the surface and supernatant steam during measurement, and return to the purging routine at will. The test vessel has plane parallel windows which should permit schlieren monitoring of currents in relation to thermocouple records and subsequent mathematical treatment. In the meantime, the simple model is serving to screen various compounds and to confirm that the temperature of purified water resting at the boiling point is measurably responsive to extremely small traces of contaminant.

KENNETH HICKMAN
IAN WHITE
Distillation Research Laboratory, Rochester Institute of Technology, Rochester, New York 14623

References and Notes

1. G. L. Gaines, Jr., *Insoluble Monolayers at Liquid-Gas Interfaces* (Interscience, New York, 1966), pp. 179–188.
2. N. K. Adam, *The Physics and Chemistry of Surfaces* (Dover, New York, 1968), pp. 53–68.
3. I. Langmuir, *J. Chem. Phys.* **1**, 756 (1933).
4. D. G. Dervichian, *ibid.* **7**, 931 (1939).
5. W. D. Garrett and J. D. Bullman, *Nav. Res. Lab. Rep. 6003* (1963), pp. ii–18.
6. N. L. Jarvis, C. O. Timmons, W. A. Zisman, in *Retardation of Evaporation by Monolayers*, V. K. LaMer, Ed. (Academic Press, New York, 1962).
7. A. Pockels, *Nature* **46**, 418 (1892); H. Benard, *Ann. Chim. Phys.* **23** (No. 7), 62 (1901); J. A. R. Pearson, *J. Fluid Mech.* **4**, 489 (1958).
8. J. W. Strutt (Baron Rayleigh), *Phil. Mag.* **32** (No. 6), 529 (1916).
9. K. Hickman, paper presented at the meeting of the American Institute of Chemical Engineers, Portland, Ore., 26 August 1969; paper presented at the meeting of the American Institute of Chemical Engineers, Denver, Colo., 30 August 1970.
10. ———, *Office Saline Water Res. Develop. Progr. Rep. No. 585* (1970).
11. P. J. Harris, *ibid.*, p. 22.
12. See O. Mady, *Ind. Eng. Chem.* **59**, 29 (1967).
13. K. Hickman, *Nature* **201**, 985 (1964).
14. ———, *Ind. Eng. Chem.* **56**, 26 (1964), figure 10-A.
15. ———, *Separation Sci.* **3** (No. 6), 551 (Dec. 1968).
16. J. C. Berg and A. Acrivos, *Chem. Eng. Sci.* **20**, 737 (1965).
17. ———, M. Boudart, *Advan. Chem. Eng.* **6**, 105 (1966), figure 17.
18. K. Hickman, *Proc. Int. Symp. Water Desalination, 1st*, 1965 (1967), pp. 180–223.
19. ———, *Desalination* **1**, 13 (1966).
20. See nomenclature in (*22*); see also Jer Ru Maa, *Ind. Eng. Chem. Fundam.* **8**, 560 (1969); *ibid.* **6**, 504 (1967).
21. W. W. Mansfield, *Nature* **172**, 1101 (1953).
22. ———, *ibid.* **175**, 247 (1955).
23. Work supported by grant 14-30-2572 from the Office of Saline Water, U.S. Department of the Interior.

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Lunar Hadley Rille: Considerations of Its Origin

Abstract. *Geomorphology, topographic configuration, comparisons with terrestrial analogs, and considerations of the chemical and physical characteristics of mare lavas indicate that the Hadley Rille is a lava channel. Some of the structure was roofed to form a lava tube, parts of which have subsequently collapsed.*

