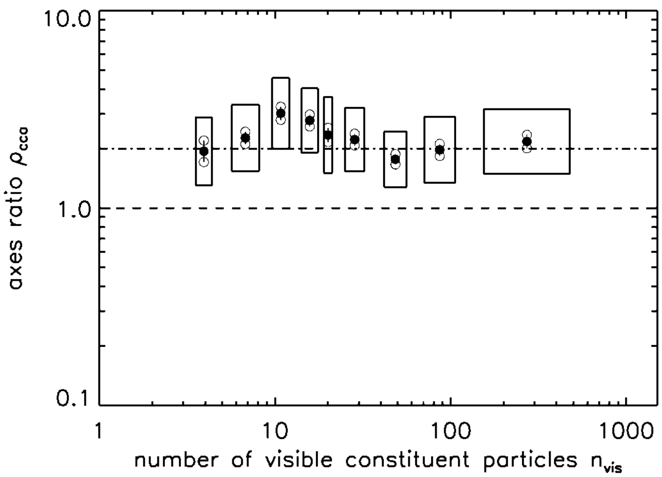

FIG. 2.—Ratios of the maximum to minimum radii of gyration ρ_{CCA} measured from the two-dimensional and binarized microscopical images plotted vs. the visible number of monomers in an aggregate. Each individual rectangular box represents the 1 σ range of data for 30 aggregates (with the exception of 11 and 24 aggregates for the first and last bin). The full circles denote the corresponding geometric mean values, and the open circles mark the 1 σ uncertainties of the mean axial ratios.

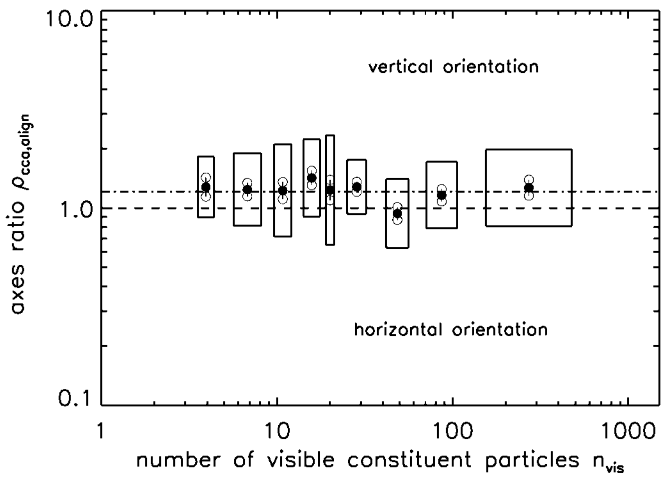

FIG. 3.—Same as Fig. 2, but with the ratios of vertical to horizontal radii of gyration $\rho_{CCA,\,align}$ plotted on the ordinate. A preferred alignment along the vertical axis is manifested by a mean value of $\rho_{CCA,\,align} = 1.21 \pm 0.02$.

3. RESULTS

Figure 2 shows the axial ratios $\rho_{CCA} = r_{g,\,max}/r_{g,\,min}$ (maximum to minimum radius of gyration) for the aggregate sample as a function of the number of visible monomers n_{vis}. Plotted are the geometric mean values averaged over 30 aggregates (with the exception of 11 and 24 binned aggregates for the first [smallest n_{vis}] and last [largest n_{vis}] bin, respectively). The value ρ_{CCA} starts at $\rho_{CCA} \approx 2.0$ and seems to reach the same value as a limit for larger aggregates. However, there is a significant increase in elongation for small clusters to a maximum value of $\rho_{CCA} \approx 3.0$. We regard this increase of ρ_{CCA} for small sizes and the rapid decrease to a limiting value for large aggregates as a manifestation of the fact that fractal growth and fractal dimension are only meaningful descriptions in the limit of large aggregates. Regardless of the fractal dimension of different processes, such as particle-cluster aggregation (PCA) or cluster-cluster aggregation (CCA) as extreme values, the initial structure of small aggregates will always be similar, i.e., if two single monomers collide and form a dimer, PCA and CCA are still meaningless characterizations. Therefore, both types of growth, which are expected to be present in molecular clouds (Ossenkopf 1993), should start with the same asymmetry ρ_{CCA}, while the limiting value of ρ_{CCA} might vary. Since our earlier analysis (Wurm & Blum 1998) of the experiment shows that aggregates grow predominantly by adhesion of similar size clusters (CCA), we conclude that, at least for this process, larger aggregates might be characterized by $\rho_{CCA} \approx 2.0$.

While ρ_{CCA} describes a general feature of the aggregates, there is a preferred axis in our experiments due to gravity and, therefore, due to sedimentation with respect to the gas. Thus, we define a second ratio of radii $\rho_{CCA,\,align} = r_{g,\,v}/r_{g,\,h}$, which describes the alignment of the particles with respect to their sedimentation. Figure 3 shows the same plot as Figure 2 but with the ratio $\rho_{CCA,\,align}$ plotted versus the visible monomer number n_{vis}. The values $\rho_{CCA,\,align} > 1$ indicate that particles are preferentially aligned along the direction of gravity and, hence, along the direction of the gas drag. A dependence on size (n_{vis}) is less obvious here and a single mean value for $\rho_{CCA,\,align} = 1.21 \pm 0.02$ might be given to describe the whole range of measured particle sizes.

