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The AAAS-Newcomb Cleveland Prize, which previously honored research papers presented at AAAS annual meetings, is now awarded annually to the author of an outstanding paper published from September through August in the Reports section of *Science*. The second competition year under the new rules starts with the 2 September 1977 issue of *Science* and ends with that of 25 August 1978. The value of the prize is \$5000; the winner also receives a bronze medal.

To be eligible, a paper must be a first-time publication of the author's own research. Reference to pertinent earlier work by the author may be included to give perspective.

Throughout the year, readers are invited to nominate papers appearing in the Reports section. Nominations must be typed, and

the following information provided: the title of the paper, issue in which it was published, author's name, and a brief statement of justification for nomination. Nominations should be submitted to AAAS-Newcomb Cleveland Prize, AAAS, 1515 Massachusetts Avenue, NW, Washington, D.C. 20005. Final selection will rest with a panel of distinguished scientists appointed by the Board of Directors.

The award will be presented at a session of the annual meeting at which the winner will be invited to present a paper reviewing the field related to the prizewinning research. The review paper will subsequently be published in *Science*. In cases of multiple authorship, the prize will be divided equally between or among the authors; the senior author will be invited to speak at the annual meeting.

Reports

Carbon Monoxide on Jupiter and Implications for Atmospheric Convection

Abstract. *A study of the equilibrium and disequilibrium thermochemistry of the recently discovered carbon monoxide on Jupiter suggests that the presence of this gas in the visible atmosphere is a direct result of very rapid upward mixing from levels in the deep atmosphere where the temperature is about 1100°K and where carbon monoxide is thermodynamically much more stable. As a consequence the observed carbon monoxide mixing ratio is a sensitive function of the vertical eddy mixing coefficient. We infer a value for this latter coefficient which is about three to four orders of magnitude greater than that in the earth's troposphere. This result directly supports existing structural and dynamical theories implying very rapid convection in the deep Jovian atmosphere, driven by an internal heat source.*

Carbon monoxide (CO) was recently detected in the atmosphere of Jupiter by Beer (1), utilizing ground-based observations with a high-resolution Fourier transform interferometer-spectrometer in the 5- μ m wavelength region. This detection has now been confirmed by Larson *et al.* (2), using similar instrumentation on the Kuiper Airborne Observatory. Both observers estimate that the volume mixing ratio for CO is about 10^{-9} if they assume that the gas is well mixed, but this assumption has been questioned because it implies a rotational temperature of roughly 210°K for CO (3). The discovery of CO is of considerable interest for, like the earlier discoveries of C₂H₂, C₂H₆, and PH₃ (4, 5), it provides direct evidence for chemical dis-

equilibrium in Jupiter's atmosphere (6, 7). These various gases are all predicted to have negligible concentrations in the visible atmosphere when we assume thermochemical equilibrium (8).

In a general sense we can identify a number of possible mechanisms whereby the observable CO concentrations on Jupiter could be substantially enhanced relative to the thermochemical equilibrium values. One such mechanism involves CO production by photochemical oxidation of CH₄ in the upper atmosphere. Such oxidation is well known as a source of CO in the earth's atmosphere (9). However, the only suitable oxidizing agents in the upper atmosphere of Jupiter are free radicals such as OH derived from dissociation of H₂O. Direct photo-

dissociation of Jovian water vapor is essentially inhibited because photons capable of dissociating H₂O do not penetrate down to levels where there are significant H₂O concentrations (10). Without somewhat arbitrarily assuming convective injection of Jovian water-cloud particles into the upper atmosphere or an extra-Jovian source for upper atmospheric H₂O, production of OH by photolysis of H₂O therefore appears to be inhibited. Dissociation of H₂O lower in the atmosphere by hot H atoms which are produced by H₂S photodissociation (11) or by lightning and thunder shock waves are two other possible OH sources. However, Jovian H₂O still has very low concentrations at the levels where the hot atoms are being produced, and the hot atoms themselves are almost immediately quenched by collisions with H₂ and He (12). In addition, in analogy with our own atmosphere, the vertical energy flux associated with lightning and thunder on Jupiter is only about 0.1 percent of the solar ultraviolet flux and a significant fraction of this flux is inoperative in the breaking of chemical bonds (13).