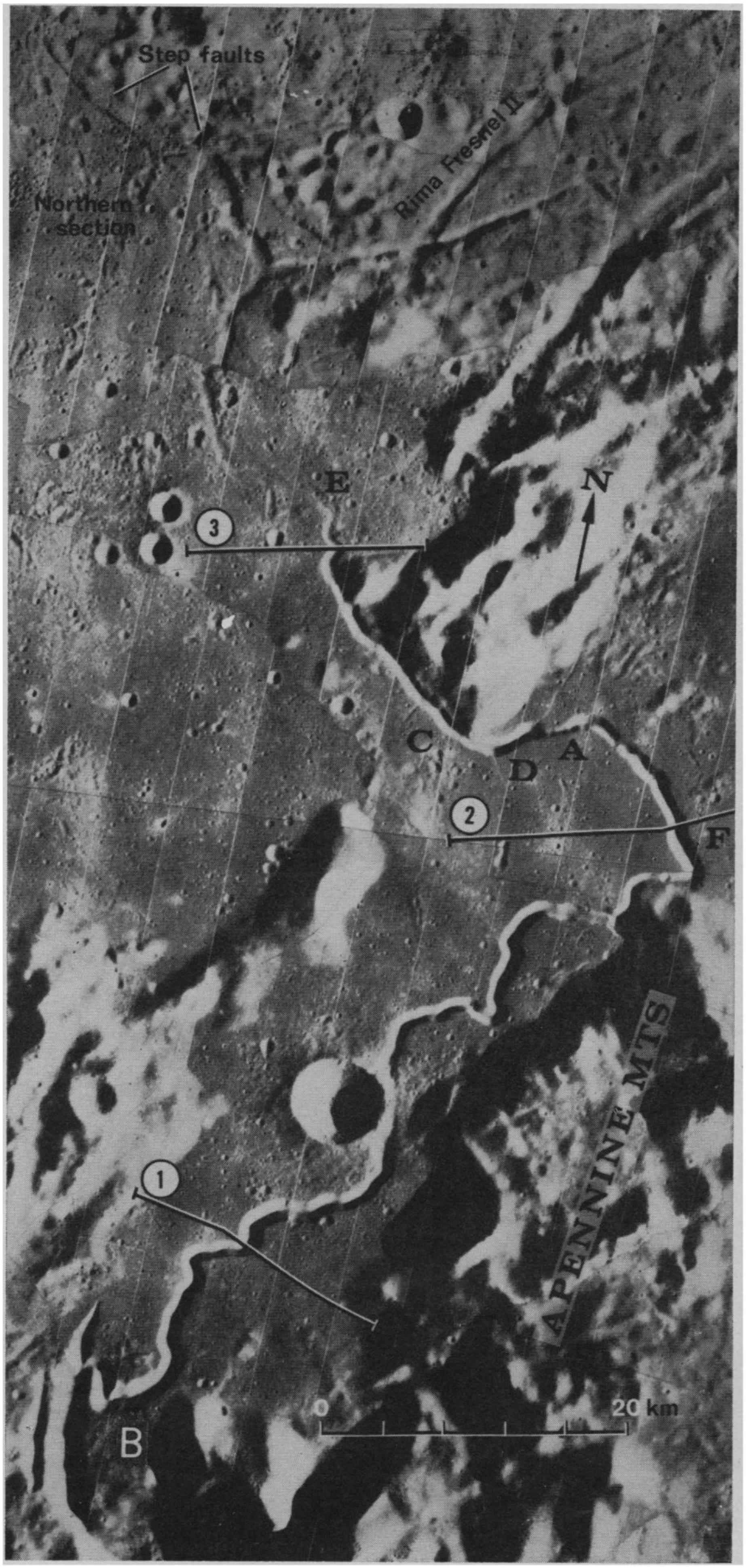
Hadley Rille, in a valley of the Apennine Mountains east of Mare Imbrium, has been selected as the Apollo 15 landing site (*1*) (*F* in Fig. 1). Considerations of its origin are essential to geologic interpretation of the site. The rille is about 135 km long and averages 1.2 km in width and 370 m in depth. The northern section (Fig. 1) is 25 km long, shallower than the main rille, and may not be genetically related to it. Rima Fresnel II, a probable graben, intersects the northern section. An increase in elevation at the northern end may reflect adjustments of the mare after formation of the rille, as indicated by lineaments interpreted as step faults. Hadley Rille is in a class of sinuous rilles which characteristically (i) appear to originate in irregularly shaped craters or depressions, (ii) trend generally downslope, (iii) have discontinuous channels and cut-off branches, (iv) are fairly uniform in width or occasionally taper toward the terminus, (v) are restricted to mare surfaces and appear to be controlled by highland or premare topography, and (vi) form topographic highs along the rille axis. These characteristics, with considerations of mare composition and recently derived elevation determinations of the area (*2*), enable speculation on the origin of Hadley Rille and similar lunar structures.

Several diverse modes of origin have been proposed for lunar sinuous rilles —erosion by ash (*3*) or water (*4, 5*), surface collapse resulting from intrusive stoping (*6*), fluidization of regolith by outgassing through fractures (*7*), or that the rilles are lava channels, collapsed lava tubes, or both (*8, 9*). Most investigators agree that fluid flow is involved; controversy arises as to type of fluid—ash, water, gases, or lava. For a particular rille each mode has one or two strong points in its favor, and it is probable that each class of sinuous rille may have a unique origin. The characteristics of the Hadley Rille, however, most closely resemble those of a lava channel and partly collapsed lava tube.

