tion artifact. It is due to irregularities in the nozzle.

High-resolution images such as those in Figs. 2 and 3 contain interesting structural information about the flow. However, the images also contain accurate absolute information on the nitrogen density. The estimated root-mean-square error in the absolute density throughout the three-dimensional image of the jet is less than 3% of the peak value.

We also theoretically calculated the density in the supersonic expansion (*13*) by means of measured values of the plenum temperature and pressure, the nozzle diameter, and the height above the nozzle. Comparing the experimentally measured densities within the barrel shock with the theoretically calculated ones at a height of 2.10 mm above the nozzle yielded a root-mean-square difference of 1.8% of the maximum density at that height, which was 0.045 mg/cm^3. There are no free parameters in the theoretical calculation. The theoretical and experimental densities are calculated entirely independently.

We have also produced images of multiple expansions. The density in horizontal planes above two and three nozzles are shown in Fig. 4, a to c and d to f, respectively. Here strong shock waves form at the intersection of the supersonic expansions. Also visible are the barrel shock waves surrounding each expansion. As for the single expansion, these images also contain accurate information on the density at every point.

Acquiring instantaneous two- or three-dimensional images with beam-deflection optical tomography would be advantageous. As the apparatus required for these measurements is very simple, multiple optical systems can be constructed to simultaneously take a number of projections. This might involve multiple laser diode-detector pairs, moiré deflectometry systems (*8*), or differential interferometry systems. Differential interferometers also measure gradients in the index of refraction and have some of the advantages described above for beam-deflection measurements. Other experiments (*7–10, 12, 13, 15*) have shown that good quality images may be produced with a small number of projections (ten or fewer). The technique that uses position-sensitive detectors described here is particularly interesting because both phase and absorption may be measured simultaneously. Combined phase-absorption tomography would be useful for concentration measurements in strongly refracting flows, for example. Considering the simplicity of the apparatus required for beam-deflection tomography and the accuracy, wide dynamic range, and high spatial resolution obtained, the technique may prove valuable in a variety of fields of study ranging from turbulence to plasma instabilities.

REFERENCES AND NOTES

1. S. A. J. Druet and J. P. E. Taran, *Prog. Quantum Electron.* 7, 1 (1981); R. J. Hall and A. C. Eckbreth, *Laser Appl.* **5**, 213 (1984).
2. G. Kychakoff, P. H. Paul, I. van Cruyningen, R. K. Hanson, *Appl. Opt.* **26**, 2498 (1987); G. Kychakoff *et al.*, *Science* **224**, 382 (1984).
3. B. Yip, D. C. Fourguette, M. B. Long, *Appl. Opt.* **25**, 3919 (1986).
4. B. Yip, J. K. Lam, M. B. Winter, M. Long, *Science* **235**, 1209 (1987).
5. S. R. Deans, *The Radon Transform and Some of Its Applications* (Wiley, New York, 1983).
6. G. W. Faris and R. L. Byer, *Opt. Lett.* **12**, 72 (1987).
7. ———, *ibid.*, p. 155 (1987).
8. J. Stricker, *Appl. Opt.* **23**, 3657 (1984).
9. R. Snyder and L. Hesselink, *ibid.* **24**, 4046 (1985).
10. H. M. Hertz, *Opt. Commun.* **54**, 131 (1985).
11. W. Alwang, L. Cavanaugh, R. Burr, A. Hauer, "Optical techniques for flow visualization and flow field measurements in aircraft turbomachinery," item 1, Final Report, Naval Air Systems Command contract N00019-69-C-0322, PWA-3942 (Pratt & Whitney Aircraft Company, East Hartford, CT, 1970).
12. R. D. Maltulka and D. J. Collins, *J. Appl. Phys.* **42**, 1109 (1971).
13. G. W. Faris and R. L. Byer, *Opt. Lett.* **11**, 413 (1986).
14. K. E. Bennett, G. W. Faris, R. L. Byer, *Appl. Opt.* **23**, 2678 (1984).
15. S. R. Ray and H. G. Semerjian, *Prog. Astronaut. Aeronaut.* **92**, 300 (1983).
16. A. J. Devaney, *IEEE Trans. Biomed. Eng.* **30**, 377 (1983).
17. F. J. Weinberg, *Optics of Flames* (Butterworth, London, 1963), p. 24.