Another mechanism for producing CO in the visible atmosphere—one which we will demonstrate is, in fact, adequate—involves very rapid vertical mixing in the hot lower atmosphere. This allows the CO formed by thermochemical oxidation of CH₄ at high temperatures to be mixed up to visible levels (12). We argue here that the observation of CO, assuming it is well mixed, can be used to make a quantitative estimate of the strength of vertical mixing in Jupiter's atmosphere. If the CO is not well mixed our analysis will apply only to the well-mixed component.

Before discussing the details of the latter mechanism we must establish what

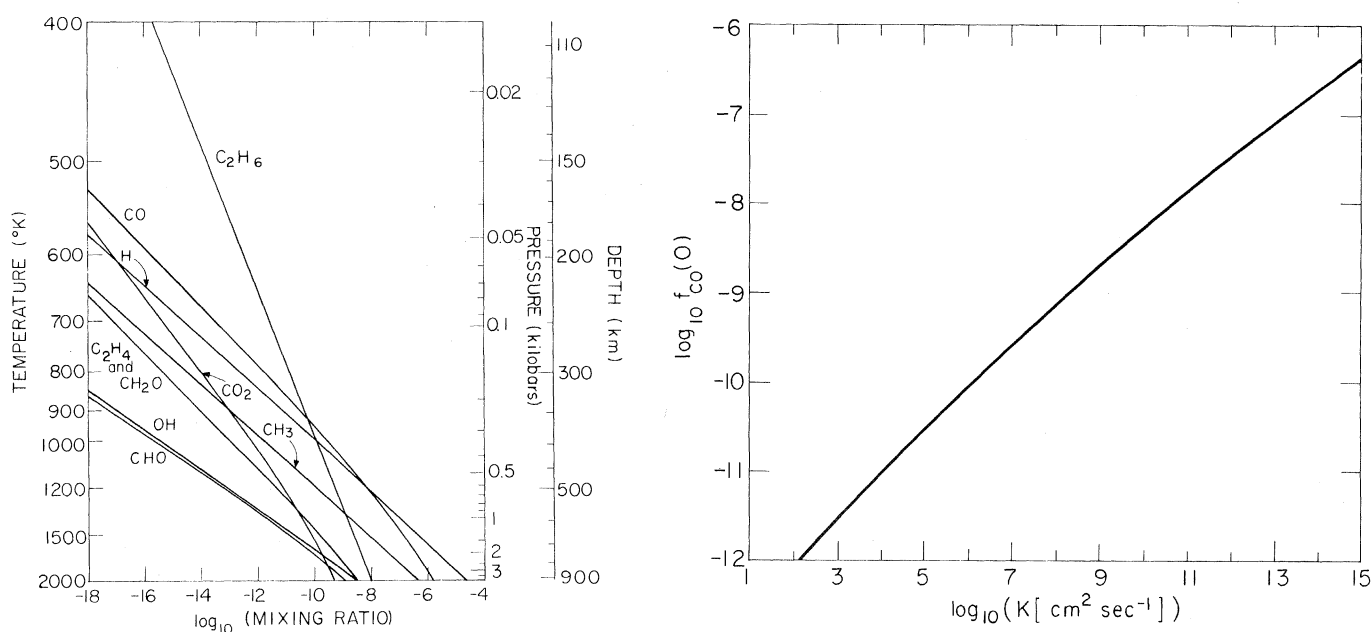


Fig. 1 (left). Predicted mixing ratios of species important in CO chemistry in the deep Jovian atmosphere. We assume thermochemical equilibrium in a solar-composition model of Jupiter with an adiabatic lapse rate. At each level in the atmosphere the temperature, pressure, and depth below the 1-bar, 175°K level are indicated. Fig. 2 (right). Values of the vertical eddy diffusion coefficient K in the deep Jovian atmosphere required to give various values for the well-mixed CO mixing ratio f_{CO} in the observable portion of the atmosphere.

