atmospheric measurements. Our best-fit model is summarized in Table 1 and the corresponding spectrum is shown in Fig. 1. Our results differ from those of Kamp *et al.*[3] who concluded that a reduction in the H_2O and CO abundances by a factor of 10 compared to their 'standard' model was needed. This difference is primarily a consequence of the use of a more complete description of the CO_2 spectrum in our model, and of an extra continuum opacity. These changes increase the gaseous opacity in our model and force the thermal emission to originate from higher altitudes. Larger amounts of H_2O and CO are therefore needed to produce the observed absorption along these shorter atmospheric paths.

The observed spectrum exhibits a drop in intensity around $4{,}115\ \text{cm}^{-1}$ which cannot be simulated using only the gaseous absorbers quoted above. This dip coincides with the R branch of the $2\nu_3$ band of COS, and can be correctly accounted for with a COS mole fraction of 2.5×10^{-7}. This abundance is more than two orders of magnitude lower than that suggested by Venera 13 and 14 gas-chromatograph measurements[15], but is compatible with the upper limit of 2×10^{-6} from the Pioneer measurements[16]. It is therefore likely that we report here the first true detection of this sulphur compound in the Venus atmosphere. There are still a few unidentified absorption features in the 2.3-μm spectrum. The sharp drop observed near $4{,}054\ \text{cm}^{-1}$ is near the $3\nu_3$-band centre of SO_2, but the lack of published spectroscopic data for this band has prevented us from investigating this possibility further. Some of the unassigned lines indicated in Fig. 3 may belong to weak CO_2 hot bands.

Spectra of the 1.7-μm region generated with a constant continuum absorption coefficient α fail to reproduce the shape of the observations (Fig. 2). There is evidence for a sharp increase in continuum absorption at wavenumbers $\gtrsim 5{,}750\ \text{cm}^{-1}$. We cannot therefore analyse the CO_2-dominated region to derive the altitudes from which radiation is emitted, as we did for the 2.3-μm region (see Fig. 3). To match the measured radiance at $5{,}745\ \text{cm}^{-1}$ with the cloud model derived from our 2.3-μm analysis, an absorption coefficient of $7.7\times10^{-9}\ \text{cm}^{-1}\ \text{amagat}^{-2}$ would be required. The maximum pressure levels sounded in this spectral region would then be located around 25 bars (18 km). For this model, the observed depths of the HCl absorption lines can be correctly reproduced with a mixing ratio of $\sim5\times10^{-7}$, a value similar to that measured in the cloud-top region by Connes *et al.*[14].

This preliminary analysis shows that our measurements are representative of pressure levels below the clouds, down to 8 bars (32 km) for the 2.3-μm region, and deeper for the 1.7-μm region. We are therefore probing an altitude range in the Venus atmosphere that is particularly interesting because the abundances of trace chemical species there are influenced by photochemical processes in and above the clouds, thermochemical equilibrium, and interactions with the crust. Moreover, it includes the region below the clouds which is so critical for cloud chemistry. The results presented here could also have an important role in the interpretation of the data that were acquired by the Galileo spacecraft during its Venus flyby on 10 February 1990. The Near Infrared Mapping Spectrometer (NIMS) instrument on that spacecraft obtained near-infrared spectra for both the day and night sides of Venus. Their spatial resolution was ~30-100 km, but their spectral resolution (0.025 μm) was much less than that described here. Our high-spectral-resolution results may improve the ability of the NIMS team to discriminate between the absorption by H_2O, and that of other gases. This must be done to produce maps of horizontal variations in the H_2O amounts in the atmosphere of Venus, which is an important goal of the Galileo encounter. □

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Meteoroid ablation processes in Titan's atmosphere

W-H. Ip

Max-Planck-Institut für Aeronomie, D-3411 Katlenburg-Lindau, FRG

SATURN'S planet-sized moon Titan has a nitrogen-rich atmosphere with a surface pressure of 1.6 bar (ref. 1). Methane, ethylene and other hydrocarbons are also present, allowing photochemical synthesis of complex organic molecules and aerosols[2–6]. The ablation of meteoroids in Titan's upper atmosphere could contribute to the atmospheric chemistry in two important respects. First, refractory elements such as sodium, iron and magnesium could recondense into small (10–100 Å) particles which could act as aerosol nucleation centres, as in the Earth's atmosphere[7,8]. Second, meteoroids from stray bodies with perihelia of ⩾3 AU could be rich in volatile ices (H_2O, CO_2, CO), and might constitute an important source of oxygen-bearing material in Titan's atmosphere. Here I use a simple model of meteoroid ablation to calculate the altitude profiles of material introduced in this way from both icy and rocky meteoroids. The source region of oxygen-bearing molecules is found to lie between 600 and 800 km altitude; on Earth, by comparison, most of the meteoritic material evaporates between 80 and 100 km (refs 9, 10).