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Was Venus Wet? Deuterium Reconsidered

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The ratio of deuterium to hydrogen on Venus has been accepted as proof of a wetter, more Earth-like past on that planet. However, the present-day water abundance and the nonthermal hydrogen escape flux on Venus imply that hydrogen is in a steady state and that a hydrogen source, most likely cometary infall, is present. An alternative interpretation of the D/H ratio is offered, in which the measured value is consistent with a steady-state evolution over the age of the solar system. No past water excess is required to explain the isotopic data.

BOTTICELLI DEPICTED A WATERY birth of Venus, standing serenely on the shell of a giant clam. Planetologists have held a similar view of the birth of the love goddess' celestial counterpart. However, it may not have been so. It is well established that Venus is approximately 1×10^{-5} times as wet as Earth (*1*). The ratio of deuterium to hydrogen (D/H ratio) on Venus is 100 times as great as that of Earth (*2, 3*). This D/H ratio has been viewed as a residue from mass-selective fractionating escape of at least 100 times the current water abundance. According to this interpretation, the estimation of the primordial water endowment on Venus might be higher by an even greater factor if deuterium has escaped as well. An alternative explanation of the observed D/H ratio, based on the current water abundance and nonthermal hydrogen escape flux, requires only a steady-state evolution of water on Venus.

Evolutionary studies have typically concentrated on accounting for the loss of water on Venus because it has been assumed that Venus and Earth had similar primordial water endowments (*4*). A consistent picture emerged, supported by detailed modeling, that Venus lost its endowment through a runaway greenhouse effect that boiled its oceans, allowing rapid photolysis of water. The hydrogen thus produced escaped into space, first by an extremely rapid hydrodynamic flux and later, when the water mixing ratio fell below 15%, by various nonthermal processes (*5, 6*).

The evolution of the D/H ratio on Venus has been presented as an example of Rayleigh fractionation (*5*). The escape of these isotopes can be represented by two differential equations

$$d\mathrm{H}/dt = -K\mathrm{H} \tag{1}$$

$$d\mathrm{D}/dt = -Kf\mathrm{D} \tag{2}$$

where H and D represent the planetary inventories of hydrogen and deuterium, respectively, and f is the fractionation factor, which represents the efficiency of deuterium escape relative to hydrogen. The use of the constant K to represent the relation between hydrogen abundance and escape rate glosses over a much more complicated nonlinear function which has been derived by Kasting and Pollack (*6*) and Kumar *et al.* (*5*). How-

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ever, if escape has occurred at a rate near the diffusion-limited flux, then the assumption of a linear relation is valid, and the solution is

$$(\mathrm{D/H})_1 = (\mathrm{D/H})_0 \, [(X_{\mathrm{H_2O}})_0/(X_{\mathrm{H_2O}})_1]^{1-f} \quad (3)$$

where $X_{\mathrm{H_2O}}$, the mixing ratio of water, is assumed to represent the total hydrogen inventory and the subscripts 1 and 0 indicate "present" and "primordial," respectively. If the primordial D/H ratio on Venus, $(\mathrm{D/H})_0$, was equal to the modern terrestrial value (1.6×10^{-4}), then this solution implies that the primordial water abundance on Venus was much greater than the present-day abundance. In the limit that only hydrogen has escaped ($f = 0$), the water abundance has declined by the same factor by which the D/H ratio is enhanced, roughly two orders of magnitude. If f is larger than zero in the present day, or has been in the past, then it is possible that vastly greater quantities of water have been lost over geological time.

This interpretation of the D/H ratio on Venus depends on two questionable assumptions. The range of D/H values observed in solar system objects has yet to be explained in a consistent manner. In particular, the origin of Earth's D/H ratio, which is enhanced by a factor of 8 to 10 over the apparent cosmic value, is unresolved (*7*). Thus, although it represents one reasonable possibility, the assumption that the initial D/H ratio on Venus was identical to the current terrestrial value should not be used to draw definitive conclusions about the history of hydrogen isotopes on that planet.

