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Jovian soot from cometary impacts?

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Abstract. It seems to be widely accepted that the dark spots on Jupiter caused by the impacting fragments of comet Shoemaker-Levy 9 are due to dust particles which have formed immediately after the impacts. However, the actual nature and origin of these grains is still uncertain. We propose that they may consist of amorphous carbon and have calculated the time-dependent formation and growth of such dust particles assuming an exponential pressure decrease in an adiabatic fireball. The resulting properties of the grains, e.g. their sizes, are consistent with observations. The question whether carbon or silicate grains will form depends critically on the chemical composition of the Jovian atmosphere. If a carbon-rich environment exists at the impact sites our model demonstrates that there is enough time to grow amorphous carbon grains in the fireballs rising immediately after the impacts.

Key words: comets: individual: Shoemaker-Levy 9 – planets and satellites: individual: Jupiter

1. Introduction

The collisions of the Shoemaker-Levy 9 fragments with Jupiter generated conspicous impact features ('dark spots' at visual and UV-wavelengths) in the jovian atmosphere (e.g. Hammel et al. 1995). Optical properties and the temporal evolution of the impact sites from days to a month are consistent with the formation and subsequent coagulation of sub-micron dust particles (e.g. West et al. 1995). We propose condensation of amorphous carbon dust (soot) in the rising fireballs as a process to provide such dust particles.

The cometary fragments enter the jovian atmosphere at approximately the escape speed (60 km s^{-1}). Such speeds are hypersonic (Mach-number $\sim$ 100 at the 1 bar-level) and result in strong shock-heating and compression of atmospheric- and impactor-material. For a strong shock sound speed increases proportional to the Mach-number, pressure proportional to its square. This estimate results in kbar-pressures and typical temperatures of a few 10^{4}K giving the subsequent fireball a hot start with molecules dissociated and partial ionisation. For a discussion of fireball initial conditions see e.g. Klumov et al. (1995) and Neukum et al. (1995). The high-pressure and -temperature mixture of jovian- and impactor-material expands and rises above Jupiter's cloud decks. Maximum heigth is reached 6-8 minutes after the impacts (Hammel et al. 1995). During the ascent the fireball cools rapidly presumably providing favorable conditions for grain condensation and growth.

Hasegawa et al. (1996) propose that the observed increase of near-IR fluxes several minutes after the impacts can be explained by the formation of dust grains. They find that the color temperature variation of the K impact is in agreement with an experimental nucleation curve of silicate grains. The formation of silicate grains by recondensation of cometary material has been considered e.g. by Field et al. (1995) or Hasegawa et al. (1995). A possible problem of this approach is whether the condensible material contained in the comet is sufficient to explain the observed grains (cf. Field et al. 1995 for estimates of the required sizes of the cometary fragments).

Drawing attention to the fact that a typical jovian-cometary mixture may be carbon-rich (cf. Niemann et al. 1996) in the astrophysical sense (with an abundance ratio of C/O larger than unity) we propose that the grains form by condensation of carbon originating from the jovian atmosphere. West et al. (1995) and Hasegawa et al. (1995) argue against carbon grains on the basis of the optical properties of graphite and the lack of corresponding features in the observational data. However, for the conditions in the plume we expect the formation of amorphous carbon grains rather than graphite – in analogy with the circumstellar dust shells of asymptotic giant branch stars where numerous observations confirm the existence of amorphous carbon grains but no graphite features are found at IR and UV wavelength region (cf. e.g. Duley 1995, Blanco et al. 1994 and references therein).

To investigate the dust condensation in the plume phase we assume a simple fireball evolution (similar to West et al. 1995) for plausible initial conditions. The growth of dust grains is treated by the so-called moment method (Gail & Sedlmayr 1988, Gauger et al. 1990) using classical nucleation theory to describe the formation of new grains. The physical assumptions

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entering the model are discussed in Sect. 2 and the modelling results are presented in Sect. 3. In summary, we want to work out what current dust formation theories predict for the condensation process in simple fireballs of jovian composition.

2. Physical background

2.1. A simple fireball model

To avoid a difficult discussion of fireball formation, we restrict ourselves to a simple fireball model that provides typical pressures, temperatures and timescales for the condensation process. We explore the physics of dust formation under the conditions provided by the model.

