Silicon Compounds in the Jupiter Atmosphere

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Z. Naturforsch. **34a**, 1541–1543 (1979);
received November 12, 1979

Due to the relatively large cosmic abundance of Si and the stability of colored silicon compounds easily formed under various nonequilibrium conditions, it is concluded here that silicon should be strongly considered as a potential major component in the observed colored material in the Jupiter atmosphere.

Silicon is one of the most abundant elements in the universe (after H, He, O, N, and C) and in the same order of abundance as Mg and Fe. In the high temperature and pressure regions of Jupiter most of the Si should be present as SiH_4. At higher altitudes, corresponding to a total pressure of less than 1000 bar and a temperature below 1200 K, SiO_2 and other compounds of silicon should dominate. These equilibria and the chemistry depend strongly upon the H_2O concentration, which is assumed to be in the order of 10^{-3}. A calculated equilibrium profile had been proposed for a model atmosphere [1] and our own estimates confirm the main features within reasonable limits.

Recent photographs taken of Jupiter emphasize the fact that the atmosphere of the planet is not in equilibrium. Atmospheric turbulence is observed corresponding to movement in the colored areas including the well-known great red spot. Assuming, therefore, that non-equilibrium processes may occur on Jupiter, the nature of such processes may be sought in the laboratory. The non-equilibrium transition of SiH_4 to SiO_2 can be observed in various ways. We have found that many of these lead to intermediates that are relatively stable and yield strong colorations very similar in appearance to those observed on Jupiter.

The purpose of this paper is to emphasize the possibility of the silicon compounds contributing substantially to the colors observed on Jupiter. We have found that the reflectivities of a reddish-brown silicon compound and reddish brown phosphorous, which look quite similar on visual inspection, have a different wavelength dependency. A comparison is needed of the spectra of compounds prepared by a variety of laboratory experiments with spectra obtained through observation of Jupiter itself.

Experimentally it can readily be shown that the thermal decomposition of silane with quartz (SiO_2) produces reddish compounds. Experiments performed using a flame impinging on a quartz vessel containing silane, with or without water vapor present, produces within seconds a reddish amorphous material. Using elemental silicon in a quartz tube and heating to temperatures above 1000 °C for several hours also results in a reddish colored material.

These colorations of the silicon compounds are reported in the literature [2]. The colors are attributed to amorphous SiO, but depending upon conditions, a stoichiometric mixture of $Si + SiO_2$ may become stable [3]. Industry has used silane for fabrication of semiconductors, and the hydrogen containing oxide has been suggested for the frequently observed reddish deposits, a fact which makes the overall problem even more complicated.

In earlier papers, emphasis was placed on the role phosphorus may play in the coloration of Jupiter [4, 5] including the interaction of hydrogen atoms in the formation and destruction processes. The cosmic abundance of phosphorus, however, is relatively low, only about 1% of that of silicon.

As mentioned, one of the major abundant elements in Jupiter is magnesium. If magnesium as MgO could chemically bind with silica forming magnesium silicates, both Mg_2SiO_4 and $MgSiO_3$ are possible depending on conditions, but the reactions of SiO_2 with MgO to form the stable magnesium silicates are slow [6] and therefore only a minor fraction of silicon could be present as magnesium silicates.

The transport of the silicon, mainly in the form of SiH_4, from the deeper regions of the Jupiter atmospheres, to the higher regions where it should be present in some oxide or silicate form, may include complex reactions which may occur rapidly

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depending on conditions in terms of vertical "air currents". Silane does not exist in the upper regions of Jupiter, or at least an upper limit has been established [7].