A more serious error is the assumption, implicit in the formulation of Eqs. 1 and 2, that the water abundance has declined monotonically. The current water abundance on Venus can be divided by the current hydrogen escape flux to yield a quantity that can be regarded as a characteristic lifetime for water on Venus. On present-day Venus, hydrogen is escaping from the upper atmosphere by nonthermal processes, mainly hot oxygen atom impact (*2*) and charge exchange with hot H^+ (*5*), with a total escape flux of 2×10^7 hydrogen atoms cm^{-2} sec^{-1}. Thus the current water abundance of 20 ppm has a lifetime of only 10^8 years, so there must be a source that is supplying hydrogen to Venus at a rate comparable to the escape flux. Possible sources include volcanic outgassing (*5*) and impact of volatile-rich bodies. Although there have been observations of secular changes in the $\mathrm{SO_2}$ abundance above the clouds, which have been interpreted as the signature of ongoing volcanism (*8*), the history and current extent of outgassing on Venus are unknown. The estimated magnitude of the current flux of comets and asteroids through the inner solar system is not well constrained at present, but it appears that the episodic impact of comets and volatile-rich asteroids is a hydrogen source of an appropriate magnitude (*9, 10*). The short lifetime of water on Venus compared to the age of the solar system strongly suggests that rather than being in a monotonic decline, as has been assumed in previous models, the water abundance is currently in a steady state.

What are the consequences of this steady state for the evolution of the D/H ratio? By modifying Eq. 1 to include a source term for hydrogen and assuming a steady state, we may write

$$d\mathrm{H_{ss}}/dt = \phi - (K/f)\mathrm{H_{ss}} = 0 \quad (4)$$

$$d\mathrm{D}/dt = \alpha\phi - K\mathrm{D} \quad (5)$$

where ϕ is the magnitude of the hydrogen source, α is the D/H ratio of the source hydrogen, and $\mathrm{H_{ss}}$ is the steady-state hydrogen abundance. These equations have the time-dependent solution

$$(\mathrm{D/H})\,(t) = \alpha/f - [(\alpha/f) - (\mathrm{D/H})_0]e^{-(\phi f/\mathrm{H_{ss}})t} \quad (6)$$

If α is set equal to $(\mathrm{D/H})_0$, then Eq. 6 reduces to equation 10 in Krasnopolsky (*11*). This assumption is probably reasonable if the major hydrogen source is endogenous. But, if the major source is exogenous, this assumption cannot be made.

A solution that has been given for the steady-state case is (*12*)

$$(\mathrm{D/H}) = \alpha/f \quad (7)$$

Although this solution is approached by Eq. 6 as t goes to infinity, it is not obvious that the time-dependent term, which represents the decaying signature of the original (D/H), can be ignored. This term declines exponentially with a decay constant given by

$$\tau = \mathrm{H}/\phi f \quad (8)$$

With the values of hydrogen abundance and escape flux given above, and Krasnopolsky's (*11*) value of $f = 0.022$ for charge exchange, $\tau = 3.97 \times 10^9$ years. Hunten *et al.* (*12*) have derived a value of $f = 0.013$ for a fractionation factor (weighted to allow for the individual fractionation factors and relative fluxes of each important escape process) that yields $\tau = 6.71 \times 10^9$ years. The value of τ seems to be on the order of the age of the solar system. However, the solar flux in the extreme ultraviolet is thought to have been more intense in the past (*13*). Thus the hydrogen escape flux may have been at or near the diffusion limit for much of the history of Venus (*11*). This would lower τ by an amount proportional to the increase in escape flux for a given water abundance. Uncertainties in estimating the present and past values of ϕ, $\mathrm{H_{ss}}$, and f make it difficult to determine whether the limiting solution, Eq. 7, should be reached in 4.5×10^9 years of steady-state evolution of the D/H ratio on Venus.

If the D/H ratio in the hydrogen source for Venus has a terrestrial value, and the weighted fractionation factor given above is used ($\alpha = 1.6 \times 10^{-4}$ and $f = 0.013$), then Eq. 7 yields a D/H ratio of 1.23×10^{-2}, which is within the uncertainty of the measurements of D/H on Venus. If the dominant hydrogen source is from cometary impacts, then the steady-state D/H ratio is dependent on the average D/H ratio in the impacting objects, and both the D/H ratio and the hydrogen abundance will fluctuate stochastically with random impacts and subsequent periods of enhanced escape (*10*). The average cometary D/H ratio is unknown. Some models of comet formation predict substantial enhancements of D/H in cometary ices (*14*). In situ measurements performed with the Giotto Neutral Mass Spectrometer found that the D/H ratio of the coma of comet Halley lies within a range from 0.6×10^{-4} to 4.8×10^{-4} (*15*). It is not known how accurately this measurement represents the bulk D/H ratio of comet Halley, or whether this should represent a cometary average D/H ratio. This range of D/H values for α in Eq. 7 gives a steady-state D/H ratio of 0.46×10^{-2} to 3.7×10^{-2} for Venus. The observed value is bracketed within this range. The inclusion of the exponential term in Eq. 6 with $\tau \approx 4.5 \times 10^9$ lowers these values to some extent depending on the chosen value for $(\mathrm{D/H})_0$. However, many reasonable combinations of the unknown parameters α, f, $(\mathrm{D/H})_0$, and $\mathrm{H_{ss}}$ in Eq. 6 give steady-state D/H values that are consistent with the observations.

