Moving Flame Experiment with Liquid Mercury: Possible Implications for the Venus Atmosphere

G. Schubert; J. A. Whitehead

Science, New Series, Vol. 163, No. 3862. (Jan. 3, 1969), pp. 71-72.

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10. C. G. A. Harrison and L. K. Somayajulu, *Nature* **212**, 1193 (1966).
11. A. Cox and G. B. Dalrymple, *J. Geophys. Res.* **72**, 2603 (1967).
12. D. H. Matthews and J. Bath, *Geophys. J.* **13**, 349 (1967).
13. C. G. A. Harrison, *J. Geophys. Res.* **73**, 2137 (1968).
14. D. Ninkovich, N. D. Opdyke, B. C. Heezen, J. H. Foster, *Earth Planet. Sci. Lett.* **1**, 476 (1966).
15. N. D. Opdyke, B. Glass, J. D. Hays, J. H. Foster, *Science* **154**, 349 (1966); J. D. Hays and N. D. Opdyke, *ibid.* **158**, 1001 (1967); N. D. Watkins and H. G. Goodell, *Earth Planet. Sci. Lett.* **2**, 123 (1967).
16. B. P. Luyendyk, J. D. Mudie, C. G. A. Harrison, *J. Geophys. Res.* **73**, 5951 (1968).
17. B. P. Luyendyk and W. G. Melson, *Nature* **215**, 147 (1967).
18. A. Cox, *J. Geophys. Res.* **73**, 3247 (1968).
19. T. Rikitake, *Proc. Cambridge Phil. Soc.* **54**, 89 (1958).
20. P. J. Smith, *Geophys. J.* **12**, 321 (1967); **13**, 417, 483 (1967).
21. The end points of the profile are 20°58.7′N, 109°25.9′W and 20°44.8′N, 108°52.8′W.
22. T. E. Chase and H. W. Menard, topographic charts 3, 4A, 5, and 6 prepared for the U.S. Bureau of Commercial Fisheries (La Jolla, California, 1964).
23. The collection of these data was made possible by the developmental efforts of the Marine Physical Laboratory's Deep Tow Group at the Scripps Institution of Oceanography. We thank C. Lowenstein, D. Boegeman, F. Stone, G. Forbes, J. Donovan, M. Benson, M. McGehee, and W. Normark for the operation of the instrumentation at sea; J. Mudie for helping to solve computer problems; B. Luyendyk, H. Menard, J. Mudie, T. Atwater, and W. Normark for discussions; Captain N. Ferris and the crew of the R.V. *Thomas Washington*. Supported by the ONR and the Deep Submergence Systems Project.

23 August 1968; revised 18 October 1968 ■

Moving Flame Experiment with Liquid Mercury: Possible Implications for the Venus Atmosphere

Abstract. *A bunsen flame rotated under a cylindrical annulus filled with liquid mercury forces the liquid mercury to rotate in a direction counter to that of the rotating flame. The rate of rotation of the liquid is several times greater than that of the flame. This observation may provide an explanation for the high velocities of apparent cloud formations in the upper atmosphere of Venus.*

The idea that periodic radiative heating of the earth's atmosphere might cause it to acquire a net angular momentum was originally suggested by Halley (*1*). Fultz (*2*) performed an experiment in which a flame was rotated around the outside bottom rim of a cylindrical vessel filled with water. Within the fluid a net angular momentum was established in the sense opposite to the motion of the flame. Stern (*3*) carried out a similar series of experiments in which the water was confined within a cylindrical annulus in order to reduce the effects of radial convection. The water acquired an average rotation in a direction counter to that of the flame which was 0.1 to 1.0 percent of the rate of rotation of the flame. A linearized analysis (*4*) of the two-dimensional motions induced in a horizontal layer of fluid by traveling sinusoidal temperature perturbations applied at the boundaries demonstrates how the Reynolds stress associated with fluctuations in the induced velocity supports the mean shear of the fluid. This analysis is valid only if the speed of the traveling thermal wave is very much greater than the mean velocity induced in the fluid.

These experiments show that a moving source of heat can impart angular momentum to a fluid in a sense opposite to the motion of the source. However, the fluid rotates with an angular speed several orders of magnitude smaller than the rate of rotation of the source. Thus the physically important question of whether a moving source of heat could produce a mean motion of a fluid with velocity comparable to or even greater than that of the source has thus far remained unanswered. We have measured mean rotational speeds in liquid mercury which are four times as great as the speed of the moving flame.