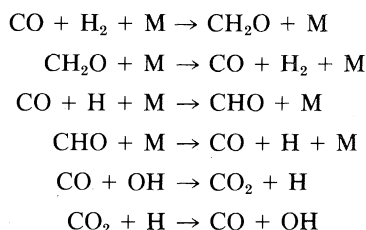
the CO abundance is in thermochemical equilibrium. A detailed study of chemical equilibrium on Jupiter involving more than 300 compounds of 22 abundant or volatile elements has recently been completed (14). This study utilizes a model Jovian atmosphere containing the elements in solar composition (15). An adiabatic temperature lapse rate (16), as implied by radiative-dynamical equilibrium calculations (17), was assumed below the 1-bar level. Earth-based and spacecraft data indicate a temperature at the latter level of 175°K (18). We are interested here in the results of this study for the important carbon-containing compounds CO, CO₂, CH₂O, CHO, CH₄, C₂H₆, CH₃, and C₂H₄ and also for H, OH, and H₂O. The computed concentrations of these various species are shown in Fig. 1 along with the relationship between altitude, pressure, and temperature used in the model atmosphere.

If we assume that CO is well mixed we expect a rotational temperature of about 210°K for the observed CO on Jupiter. In comparison, the volume mixing ratio for CO in thermochemical equilibrium at the 210°K level is 6×10^{-46} , or some 36 orders of magnitude less than the observed value. Clearly, the observations imply the existence of a potent disequilibrating mechanism.

In developing our explanation for the appearance of CO in the visible atmosphere we must obtain a rough estimate for the rate of irreversible reduction of CO to CH₄ on Jupiter. The high-temper-

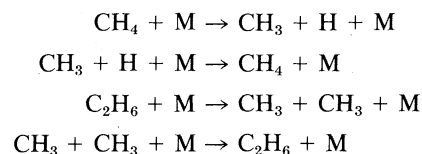
ature kinetics of mixtures of CO, H₂, and O₂ and of CH₄ and O₂ have been studied in some detail by combustion chemists (19). Reaction paths in the hydrogen-rich but oxygen-deficient Jovian atmosphere will, of course, differ from those in the latter studies, but the rate constants of all the elementary reactions will remain the same.

In our study of the expected reaction paths on Jupiter we have found it convenient to divide the abundant carbon-containing compounds into two distinct families: oxidized carbon, comprising those with a carbon-oxygen bond (such as CHO, CO, CO₂, and CH₂O), and reduced carbon, comprising those without (such as CH₄, C₂H₆, CH₃, and C₂H₄). Using measured rate constants (19, 20) and the concentrations shown in Fig. 1, we find that conversions within each family are generally very rapid at temperatures at or above 1100°K. For example, in the oxidized carbon family the reactions



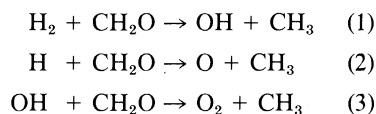
where M is another atom or molecule, enable conversions between CO, CO₂, CH₂O, and CHO to occur on time scales shorter than any feasible time scales for vertical transport. Thus the relative concentrations of these four species should

always closely approximate their thermochemical equilibrium values. Similarly, the reactions



permit sufficiently rapid conversions between CH₃, C₂H₆, and CH₄ in the reduced carbon family (20).