We use (1) fireball initial conditions as estimated from a simple consideration based on shock physics as noted above ($\sim$ 10 kbar, 10^4 K), (2) the timescale needed by the plumes to reach maximum height and (3) a typical pressure that corresponds to the atmospheric pressure levels at which the particles come to rest after the plume-phase (10^{-3}-10^{-6} bar, cf. West et al. 1995). In summary the fireball starts with a few kbar at $2\,10^4$ K and arrives at 10^{-3}-10^{-6} bar after about 10 minutes. From that we calculate a rate for an exponential pressure decrease along an adiabat that we use as our fireball model, i.e.: $1/\tau_{\rm P} := \Delta \ln P/\Delta t$. The corresponding temperatures ($\sim$ 500 K at the end of the plume-phase) are consistent with observations at comparable fireball ages (e.g. Meadows and Crisp 1995).

We vary the initial pressure as well as the expansion rate to estimate the effects of the observational and theoretical uncertainties that are involved in the construction of such a simple 'fireball-model'.

For the composition of the fireball we use the elemental abundances given by Gautier and Owen (1989) for pure jovian atmospheric material (in particular we assume half of the solar oxygen abundance for Jupiter). A key property of pure jovian abundances concerning dust formation is that they indicate a mixture that is carbon-rich, i.e. C/O $>$ 1. Note that even a 1:1 mixture of jovian and cometary material leads to a carbon chemistry with large amounts of C_2H_2 (Borunov et al. 1995). C_2H_2 is the key growth species in amorphous carbon dust formation.

2.2. Dust formation

Amorphous carbon grains in circumstellar shells of C-rich asymptotic giant branch stars are a well-studied phenomenon both observationally and theoretically (e.g. Duley 1995, Sedlmayr 1994). The radiative acceleration of newly formed dust particles and momentum transfer from dust to gas play a key role in driving the slow but massive winds of such stars which contribute significantly to the chemical enrichment of the interstellar medium.

The evolution of the fireball material is in some sense analogous to the situation in a dust forming stellar wind: Starting at high densities and temperatures the gas cools down as it expands. When the temperature has become low enough, first the formation of simple molecules and then the condensation of dust takes place. Note however, that the change of the thermodynamical conditions is much more rapid in the fireball and that the densities are significantly (i.e. several orders of magnitude) higher than in a stellar wind. That results in much shorter timescales for grain formation and growth.

We describe the formation and growth of dust grains by the so-called moment method (Gail & Sedlmayr 1988, Gauger et al. 1990) which has been successfully applied to the self-consistent dynamical modelling of dust driven mass loss from C-rich asymptotic giant branch stars (e.g. Fleischer et al. 1992, 1995, Höfner et al. 1995, Höfner & Dorfi 1996). In this approach an ensemble of dust particles is represented by moments K_j of the grain size distribution which are related to averages of $r_{\rm gr}^j$ where $r_{\rm gr}$ is the grain radius and j an integer exponent. The zeroth moment K_0 is equal to the total number density of grains of all sizes $n_{\rm d}$ and K_i/K_0 is proportional to $\langle r_{\rm gr}\rangle^j$. Usually, for dynamical models of dust-driven stellar winds the information contained in these moments (up to $j = 3$) is sufficient but, additionally, the grain size distribution itself can be reconstructed once the moments are known (Dominik et al. 1989).

The temporal evolution of these moments (in a frame of reference co-moving with the gas-dust mixture) is governed by the following equations:

$$\frac{d}{dt}\int_V K_0 \; dV = \int_V J \; dV \tag{1}$$

$$\frac{d}{dt}\int_V K_j \; dV = \int_V N_l^{j/3} J \; dV + \frac{j}{3}\int_V \frac{1}{\tau} K_{j-1} \; dV \tag{2}$$

for ($1 \leq j \leq 3$) where $1/\tau$ is the net growth rate of the dust grains, J the net grain formation rate per volume and N_l the lower size limit of grains contributing to K_j (minimum number of monomers contained in a grain). For details see Höfner & Dorfi (1992).

The moment method describes the growth of an ensemble of dust particles without specifying how the smallest grains, i.e. the condensation nuclei, are actually formed out of the gas phase. It requires the net grain formation rate J as an additional input. For the calculations presented in this paper we have used a classical thermodynamical nucleation rate which has been modified to account for heteromolecular reactions. Let us note that such a thermodynamical treatment of nucleation may be inaccurate in astrophysical environments (cf. Sedlmayr 1994, Tielens 1990). Nevertheless – regarding the intrinsic chemical and physical uncertainties of the fireball evolution – we think that this method is appropriate as a first step towards a consistent model of dust formation in the plume phase. A major point of the results discussed in the following sections is that the growth of grains may be severely limited by the rapid dilution of the condensible material. As long as the formation of supercritical nuclei is fast compared to the time-scales of grain growth the picture will be qualitatively correct independent of the details of the nucleation process. The simple assumption about nucleation enables us to follow the growth of particles in the observable size range with a fully time-dependent description.