The experimental apparatus (Fig. 1) consisted of a cylindrical annulus of rectangular cross section. The bottom of the channel was an aluminum disk 1 mm thick; the side and top walls of the channel were made of Plexiglas (5 mm thick). Inside and outside diameters of the channel were 25 cm and 35 cm, respectively, and the channel height was 2 cm. A bunsen flame, mounted on a turntable, provided a rotating source of heat beneath the bottom wall of the channel. The flame was spread out radially in order to provide uniform heating and to minimize the radial motions within the liquid. Liquid mercury filled the channel to a depth of 1.5 cm and was covered with a layer of distilled water 0.5 cm thick in order to retard oxidation. If we interpret the mean length of the annular channel as an equivalent wavelength, then 2π times the ratio of the depth of the mercury to the wavelength is 0.1. The rotation rate of white ball bearings (4 mm in diameter), floating at the mercury-water interface, provided a measure of the angular velocity of the mercury, and the speed of the bunsen flame was indicated by a synchronized pointer directed at the flame.

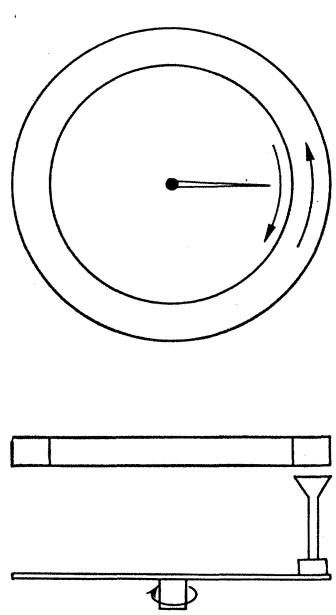

Fig. 1. Schematic diagram of the apparatus for the moving flame experiment.

The speed of the flame was 1 mm/sec, and the temperature of the mercury increased from room temperature at the rate of about 3°C per minute. The time scale for thermal diffusion from the bottom to the top of the mercury is about one flame rotation period. A steady-state flow was established after about 5 minutes (about one-third the time required for the flame to complete a rotation); however, the mercury was rotating so rapidly in a direction counter to that of the flame, about 4 mm/sec, that it completed almost two revolutions over the flame in this time.

The motion of a large number of vapor bubbles floating at the mercury-water interface showed that the flow was uniform over a large portion of the cylindrical annulus. However, immediately above the flame, and in a small wake behind it, the motion was disorganized. An indication of the velocity below the surface of the mercury was obtained by observing a ball bearing 1 cm in diameter moving almost as fast as the smaller ones (the speed of the large bearing was within a few percent of that of the smaller ones). With water as the working fluid, velocities that were negligibly small compared with the flame speed were imparted to the liquid.

The high angular velocities observed in the experiment with liquid mercury are the result of the rapidity of thermal diffusion as compared with viscous diffusion. The Prandtl number, the ratio of kinematic viscosity to thermal diffusivity, for liquid mercury is two orders of magnitude less than that of water. Linearized analysis of two-dimensional motions predicts that the ratio of the mean fluid velocity to the speed of the traveling thermal wave becomes large as the Prandtl number becomes small; thus the theory is not valid in the limit of Prandtl number approaching zero. Results from an extended analysis which includes nonlinear interactions between the perturbations and the mean flow are shown in Fig. 2, where the ratio of mean flow velocity to wave speed is plotted against Prandtl number. This velocity ratio, which is approximately proportional to the 15/4 power of the inverse Prandtl number for Prandtl numbers between 1 and 0.1, is of the order of unity for Prandtl numbers of the order 10^{-1}.

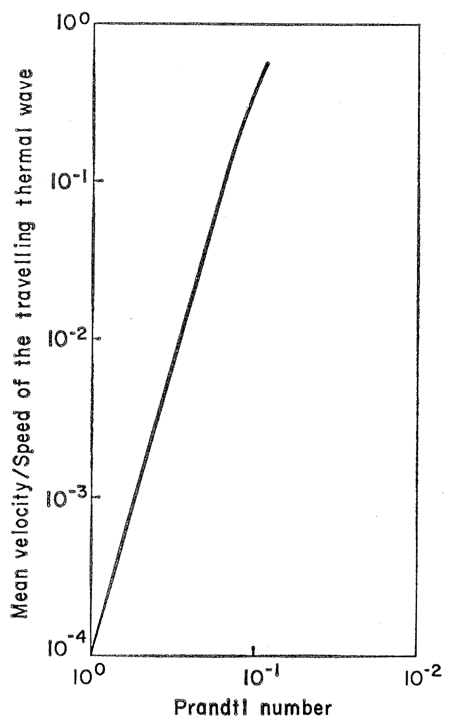

Fig. 2. Ratio of the mean velocity of the fluid to the speed of the forcing thermal wave plotted against Prandtl number. Fluid was confined within a two-dimensional channel, and temperature perturbations of the traveling wave were applied at the walls. The Boussinesq equations of motion were solved numerically for the following case: $\Delta T/T = 10^{-2}$, $\omega h^2/\kappa = 1$, $gh/U^2 = 10^4$, $kh = 10^{-2}$, where ω is the angular frequency, k is the wave number of the thermal wave, h is the channel height, κ is the thermal diffusivity, g is the acceleration of gravity, $U = \omega/k$, and $\Delta T/T$ is the relative magnitude of forced fluctuations of the wall temperature. The nonlinear interaction of the perturbations and the mean flow is included in the solution.