In contrast to this situation, we have found that conversions from one carbon family to the other are a good deal slower. Available kinetic data (19) imply that oxidized carbon will be converted to reduced carbon on Jupiter by the reactions



We have computed the rate constants for these three reactions, using the measured rate constants for the reverse reactions (19) together with their appropriate equilibrium constants (14). Reaction 1 is much more important than reactions 2 and 3 because of the large excess of H₂. The rate constant k computed for reaction 1 is

$$k \approx 2.3 \times 10^{-10} \exp\left(-\frac{36,200}{T}\right) \text{ cm}^3 \text{ sec}^{-1}$$

Since CO and CH₄ are, respectively, the dominant forms of oxidized and reduced carbon, the rate of conversion of CO to

CH₄ can be equated with the rate of reaction 1. Thus the lifetime t_{chem} of CO in an air parcel containing a large excess of CO over its equilibrium value (21) can be expressed as

$$t_{\text{chem}} \approx \frac{[\text{CO}]}{k[\text{H}_2][\text{CH}_2\text{O}]}$$

where the square brackets denote the number concentrations of the particular molecules. To compute these t_{chem} values we use the fact that the relative concentrations of CO and CH₂O will be close to their equilibrium values.

We are now in a position to discuss the effects of vertical mixing on CO concentrations. To facilitate this discussion we have divided the atmosphere into two regions. One lies below the altitude $z = 0$, and all species in this lower region are assumed to be in thermochemical equilibrium. In practical terms, $z \leq 0$ will imply that $t_{\text{chem}} \leq t_{\text{conv}}$, where t_{conv} is the time constant for vertical mixing. The other region lies above $z = 0$, and in this upper region we can conveniently write the CO destruction rate as

$$\frac{[\text{CO}]}{t_{\text{chem}}} = \frac{[\text{CO}](0)}{t_{\text{chem}}(0)} \exp\left(-\frac{z}{h_{\text{chem}}}\right)$$

where the "chemical scale height" h_{chem} is given by

$$h_{\text{chem}} = -\frac{[\text{CO}] t_{\text{chem}}^{-1}}{\frac{d}{dz} ([\text{CO}] t_{\text{chem}}^{-1})}$$

To predict the CO volume mixing ratio f_{CO} in the region above $z = 0$, we must solve the following equation, which expresses the continuity of mass for CO

$$\frac{d}{dz} \left[K \exp\left(-\frac{z}{H}\right) \frac{df_{\text{CO}}}{dz} \right] = \frac{f_{\text{CO}}(0)}{t_{\text{chem}}(0)} \exp\left[-\frac{z}{h_{\text{chem}}}\right]$$

Here H is the atmospheric "density scale height" and K is the vertical eddy diffusion coefficient. The two boundary conditions necessary for solution of this continuity equation are $f_{\text{CO}} = f_{\text{CO}}(0)$ at $z = 0$ and f_{CO} finite and positive as z approaches infinity. Noting that $t_{\text{chem}}(0) = t_{\text{conv}}$ and that t_{conv} is given approximately by

$$t_{\text{conv}} \approx \frac{H^2}{K}$$

the resultant expression for f_{CO} when $0 < h_{\text{chem}} < H$ is (22)

$$f_{\text{CO}} = f_{\text{CO}}(0) \left(1 - \frac{h_{\text{chem}}^2}{H[H - h_{\text{chem}}]} \times \left\{ 1 - \exp\left[-\left(\frac{1}{h_{\text{chem}}} - \frac{1}{H}\right)z\right] \right\} \right)$$

Since $h_{\text{chem}}^2 \ll H^2$ (23), this equation tells us that f_{CO} in the visible atmosphere (that is, at $z \gg H$) is not much less than at $z = 0$. In essence, once $t_{\text{chem}} \sim t_{\text{conv}}$, vertical mixing results in CO in an air parcel being chemically quenched by rising a distance from $z = 0$ which is considerably less than H .