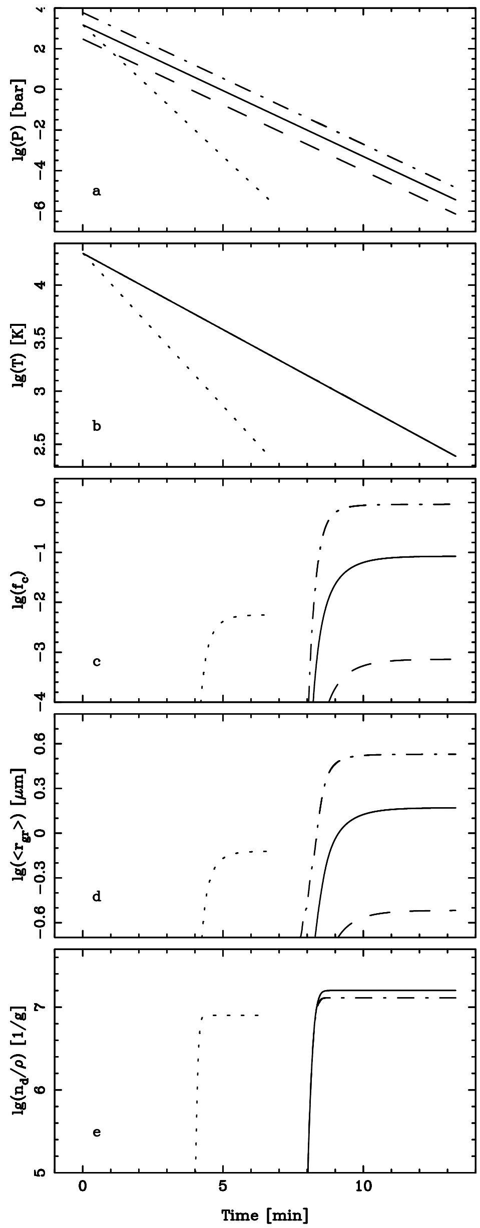

Fig. 1a–e. Temporal evolution of **a** the gas pressure P, **b** temperature T, **c** degree of condensation f_c, **d** mean grain radius $\langle r_{gr} \rangle$ and **e** number of dust particles per unit mass n_d/ρ for models with initial pressure P_0 = 1.5·10^3 bar (full line; dotted: double expansion rate), P_0 = 3.0·10^2 bar (dashed) and P_0 = 6.0·10^3 bar (dash-dotted) and initial temperature T_0 = 2 · 10^4 K.

3. Condensation and grain properties

3.1. Time-dependent dust formation and grain growth

As the fireball expands and cools during its rise the condensible material in the gas becomes supersaturated. The question whether dust grains can actually form and grow to the observed sizes, however, depends on the various time scales involved, i.e. the temporal changes of the thermodynamical conditions and the grain formation and growth rates. In this context we have to stress the importance of a time-dependent description of the dust formation and growth.

The onset of grain formation is basically determined by the temperature of the gas. As soon as the temperature has dropped below a certain threshold value the creation of small dust particles starts. On the other hand the growth of these nuclei to macroscopic sizes (in the thermodynamical sense of the word) depends on the density of the gas which determines the growth rate.

Fig. 1 shows the temporal evolution of selected models. In all cases the formation of new nuclei ceases after a short timespan – the ratio of the number density of grains n_d to the mass density of the gas ρ becomes constant – but the growth of the existing grains continues at first, i.e. $\langle r_{gr} \rangle$ rises. Due to the dilution and consumption of the condensible material, however, the growth rate continuously decreases and gradually the particle growth stops. The degree of condensation f_c is the fraction of condensible material (i.e. all carbon not blocked in CO) which is actually contained in dust grains. Note that the final value of f_c may be far from unity due to a stagnation of the growth process caused by the decreasing density. This demonstrates the restrictions of simpler models as e.g. West et al. (1995) who calculate the mean grain radius from an equation describing the growth of the dust particles but estimate the number of grains afterwards by assuming complete condensation.

Summarizing, we state that the dust production in the cooling and expanding gas is controlled by the competing effects of falling temperature (which favours condensation) and decreasing density (which slows down grain growth). The condensation process finally is stopped either by the consumption of the condensible material or by the growth time-scale becoming larger and larger due to the rapidly decreasing density. Thus, the properties of the grains, i.e. their abundance and their sizes will depend on the thermal history of the fireball.