Recent investigations of prehistoric basalt flows (*10*) and observations of active flows (*11*) provide qualitative and quantitative data on the geomorphology of lava tubes and channels. Tubes and channels are morphologically similar, and, because channels frequently form well-defined crusts of solidified lava, it is often difficult to separate channels from tubes in active flows. For convenience, tubes may be defined as having freestanding roofs after drainage of molten lava, while channels result from open (noncrusted) flow, or from crustal collapse during lava drainage. Depending upon gradient and other parameters, a single structure may have both roofed and unroofed segments, giving the appearance from the air of a discontinuous channel similar to Hadley Rille (*A* in Figs. 1 and 2). Lava tubes and channels form commonly in fluid varieties of basalt. Experimental studies of lunar basaltic lavas (*12*) show that the lavas were very fluid, permitting the formation of tubes, and that the thermal conductivity was quite low, permitting long lava flows and hence long lava tubes. It is, therefore, reasonable to expect lava tubes and channels on mare surfaces and to expect that under prolonged meteoroid bombardment many tube roofs would collapse, leaving sinuous trenches.

Lava tubes and channels often originate in vent craters or depressions associated with regional tectonic features, such as faults, fissures, or fracture systems concentric to calderas. Hadley Rille, similarly, is on the mare-highland boundary marked by fault systems concentric to the Imbrium basin (*13*). The apparent source of the rille is a cleft-shaped structure (*B* in Fig. 1) probably of internal, rather than impact, origin. Lingenfelter *et al.* (*4*) proposed sinuous rille formation from erosion by water that originated from subsurface reservoirs tapped by meteoroid impact. Because impact is required for the initial stage, this process is not likely to explain the origin of Hadley Rille. In addition to the lack of initiating impact there are several other objections to erosion of the rille by water. (i) Estimated volume of the rille is 2.8×10^{10} m^3. Although this material should form a significant alluvial fan or outwash plain, there is no indication of sedimentary structures at the terminus. If the material were spread over the surface at the end of the rille and thinned to featheredges, the unit would have no well-defined boundaries and would be younger than the eroded mare surface. Crater count-

Fig. 1. Hadley Rille; numbered lines refer to cross sections of Fig. 4; sun is about 19° above eastern horizon. (Base photomosaic prepared by U.S. Army TOPOCOM from Lunar Orbiter V frames M-104 through M-107.)



ing, a technique to determine relative ages of lunar surfaces (*14*), however, shows no difference in age for the surface at the terminus compared to the surface along the rille. (ii) There is no indication of tributaries having carried water from the "watershed" to the rille. (iii) The rille narrows "downstream," rather than widens as is normal for rivers. (iv) The rille is discontinuous (*A* in Figs. 1 and 2), a situation not possible for fluvial channels, but quite common in lava tubes and channels (Fig. 3).

Most proposals of water erosion require relatively short times for water erosion to occur, which in turn requires an easily eroded regolith extending several hundred meters deep (at least, equal to rille depths). Evidence does not support these conditions. Apollo results show that the lunar soil is composed of poorly sorted material containing rocks 10 cm and more in diameter, not the fine, homogeneous sand required by Lingenfelter *et al* (*4*). In addition, the regolith is so compacted (a few centimeters below the surface) that Apollo 11 astronauts were able to drive the coring device to a depth of only about 15 cm (*15*), in contrast to the contention that the soil is loosely bonded to depths of tens of meters. It has been shown (*16*) that the average mare regolith thickness ranges from about 3.3 to 16 m, much less than the several hundred meters required by water erosion of short duration.

Hadley Rille is situated on the crest of a topographic high (Fig. 4B). It is unlikely that any erosive agent, whether ash or water, could have cut a channel along the top of a ridge. It is more plausible for the ridge and channel to have formed simultaneously through a constructional process. Lava tubes and channels are the primary structures permitting fluid basalt flows to advance from the vented magma chamber. Distributary tubes, formed radially from the main structure, and overflow of lava from open channels deposit lava parallel to the structure, forming broad ridges (Fig. 4A) very similar to Hadley Rille. Similar relations have been noted for rilles in the Marius Hills (*17*). Structures *C* and *D*