The presence of CO in Titan's stratosphere has been confirmed[11–13], and requires an exogenous source. Theoretical modelling of the chemical composition of Titan's atmosphere suggests that, on average, there should be a steady influx of the order of $\sim6.1\times10^5$ water molecules $\text{cm}^{-2}\ \text{s}^{-1}$ from meteoroid bombardment (ref. 4; M. Allen, personal communication). To understand the global chemistry and dynamical transport of the trace gases such as CO and possibly H_2O, the source distribution of the oxygen-bearing molecules must be clarified.

Here the equation of motion of the meteoroid under the influence of atmospheric drag is expressed as[7]

$$\frac{\mathrm{d}v}{\mathrm{d}t} = -\frac{3C_\mathrm{d}\rho_\mathrm{a}v^2}{4\rho_\mathrm{m}R} \tag{1}$$

where v is the instantaneous velocity of the meteoroid at altitude Z, C_d the drag coefficient of order unity, ρ_a the atmospheric density, ρ_m the density of the meteoritic dust particle, and R is the meteoroid radius.

The kinetic energy loss through interaction with the atmosphere is balanced by the thermal radiation from the meteoroid surface, heating of the particle and surface sublimation or ablation

$$\xi\frac{\pi}{2}R^2\rho_\mathrm{a}v^3 = 4\pi R^2\varepsilon\sigma(T_\mathrm{m}^4 - T^4) + \frac{4\pi}{3}R^3\rho_\mathrm{m}C\frac{\mathrm{d}T_\mathrm{m}}{\mathrm{d}t} + L\dot{m} \tag{2}$$

where ξ is the energy transfer coefficient relating the efficiency of conversion of the meteoroid kinetic energy to heating, radiation and sublimation, ε is the emissivity of the meteoroid material, σ is Stefan's constant, C the heat capacity, T the temperature of the atmosphere, and T_m the temperature of the meteoroid. I have assumed that $\xi \approx 0.2$ (ref. 14).

The temperature increase of the meteoroid as a function of flight time (and hence altitude) is determined from equation (2). The surface sublimation rate is then estimated by applying the Clausius-Clapeyron equation relating the vapour pressure P_v to T_m. The appropriate expressions for the Clausius-Clapeyron equations for ice and rocky material are given in ref. 15 from which I have also adopted the following physical parameters. For rocky material: $\rho_m = 3.4\ \mathrm{g\ cm^{-3}}$, $C = 9.0 \times 10^6\ \mathrm{erg\ K^{-1}\ g^{-1}}$, $L = 8.1 \times 10^{10}\ \mathrm{erg\ g^{-1}}$, $T_b = 1{,}800$ K. For icy material: $\rho_m = 1.0\ \mathrm{cm^{-3}}$, $C = 4.2 \times 10^7\ \mathrm{erg\ K^{-1}\ g^{-1}}$, $L = 2.8 \times 10^{10}\ \mathrm{erg\ g^{-1}}$, $T_b = 273$ K. T_b denotes the temperature at which surface sublimation will become significant. In the numerical calculations, equations (1) and (2) are integrated with initial values of the meteoroid velocity V_0 and temperature T_0 at the starting altitude Z_0. I also assumed that the meteoroid trajectory remains a straight line and that the entry angle (relative to the zenith) is $\chi = 45°$.

The ablation profiles for a 100-μm meteoroid entering Titan's atmosphere are illustrated in Fig. 1. The mass vaporization rate as a function of altitude varies according to the initial relative velocity. For very high entry velocity ($V_0 = 40\ \mathrm{km\ s^{-1}}$) the onset of surface sublimation of an icy particle occurs rather suddenly at $Z \approx 900$ km. After reaching a peak value, the mass loss rate at lower altitudes slowly decreases because of the reduction in the size of the meteoroid. The icy meteoroid would be completely destroyed in flight before reaching altitudes below 650 km. For smaller incoming velocity, ablation begins to occur at lower altitudes. Because of the high volatility of the icy material, significant mass loss could still take place for V_0 as small as $5\ \mathrm{km\ s^{-1}}$. The orbital distribution of the interplanetary meteoroids at Saturn's orbit is not known so it is difficult to estimate the actual distribution of the impact velocity. A plausible velocity range is $\langle V_0 \rangle = 15 \pm 5\ \mathrm{km\ s^{-1}}$ when the presence of meteor streams from long-period comets in retrograde orbits is taken into consideration[16]. If this holds, icy particles of 100-μm radius are expected to deposit their mass at altitudes between 500 and 850 km.