Thus, although the preceding calculations do not prove that Venus had a dry past, it is not necessary to postulate the existence of ancient oceans to explain the observed D/H ratio on Venus. Indeed, there is no other evidence that Venus was wet, other than arguments based on a preference for accretion models in which the terrestrial planets formed relatively homogeneously. More detailed knowledge of the surface morphology of Venus, soon to be provided by the Magellan Radar Mapper, and future studies of the surface mineralogy are the most promising avenues of study to determine definitively whether Venus was wet.

REFERENCES AND NOTES

1. C. Sagan, *Science* 133, 849 (1961). For a more recent review see J. S. Lewis and R. G. Prinn, *Planets and Their Atmospheres* (Academic Press, New York, 1984), pp. 128–197. Water abundance observations are reported in: M. J. S. Belton and D. M.

Hunten, *Astrophys. J.* **146**, 307 (1966); R. W. Boese, J. B. Pollack, P. M. Silvaggio, *Science* **203**, 797 (1979); V. I. Moroz *et al.*, *Pis'ma Astron. Zh.* **8**, 404 (1982); L. D. G. Young, A. T. Young, L. V. Zasova, *Icarus* **60**, 138 (1984).

2. M. B. McElroy, M. J. Prather, and J. M. Rodriguez [*Science* **215**, 1614 (1982)] reported a D/H ratio on Venus of approximately 1.0×10^{-2}.
3. T. M. Donahue, J. H. Hoffman, R. R. Hodges, Jr., and A. J. Watson [*ibid.* **216**, 630 (1982)] reported a D/H ratio of $(1.6 \pm 0.2) \times 10^{-2}$.
4. The theory of equilibrium condensation, in which the nebular temperature gradient controls the composition of condensates, places the inner boundary of hydrated silicate condensation at a heliocentric distance between the orbits of Earth and Mars and predicts a much greater initial water abundance on Earth than on Venus [J. S. Lewis, *Icarus* **16**, 241 (1972)]. Proponents of a wet young Venus argue that sufficient mixing occurred among the terrestrial planetesimals to provide them with nearly identical volatile abundances. However, the theory of planetary accretion is incomplete, and scenarios range from those in which planetesimals from a wide range of heliocentric distances are incorporated into each planet to those in which eccentricities remain low and a large degree of segregation is maintained [R. Greenberg, in *Planetary and Satellite Atmospheres: Origin and Evolution*, S. K. Atreya, J. B. Pollack, M. S. Matthews, Eds. (Univ. of Arizona Press, Tucson, in press)]. The observed differences in bulk density among the terrestrial planets must be the result of incomplete mixing among their precursors. The extent of such mixing should be regarded as an open question, awaiting more complete condensation-accretion models.
5. S. Kumar, D. M. Hunten, J. B. Pollack, *Icarus* **55**, 369 (1983).
6. J. F. Kasting and J. B. Pollack, *ibid.* **53**, 479 (1983).
7. D. H. Grinspoon and J. S. Lewis, *ibid.*, in press.
8. L. W. Esposito, *Science* **223**, 1072 (1984).
9. J. S. Lewis, *Earth Planet. Sci. Lett.* **22**, 239 (1974).
10. D. H. Grinspoon and J. S. Lewis, *Icarus*, in press.
11. V. A. Krasnopolsky, *ibid.* **62**, 221 (1985).
12. D. M. Hunten, T. Donahue, J. F. Kasting, J. C. G. Walker, in *Planetary and Satellite Atmospheres: Origin and Evolution*, S. K. Atreya, J. B. Pollack, M. S. Matthews, Eds. (Univ. of Arizona Press, Tucson, in press).
13. K. J. Zahnle and J. C. G. Walker, *Rev. Geophys. Space Phys.* **20**, 280 (1982).
14. W. H. Ip, in *Ices in the Solar System*, J. Klinger, Ed. (Reidel, Dordrecht, the Netherlands, 1984), vol. 156 of *NATO Advanced Science Institute Series, Series C*, pp. 389–396; V. Vanysek and P. Vanysek, *Icarus* **61**, 57 (1985).
15. P. Eberhardt *et al.*, in *Proceedings, Lunar and Planetary Science Conference, 18th* (Lunar and Planetary Institute, Houston, 1987), pp. 252–253.