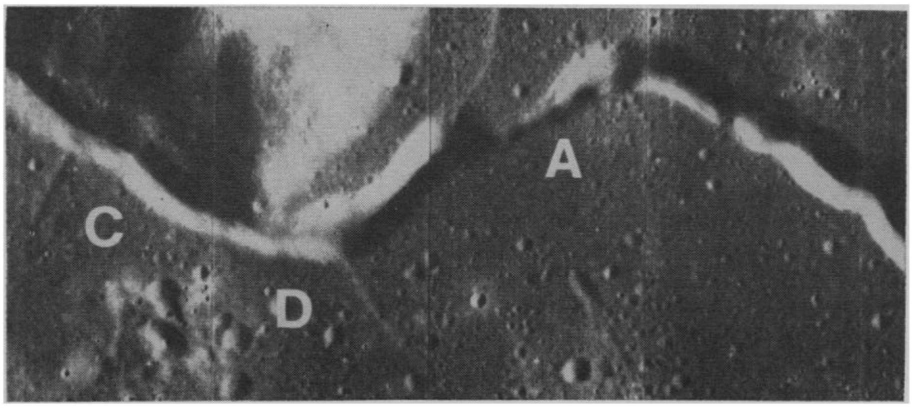


Fig. 2. Enlargement of rille section showing small distributary channels (*C* and *D*) on the rille flanks and one of the discontinuous rille sections (*A*). Photograph covers an area about 18 by 9 km.

(Figs. 1 and 2) may be remnants of overflow channels or collapsed distributary tubes from Hadley Rille.

Fluidization of lunar regolith by outgassing through fractures may also produce depressions with lateral levees, shown experimentally by Schumm (*7*). Unlike the large, broad ridges of lava tubes and channels and the Hadley Rille, fluidization channel levees are small compared to channel width (Fig. 4C). Outgassing through fractures should result in structures reflecting the trend of the fracture. Although many terrestrial fractures are arcuate, no single fracture is as sinuous as the Hadley Rille. Fractures are relatively independent of topography, yet the Hadley Rille is restricted to the mare between highland blocks. Basaltic lava flows are almost completely controlled by preflow topography, and tubes and channels represent the axis of most rapid flow. Thus, tubes and channels often meander from one side of the confining valley to the other, occasionally eroding parts of the valley wall.

Considerations of topography, photographic interpretation, comparison with terrestrial analogs (*10, 11*), and extrapolation from experimental studies (*12*) permit a tentative proposal for the origin of Hadley Rille. Following formation of the Imbrium basin, basaltic lava was emitted through faults and fissures at the base of the Apennine Mountains and poured into the basin. Although many of the fissure vents probably have no surface expression (similar to terrestrial fissure vents) detectable on Lunar Orbiter photographs, the elongate cleft at the head of Hadley Rille is interpreted to be a volcanic vent situated on or near a fissure. Typical of basalt flows on earth, the very fluid lunar lavas flowed from the vent into the basin through a lava channel that in some places became roofed to form a tube. Although terrestrial tubes and channels are not as long or as wide as Hadley Rille, considerations of the lunar environment (*9*) and laboratory analysis of viscosity and thermal conductivity for mare lavas (*12*) indicate that weathered lunar lava tubes and channels could easily be as large as Hadley Rille.

Controlled by preflow topography, the lava filled low regions and the tube-channel structure was relatively free to meander within the flow. Where slope was low, the velocity of the flow decreased, permittting the formation of a thick stable crust over the channel. The discontinuous channel, irregular width and depth, and coalesced elongate craters making up the rille at *A* (Figs. 1 and 2) are remnants of a lava tube possibly formed in conjunction with low velocities where the flow passed through the highland blocks into the basin. Multiple surges of lava from the vent, or possibly multiple eruptions over a long period of time, resulted in overflow of lava from the main channel through distributary channels and tubes (*C* and *D* in Figs. 1 and 2) to build a topographic high along the rille axis.

Meteoroid bombardment collapsed nearly all roof sections and caused slumping of the rille rim (slump blocks 80 m wide by several hundred meters long (*A* and *E* in Fig. 1; *A* in Fig. 2), thus widening the rille. The lava flow has been impact-fragmented to a relatively shallow depth (similar to other mare surfaces) indicated by the boulder ledge that crops out in several places along the rille very near the rim. Roof collapse, channel crust material, lateral slumping, and impact-generated debris have partly filled in the rille with blocks (visible at the surface) 30 m in diameter and smaller, resting at an

Fig. 3. Lava channel, partly roofed to form a tube at *A*, originating from the Southwest Rift Zone (*B*) of Mauna Loa, Hawaii.