4. DISCUSSION

In a recent attempt to build a unified model of interstellar dust, Li & Greenberg (1997) fitted the interstellar polarization by rod-shaped particles with an axial ratio of $\rho_{rod} \approx 2.0$ assuming total alignment. This is in agreement with our result that $\rho_{CCA} \approx 2.0$ for coagulated grains. Although this might be regarded as a first-order agreement, one should be aware that, although the general tendency should be the same, the exact extinction and polarization features might vary considerably due to the difference in shape between dust aggregates and rods/spheroids with similar axial ratios. Calculations of scattering features of aggregates are not as simple as for rods or spheroids, and further calculations with improving numerical capabilities as well as light-scattering measurements with fractal aggregates have to be carried out. It was argued by Akeson et al. (1996) that some decrease of the polarization toward denser regions of the young stellar object NGC 1333/IRAS 4A indicates that growth of aggregates might lead from a nonspherical dust grain to a spherical structure or that the increasing gas-grain collisions might randomize the orientation and overcome the alignment of the dust. The tendency for a decrease of the polarization toward denser regions is also supported by measurements of Hildebrand et al. (1995). Hildebrand & Dragovan (1995) gave limits for the axial ratios of assumed dust particles in interstellar clouds of $1.1 < \rho_{limit} < 3$, depending on the degree of alignment. Furthermore, Rao et al. (1998) interpret their polarimetric data from the dense hot core of Orion KL as the alignment of dust but admit difficulties in applying Davis-Greenstein alignment.

As we have shown, spherical grain growth (as one possible explanation for decreasing polarization) cannot be achieved by a cluster-cluster type of aggregation which we assume to be present for the moment. On the contrary, dust aggregation by this mechanism offers a rather natural way to generate elongated particles with mean axial ratios of $\rho_{CCA} \approx 2.0$ in the limit of large aggregates and somewhat larger for the smaller aggregates. Our experiments suggest that a thorough description of cosmic dust particles as fluffy aggregates might be superior to the picture of spheres and ellipsoids and might simplify the interpretation of astronomical observations, since it avoids some of the postulated unnecessary parameters. Concerning the evolution of dust in protoplanetary disks, the description of dust and dust growth by means of a fractal dimension has already become quite common (Ossenkopf 1993; Weidenschilling & Cuzzi 1993; Wurm & Blum 1998; Blum & Wurm 1999). We agree with Fogel & Leung (1998) that the cosmic view of dust might benefit from the description by fractal dimensions.

The alignment of dust particles due to a relative motion between the dust grains and the ambient gas is of significant importance if Brownian motion is not randomizing the grain orientation. This is the case if the rotation angle α_{τ_f} of an aggregate with mass m and radius of gyration r_g due to Brownian rotation during one gas-grain friction time τ_f is small, i.e., if

$$\alpha_{\tau_f} \approx \tau_f \sqrt{\frac{kT}{m r_g^2}} \ll 2\pi. \quad (3)$$

With respect to our experimental parameters, we find that the right-hand side of equation (3) is always satisfied. In protoplanetary disks, however, equation (3) is not fulfilled for all particle sizes. For a typical gas density of $\rho_{\rm gas} = 1.4 \times 10^{-6}$ kg m^{-3} and temperature $T = 280$ K at 1 AU from the central star (Hayashi, Nakazawa, & Nakagawa 1985), the condition in equation (3) is only valid for CCAs consisting of more than $N = 1000$ micron-sized particles. This means that an ensemble of large aggregates in protoplanetary disks that is aligned due to gas friction should emit polarized radiation. This should be measurable at millimeter wavelengths, where the dust disks are optically thin. Thus, modern interferometric techniques might be capable to track the particle motion by means of polarimetry.

Besides the influence on the polarization, the alignment of dust aggregates is of relevance for further grain growth, since it decreases the collision cross sections and influences the collision velocity due to different gas-grain coupling times for different axes. A perfect alignment of CCAs in the interstellar medium might be of significance, since the extreme collision cross sections of aligned elongated particles (2 : 1) might deviate by roughly a factor of 4, which implies similar deviations in the characteristic collision timescales. In the case of a gas drag–dominated collision regime, this might be compensated by larger/smaller velocities due to different gas-grain coupling times for the different axes so that the net effect on the growth timescale of aggregates might not be very different. This is especially true if the alignment by gas drag in protoplanetary disks is concerned, since it is far from perfect ($\rho_{\rm CCA,\,align} = 1.21$), which might result in an influence on the polarization but should have no significant effect on the growth process. However, this has to be studied in more detail because larger collision velocities have an effect on the sticking probability and, therefore, alignment might be significant in a velocity range between sticking and bouncing or on the threshold of particle restructuring (Blum & Wurm 1999).

The laboratory experiments were funded by the German Space Agency (DLR) as part of the CODAG program. J. B. and G. W. were supported by DLR grant 50 QV 9603 0.

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