3.2. Parameter dependence of dust properties

Using the simple model of Sect. 2.1 to describe the thermodynamical conditions within the rising fireball we basically have the following parameters: The initial temperature T_0, the initial pressure P_0 and the rate of change $1/\tau_P$ for the pressure (depending on the velocity at which the fireball rises in the Jovian atmosphere).

We keep a value of T_0 = 2 · 10^4 K for all models and vary the initial pressure P_0 in the range of 1.5 · 10^2 to 3.0 · 10^4 bar. At lower values of P_0 no significant dust formation occurs and beyond the upper limit of this range we find unrealistically large grains. Two different values of the expansion rate $1/\tau_P$ (-2.487 · 10^{-2} and -4.974 · 10^{-2} s^{-1} corresponding to a rise of the fireball within about 10 and 5 minutes, repectively) are used to demonstrate how the results depend on the assumed fireball rise-times.

Fig. 2 depicts the final grain properties as a function of the initial pressure P_0. Note that the value of the expansion rate $1/\tau_P$ for the models plotted as crosses is twice the value used in the series represented by circles.

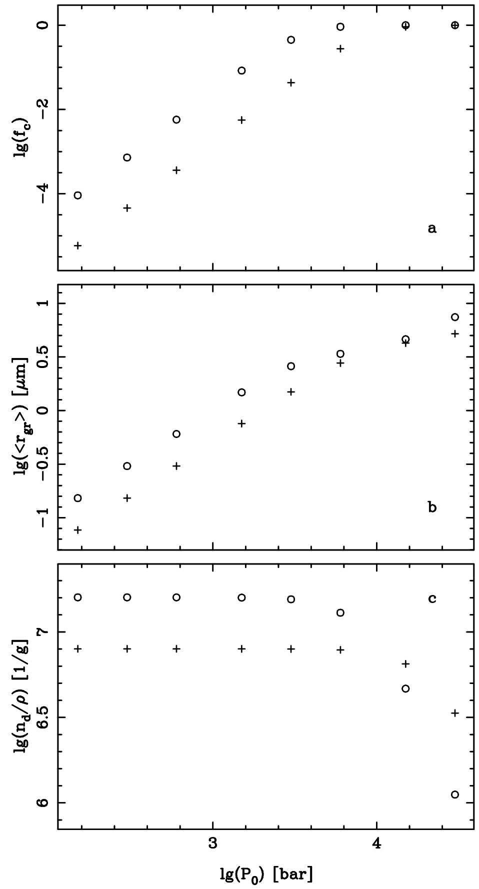

Fig. 2. a Final degree of condensation f_c, **b** mean grain radius $\langle r_{gr} \rangle$ and **c** number of dust particles per unit mass n_d/ρ as a function of the initial pressure P_0 for models with different expansion rates: $1/\tau_P$(crosses) = $2 \cdot 1/\tau_P$(circles).

We find that both, the degree of condensation f_c and the mean grain radius $\langle r_{gr} \rangle$ increase with the initial pressure P_0 and complete condensation occurs for the models with the highest values of P_0. In these models – due to the relatively high densities at a given temperature – the growth of grains is so efficient that the formation of new nuclei is actually limited by the growth of the existing particles. This can be seen from the number of grains per mass which is constant for the models with lower P_0 and becomes smaller for models where complete condensation is reached.

Furthermore, the effects of dilution become apparent by comparing the two series with different expansion rates. Both f_c and $\langle r_{gr} \rangle$ are smaller at a given P_0 for the model with the higher rate (crosses) though the differences become significantly smaller around the point where complete condensation occurs for the first time.

4. Conclusions

We assume a simple fireball model and a carbon-rich environment at the impact sites and demonstrate that amorphous carbon dust (soot) may form in the rising fireballs following the Shoemaker-Levy 9 impacts on Jupiter. With plausible thermodynamical parameters we obtain grains with radii of 0.1-10 μm several minutes after the impact while the condensation process itself takes typically about 2 minutes. We want to stress the importance of a detailed time-dependent description of the grain formation and growth since the condensation time-scales are comparable to the time-scales of cooling and expansion for the fireball material and condensation may be far from complete due to the rapid dilution of the gas.

A key requirement, namely a carbon to oxygen abundance-ratio larger than unity is indicated by present abundance determinations of the jovian atmosphere. More detailed time-dependent dust-formation calculations may be used in the future to restrict the physical conditions in the fireballs by determining the properties of dust resulting from various fireball histories.

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