This experiment demonstrates that the periodic motion of a source of heat can lead to a mean fluid motion with speed several times faster than that of the source. This phenomenon may explain the relatively rapid displacements of clouds in the high atmosphere of Venus which have been observed in ultraviolet photographs (*5*). These observations suggest that at least the upper layers of the atmosphere of Venus are moving with speeds of 300 km/hour relative to the planet's surface. The overhead motion of the sun would provide a periodic traveling thermal source, and the zonal flow induced by this movement would be in the direction of the cloud motion, which is some 20 times faster than the overhead speed of the sun.

In the atmosphere of Venus, a near-infrared band of carbon dioxide absorbs a significant fraction of the incident solar radiation. At altitudes of tens of kilometers where pressures are of the order of an atmosphere or less (*6*), a kilometer of CO_2 absorbs several percent of the incident solar radiation (*7*). The radiative transfer would be characterized by an effective diffusion coefficient (*8*)

$$\kappa = 16\sigma T^3 l / 3\rho c_p$$

where σ is the Stefan-Boltzmann constant, T is the temperature, l is the mean free path of the radiation, ρ is the density, and c_p is the specific heat at constant pressure. At heights of tens of kilometers, $\kappa \approx 3l$ cm^2 sec^{-1}, and l is at least of the order of 10^5 cm (*7*). Momentum transport would at best be accomplished by turbulent mixing, for which the mixing coefficient is not likely to exceed 10^4 cm^2 sec^{-1} (*8*). Thus it is possible that in the high atmosphere of Venus periodic heating from above occurs in a medium that can transport heat more effectively than momentum. Under such circumstances, zonal motions at high velocity could be induced in the Venus atmosphere.

G. SCHUBERT

Department of Planetary and Space Science, University of California, Los Angeles

J. A. WHITEHEAD

Institute of Geophysics and Planetary Physics, University of California, Los Angeles

References and Notes

1. E. Halley, *Phil. Trans. Roy. Soc. London Ser. A Math. Phys. Sci.* **16**, 153 (1686).
2. D. Fultz, *Meteorol. Monogr.* **4**, 36 (1959).
3. M. E. Stern, *Tellus* **11**, 175 (1959).
4. A. Davey, *J. Fluid Mech.* **29**, 137 (1967).
5. B. A. Smith, *Science* **158**, 114 (1967).
6. V. S. Avduevsky, M. Ya. Marov, M. K. Rozhdestvensky, *J. Atmos. Sci.* **25**, 537 (1968).
7. P. Fabian, T. Sasamori, A. Kasahara, in preparation.
8. R. M. Goody and A. R. Robinson, *Astrophys. J.* **146** (1966).

9. We thank W. V. R. Malkus for providing the equipment and laboratory facilities for this experiment, and P. Cox for constructing the apparatus.

5 November 1968

Species Diversity: Benthonic Foraminifera in Western North Atlantic

Abstract. *Maximum species diversity occurs at abyssal depths of greater than 2500 meters. Other diversity peaks occur at depths of 35 to 45 meters and 100 to 200 meters. The peak at 35 to 45 meters is due to species equitability, whereas the other two peaks correspond to an increase in the number of species.*

Populations of benthonic Foraminifera exhibit species-diversity peaks at depths of 35 to 45 m, 100 to 200 m, and greater than 2500 m in the western North Atlantic. The peaks progressively increase in diversity as depth increases, the maximum diversity occurring in depths greater than 2500 m. The depths of the peaks correspond to effective wave base, the edge of the continental shelf, and the abyss. The peak in diversity at 35 to 45 m is due to species equitability rather than to an increase in the number of species, whereas the other two peaks correspond to an increase in the number of species. Data for this pattern are from 84 samples taken at depth ranges from 29 to 5001 m in the western North Atlantic (Fig. 1).

Many foraminiferal species have been recorded in abyssal depths in the Gulf of Mexico (*1*), off California (*2*), and off Panama in the eastern Pacific (*3*). The high foraminiferal diversities in abyssal environments closely reflect the diversity of the other groups of marine invertebrates including Mollusca, Arthropoda, and Echinodermata (*4*). The formerly erroneous viewpoint of very low diversity in the deep sea probably resulted from difficulty in obtaining enough individuals of larger invertebrates for an accurate estimate of the number of species (*4*).

The benthonic Foraminifera, being small, of high density and ubiquitous distribution, do not present many problems encountered in sampling larger organisms. Even in the abyss, hundreds