If we regard K as an unknown quantity we can identify the level $z = 0$ for each K value by finding where $t_{\text{chem}} = H^2/K$. We can then obtain $f_{\text{CO}}(0)$ at this same level from the thermochemical equilibrium calculations presented in Fig. 1. In this manner we obtain the $f_{\text{CO}}(0)$ value corresponding to each K value. The results are illustrated in Fig. 2. Since the observed f_{CO} value is approximately $f_{\text{CO}}(0)$, Fig. 2. demonstrates the dependence of the observed CO concentrations on the K value in the deep atmosphere. From observations (1, 2) $f_{\text{CO}} \approx 10^{-9}$, which implies $K \approx 2 \times 10^8 \text{ cm}^2 \text{ sec}^{-1}$. The corresponding temperature at $z = 0$ is 1064°K. By way of comparison, $K \approx 10^5 \text{ cm}^2 \text{ sec}^{-1}$ in the terrestrial troposphere. In view of the several assumptions and approximations we have made, we caution that this result should be regarded only as indicating the order of magnitude of K in the deep atmosphere. A detailed laboratory study of the high-temperature reduction of CO to CH₄ by H₂ will be necessary before better accuracy can be obtained.

Recent measurements from Pioneer 10 (24) confirm earlier earth-based observations (25) suggesting that Jupiter emits at thermal wavelengths about twice the energy it receives from the sun at visible wavelengths. The internal heat source implied from these observations has been used to argue that Jupiter is a convective fluid throughout most of its interior (26). The required K value can be calculated from theories for free convection and is about 10^7 to $10^9 \text{ cm}^2 \text{ sec}^{-1}$ in Jupiter's deep atmosphere (27). Considering the approximations we have made, the agreement between our deduced K value and the latter theoretical values must be regarded as surprisingly good. The observation of CO on Jupiter has thus provided independent evidence for very rapid vertical mixing in its deep atmosphere.

The mechanism proposed here for producing nonequilibrium concentrations of CO in the atmosphere should also apply to a large number of other molecules. This mechanism has already been used to explain the observation of PH₃ (27). It has been advanced for GeH₄ (12), which has also recently been observed (5). If CO₂ has a chemical time constant similar to that of CO, then its observed mixing

ratio should be roughly that at the 1100°K level, which from Fig. 1 is 5×10^{-12} . Larson *et al.* (2) place an observational upper limit on CO₂ of 67 times the observed CO value. A complete list of the mixing ratios of abundant species in chemical equilibrium in the region between 800° and 1500°K on Jupiter is given elsewhere (14). Since some or all of these species may be transported up to visible regions of the atmosphere, they could be observable by remote spectroscopy or by an entry-probe mass spectrometer.

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 21. Our estimate of t_{chem} will be too small if partial reformation of CO by reactions such as the reverse of reaction 1 is appreciable. Since CH_3 and OH have very short lifetimes for conversion to CH_4 and H_2O , their concentrations should be close to their equilibrium values. Consequently, in an excess of CO the reformation of CO by the reverse of reaction 1 will be much slower than the forward reaction and can thus be ignored. On the other hand, our estimate of t_{chem} will be too large if other CO-to- CH_4 conversion mechanisms (such as heterogeneous reactions on Fe particles) exist. We are concerned here primarily with the order of magnitude of t_{chem} , which we expect to be less sensitive to the exact details of the kinetics.
 22. Because $Kt_{\text{chem}}(0) = H^2$ the influence of K in this expression is not immediately apparent. Its influence is, in fact, considerable since it determines the level $z = 0$ and thus the value for $f_{\text{CO}}(0)$.
 23. From its definition we compute $h_{\text{chem}} \approx 25$ km at the 1100°K level, where $H = 220$ km. Thus $h_{\text{chem}}^2/H^2 \approx 0.013 \ll 1$.
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 28. We thank J. Lewis, H. Larson, R. Beer, and F. Taylor for valuable discussions. The research was supported by NSF grant DES-74-14116 and NASA grant NGL-22-009-521. Part of this work was completed while R.G.P. was a summer visitor at the Jet Propulsion Laboratory, California Institute of Technology, which is supported by NASA contract 7-100.