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Blocking of HIV-1 Infectivity by a Soluble, Secreted Form of the CD4 Antigen

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The initial event in the infection of human T lymphocytes, macrophages, and other cells by human immunodeficiency virus (HIV-1) is the attachment of the HIV-1 envelope glycoprotein gp120 to its cellular receptor, CD4. As a step toward designing antagonists of this binding event, soluble, secreted forms of CD4 were produced by transfection of mammalian cells with vectors encoding versions of CD4 lacking its transmembrane and cytoplasmic domains. The soluble CD4 so produced binds gp120 with an affinity and specificity comparable to intact CD4 and is capable of neutralizing the infectivity of HIV-1. These studies reveal that the high-affinity CD4-gp120 interaction does not require other cell or viral components and may establish a novel basis for therapeutic intervention in the acquired immune deficiency syndrome (AIDS).

THE PRIMARY IMMUNOLOGIC ABNORMALITY resulting from infection by the human immunodeficiency virus (HIV-1) is the progressive depletion and functional impairment of T cells expressing the CD4 antigen (*1*). CD4 is a nonpolymorphic surface glycoprotein with partial sequence identity to immunoglobulins (*2*). The CD4 and CD8 antigens define distinct subsets of mature peripheral T cells, whose ability to interact with antigen is restricted by the expression of class II and class I major histocompatibility antigens on the antigen-presenting cell, respectively (*3*). Most CD4$^+$ T cells have helper/inducer function, although some have cytotoxic/suppressor activity, usually associated with CD8$^+$ T cells (*4*). The ability of HIV-1 to selectively infect, replicate in, and destroy CD4$^+$ T cells in part explains the loss of CD4$^+$ helper/inducer function characteristic of AIDS (*5*). That the CD4 molecule itself is the cellular receptor for HIV was first suggested by the ability of antibodies to CD4 to block HIV-1 infection and syncytia induction (*6*), and confirmed by the detection of CD4 binding to gp120, the major envelope glycoprotein of HIV-1 (*7*), and the finding that nonpermissive human cells are rendered susceptible to HIV-1 infection after the stable expression of a CD4 complementary DNA (cDNA) (*8*). The interaction of CD4 with gp120 also plays a critical role in the formation of multinucleated giant cells by cell fusion, the major cytopathic effect induced by HIV-1 (*9, 10*). Fusion of uninfected CD4$^+$ cells with HIV-1 infected cells is blocked by antibodies to CD4 (*9*); furthermore, cells producing HIV-1 *env* polypeptides in the absence of other viral gene products efficiently induce the fusion of uninfected CD4$^+$ cells (*11*). Given its essential role, the interaction of gp120 with CD4 is probably not significantly affected by genetic variation among HIV isolates (*12*), and thus provides an attractive approach to therapeutic intervention against HIV-1 (*13*). One successful strategy for the treatment of receptor-mediated abnormalities has been the design of antagonists that block binding of the natural ligand (*14*). To begin development of inhibitors of HIV-1 attachment and gp120-mediated cell fusion, we have produced soluble CD4 analogs with an affinity for gp120 comparable to that of intact CD4. The ability of soluble CD4 to efficiently neutralize HIV-1 infection of CD4$^+$ cells in vitro suggests the potential application of such molecules in the treatment of AIDS and related conditions.

The CD4 precursor consists of a signal peptide, a 370–amino acid extracellular region containing four immunoglobulin-like domains, a membrane-spanning domain, and a charged intracellular region of 40 residues (*2*) (Fig. 1). We previously expressed the intact CD4 antigen in Chinese hamster ovary (CHO) cells under the transcriptional control of the SV40 early promoter; the CD4 expressed by these cells is located on the cell surface and binds gp120 (*15*). To produce soluble versions of CD4, we replaced the transmembrane domain, which presumably anchors the molecule to the cell surface, and the cytoplasmic domain, with a short linker sequence containing an in-frame stop codon. The resulting truncated CD4-encoding cDNAs were inserted into expression vectors (*15*) and examined for the ability to direct the biosynthesis and secretion of CD4 antigens. Two constructs were studied: the first included the natural signal sequences of CD4 itself (CD4T), while in the second the CD4 leader was replaced by the signal peptide and first 27 amino acids of the glycoprotein D (gD) of herpes simplex virus type I (GDCD4T) (Fig. 1).

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