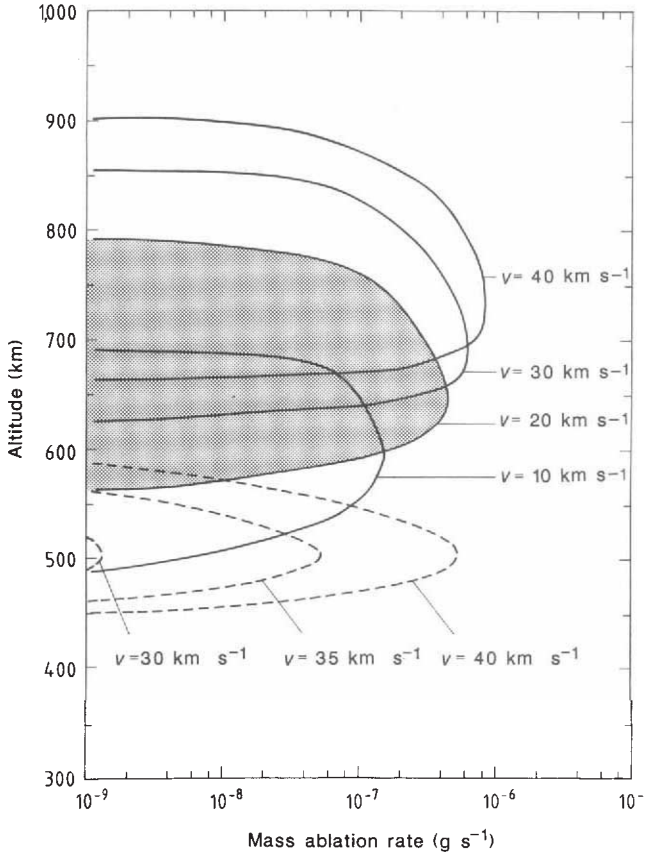

FIG. 1 The ablation zones for interplanetary meteoroids of 100-μm radius with different incoming velocity starting at an altitude of 2,000 km. The dashed curves are for rocky particles and the solid curves are for icy bodies. The entry angle from the zenith is assumed to be $\chi = 45°$. The shaded region represents the meteoroid ablation zone expected for water-ice particles with atmospheric entry velocity near the high-velocity limit of $20\ \mathrm{km\ s^{-1}}$ at Titan.

For rocky meteoroids with $V_0 < 10\ \mathrm{km\ s^{-1}}$, the continuous deceleration in the upper atmosphere is sufficient to slow down 100-μm particles such that the surface temperature is always smaller than T_b (1,800 K). No significant vaporization would occur for objects in such slow-moving trajectories. The main contribution would have come from particles with $V_0 \gtrsim 20\ \mathrm{km\ s^{-1}}$. I therefore expect the effective ablation zone of such rocky meteoroids to be found between 450 and 600 km altitude, just below the ablation region of the icy meteoroids.

If the size distributions of the icy and rocky meteoroids orbiting at 10 AU are similar to that found at 1 AU (see ref. 17), particles with $R_0 \approx 100$ μm should be responsible for a large part of the mass influx to Titan's atmosphere. In this case, it is likely that at Titan the vertical distribution of metallic atoms and ions of meteoritic origin should be confined below 600 km altitude. The source region of the oxygen-bearing molecules would be located higher up, between 600 and 800 km altitude.

I have considered the possible consequences of meteoroid ablation in Titan's atmosphere for two different compositions of the interplanetary dust particles. The meteoroids might actually consist of a mixture of ice and rocky material such that the detailed mass vaporization profiles could be different from those described here. Also, the mass ratio of icy and rocky particles is unknown except for the requirement that the influx of oxygen-bearing material should be $\sim 6 \times 10^5$ molecules $\mathrm{cm^{-2}\ s^{-1}}$ (ref. 4). A clarification of this important issue would require analyses of the compositions of interplanetary dust particles by dust instrument(s) in the environment of Saturn. Irrespective of the chemical nature of the interplanetary meteoroids, I expect the meteoritic ablation process to introduce two principal aeronomical effects in Titan's atmosphere in addition to the injection of oxygen-bearing material—the formation of smoke particles and the introduction of metallic atoms and ions in the upper atmosphere. Because the $\mathrm{Na^+}$ and $\mathrm{Fe^+}$ ions do not react strongly with N_2 and CH_4 (ref. 18), they might have a chance to accumulate, forming a metallic-ion-enriched layer. My calculations indicate that such a layer should have its maximum vertical altitude at about 500 km. Finally, it should be mentioned that the small metallic-ion clusters produced in the meteor vapour trails could have interesting chemical interactions with the organic hydrocarbon polymers. The ionosphere and photochemistry of Titan's atmosphere thus may be strongly coupled to the interplanetary medium. ☐

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