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Minimum Size of Mammalian Homeotherms: Role of the Thermal Environment

Abstract. *The minimum size of a mammalian homeotherm appears to be related to the animal's maximum rate of endogenous heat production, the ambient thermal environment, and the animal's ability to be a facultative homeotherm.*

Pearson (1) analyzed data for metabolism of shrews and small mice and concluded that because metabolic rates per unit of body mass become increasingly large for smaller and smaller mammals, there exists a lower limit to mammalian size beyond which metabolic rates would become impossibly large. Indeed, his analysis predicted that the smallest mammal should be approximately the size of the smallest shrew (approximately 2.5 g). In this report I extend the work of Pearson to ask, Is the minimum size of mammalian homeotherms entirely a property of the animals, or is it, in part, determined by the thermal environment?

Many additional data now have been accumulated on the minimum metabolic rates of small mammals (Fig. 1). The relationship between minimum metabolic rate and body size in thermoneutrality is essentially linear ($r^2 = .42$), although a power function provides a slightly better fit ($r^2 = .48$; see Fig. 1 for regression). The smallest (about 7 g) adult mammals (excluding shrews and bats) have metabolic rates that are only one-third the rate reported (2) for the masked shrew.

The metabolism-body mass relationships for most homeotherms do not show the dramatic increase in metabolism near

the minimum size of mammalian homeotherms that has been reported for shrews (1). This is partly because the metabolic data for shrews were all determined for animals held at 24°C , which is lower than thermal neutrality for all shrews (3). Thus, the experimental conditions were cold enough that the animals responded with elevated metabolic rates to maintain homeothermy. Because the amount of cold stress to the shrews is related inversely to body size, smaller and smaller shrews had higher and higher metabolic rates. However, it is not so clear that very small shrews would necessarily have extraordinarily high metabolic rates if subjected to conditions of thermal neutrality, and, indeed, there are some data showing that British shrews have metabolic rates (at rest and during activity) that are not different from those of similarly sized mice (4).

For several reasons related to heat transfer from organisms (namely, that the surface area/body mass ratio of homeotherms is greater in smaller animals, and that the convective boundary layer of still air around any animal is thinner for smaller animals), smaller body size (with all other things held constant) is usually related to greater heat losses from animals. That the minimum metabolic rates (heat production) relative to body size for small mammals do not show a dramatic increase as body size becomes smaller (5) indicates that very small mammals need not have extraordinarily high rates of metabolic heat production to remain homeothermic. However, the range of thermal environments in which an animal can maintain a minimum metabolic rate and a constant body temperature becomes smaller for smaller animals, such that an infinitely small animal can maintain a constant body temperature only in a perfectly constant thermal environment. Thus, a very small animal can be homeothermic if (i) it has the capacity for extraordinarily high heat production (6), or (ii) it has the capacity for precise body temperature regulation through nanoclimate selection and possibly the ability to be facultatively homeothermic. The former seems to describe endothermic mammals and birds, and the latter tends to describe numerous reptiles and insects.

How, then, can one predict the minimum size of endothermic homeotherms? The answer is that it is not possible to predict the smallest size of endothermic homeotherms without also specifying the environment in which the animal exists. Homeotherms theoretically can be infinitely small (in thermoneutral environ-

Fig. 1. Metabolic rates (M) of homeotherms as a function of body mass (m). Minimum metabolic rates of (●) small mammals at thermoneutrality (12), (▲) shrews held at 24°C (1), and (■) small mammals held at 0°C (2). The best-fit equation for mammals at thermoneutrality is $M = 0.033m^{-0.39}$ ($r^2 = .48$); the best fit for shrews at 24°C , $M = 0.103m^{-0.475}$ ($r^2 = .96$); and the best fit for mammals at 0°C , $M = 0.27m^{-0.64}$ ($r^2 = .92$).