One may conclude from thermodynamics that silane, stable at low altitudes with high temperatures and pressures would be converted to white powders of silicates or silicon dioxide at high altitudes of Jupiter over long periods of time. However, the colored intermediates may be the result of relatively rapid amorphous silicon monoxide formation, produced in vertical atmospheric currents in region near the great red spot and in the red spot itself. These amorphous particles may develop most readily on particles such as SiO_2 itself. These colored dust particles may acquire in addition a colorless SiO_2 coating which protects the coloration for a relatively long time from further oxidation to SiO_2 as is readily observed in the laboratory. Due to eddy diffusion the SiO_2 dust will be aboundant, about 10^{-3} grams per liter at high pressures. Silane would decompose rapidly in a surface-catalyzed process on these dust particles, and the reddish brown SiO type intermediate would be formed. This intermediate is anticipated to be present in a surface layer and small amounts would be easily observed and the appearance would not only be pronounced but also to a certain extent persistent. Over long periods of time, however, the coloration must be lost because the colorless SiO_2 is the stable compound and, in fact, this is a necessary factor in combination with the turbulence for the non-homogeneous appearance of the planet-atmosphere.

It must be recognized that the role of hydrogen in these silicon oxide compounds is not clear, but indeed the similarity in appearance of the material suggested as amorphous silicon monoxide and those measured to be hydrogen containing silica oxide compounds prevent elimination of either at this time as contributors to the coloration observed on Jupiter.

The reactions corresponding to these conditions will not be specified here, since these would be mainly based on conjecture. However, one can note that the reaction occurring in the laboratory between silicon and quartz has an analogy to the Boudouard reaction

$$C_{(s)} + CO_2 \rightarrow 2\,CO\,,$$

where the analog reaction may be written as

$$Si_{(s)} + SiO_{2\,(s)} \rightarrow 2\,SiO\,.$$

SiO is known to exist in the vapor phase [3] and does exert a vapor pressure which is higher than the vapor pressure of Si or SiO_2.

The recent beautiful pictures of Jupiter taken by the Voyager [8] are of tremendous value for the understanding of Jupiter atmosphere. The unique pattern between reddish brown and white coloration gives evidence for a strong turbulence. We concluded that at the present state of knowledge only silicon compounds can explain the observation and behavior of the Jupiter atmosphere. It is obvious that it will take considerable further efforts to duplicate the conditions prevailing on Jupiter in laboratory experiments to further evaluate the role of silicon. For example reactions like [9]

$$3\,SiH_4 + 4\,NH_3 \rightarrow Si_3N_{4\,(cond)} + 12\,H_2$$

or reactions of the type [10]

$$Al_2Si_2O_7 + 2\,Si \rightarrow Al_2O_3 + 4\,SiO$$

are not included in our discussion.

Acknowledgement

This research was supported by NASA Grant NGL 33-018-007. The authors wish to express their thanks to Gary Greenblatt for assistance with experimental work and to Fred W. Billmeyer and Danny Rich for reflectance spectra of SiO and red phosphorous.

[1] St. S. Barshay and J. S. Lewis, Icarus **33**, 593 (1978).
[2] W. F. Biltz and P. Ehrlich, Zur Verflüchtigung von Silicium als niederes Oxyd, Naturwissenschaften **26**, 188, 1938.
[3] Hypothetical phase diagram of the Si-O system (from A. S. Berezhnoi, Silicon and its Binary Systems, Consultants Bureau, New York 1960).
[4] B. G. Prinn and J. S. Lewis, Phosphine on Jupiter and Implications for the Great Red Spot, Science **190**, 274 [1975].
[5] G. R. Howland, P. Harteck, and R. R. Reeves, The Role of Phosphorus in the Upper Atmosphere of Jupiter, Icarus **37**, 301 (1979).
[6] W. Wander and J. Wuhrer, Z. Anorg. Allg. Chem. **222**, 227 (1936).
[7] R. R. Treffers, H. P. Larson, U. Fink, and T. N. Gautier, Upper Limits to Trace Constituents in Jupiter's Atmosphere from an Analysis of its 5 Micrometer Spectrum, preprint.
[8] NASA, Voyager Encounters Jupiter, July 1979.

[9] G. Cochet, H. Mellottee, and R. Delbourgo, C.N.R.S., Centre de Recherches sur la Chimie de la Combustion et des Hautes Temperatures, Experimental Investigation of the Gas Phase in a Chemical Vapour Deposition Reaction, Proceedings of the Conference on Chemical Vapor Deposition, Fifth International Conference, 1975.
[10] E. Zintl, Z. anorg. Chem. **1940**, 245.