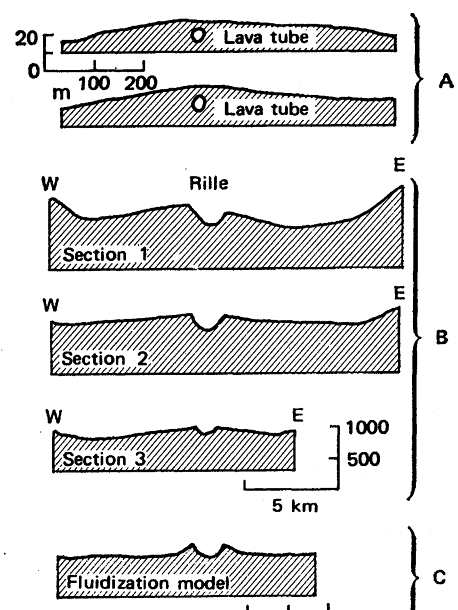


Fig. 4. Cross sections of (A) Modoc Lava Tube, Lava Beds National Monument, California; (B) Hadley Rille (prepared from U.S. Army TOPOCOM elevation determinations); and (C) fluidization channel [estimated from photographs of Schumm (*7*)]. Vertical exaggeration × 3.5.

angle of repose of about 28°, similar to that measured for basalt blocks over collapsed terrestrial lava tubes.

While the above now appears to be a satisfactory account of the origin of Hadley Rille, geologic observations, returned samples from the rille region, and improved photographs and topographic maps from the Apollo 15 mission will undoubtedly enable refinement of this interpretation.

RONALD GREELEY

Space Science Division, Ames Research Center, National Aeronautics and Space Administration, Moffett Field, California 94035

References and Notes

1. Anonymous, *Geotimes* **17**, 21 (1970).
2. Lunar topographic photomap *Rima Hadley* [U.S. Army Topographic Command (TOPOCOM), 1970]; vertical control was established by photogrammetric triangulation with orbit constraints and based on Lunar Orbiter V ephemeris data 15 October 1968; vertical accuracies are expressed at 90 percent probability.
3. W. S. Cameron, *J. Geophys. Res.* **69**, 2433 (1964).
4. R. E. Lingenfelter, S. J. Peale, G. Schubert, *Science* **161**, 266 (1968); G Schubert, R. E. Lingenfelter, S. J. Peale, *Rev. Geophys. Space Phys.* **8**, 199 (1970).
5. H. C. Urey, *Nature* **216**, 1094 (1967).
6. G. Fielder, *Lunar Geology* (Dufour, Chester Springs, Pa., 1965).
7. S. A. Schumm, *Geol. Soc. Amer. Bull.* **81**, 2539 (1970).
8. G. P. Kuiper, R. G. Strom, R. LePoole, *Cal. Inst. Tech. Jet Prop. Lab. Tech. Rep.*, No. 32-800 (1966), p. 35; A. W. Hatheway and A. K. Herring, *Commun. Lunar Plan. Lab.* **8**, 299 (1970).
9. V. R. Oberbeck, W. R. Quaide, R. Greeley, *Modern Geol.* **1**, 75 (1969).
10. R. Greeley, *Ore. Dept. Geol. Min. Res. Bull.*, in press.
11. ——, NASA TM X-62014 (1971) (*Modern Geol.*, in press).
12. T. Murase and A. R. McBirney, *Science* **167**, 1491 (1970); *ibid.* **170**, 165 (1970).
13. W. K. Hartmann and G. P. Kuiper, *Commun. Lunar Plan. Lab.* **1** (No. 12) 51 (1962).
14. D. E. Gault, *Radio Sci.* **5**, 237 (1970).
15. N. C. Costes, W. D. Carrier, J. K. Mitchell, R. F. Scott, NASA SP-214 (1969), p. 85.
16. V. R. Oberbeck and W. L. Quaide, *Icarus* **9**, 446 (1968).
17. R. Greeley, *Meteoritics* **5**, 202 (abstr.) (1970); NASA TM X-62013 (1970).
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Molecular Conformation of Dihydrouridine: Puckered Base Nucleoside of Transfer RNA

Abstract. *The crystal structure of dihydrouridine hemihydrate has been determined by x-ray diffraction. Crystals of dihydrouridine contain two independent molecules in the asymmetric unit and a molecule of water. The x-ray structure determination has shown that the conformations of both molecules differ in important respects in the saturated base and the ribose. The molecular conformation of dihydrouridine has, for the first time, provided structural evidence that the rare nucleoside can promote "loop" formation in the sugar-phosphate chain.*

X-ray crystallographic studies on the monomers of DNA and RNA have provided considerable insight into their intricate conformational properties (*1*). In addition, the important rule has been established that the preferred conformations of the monomers are the same as those of the monomeric units in the polymer (*1*). In transfer RNA (tRNA), a number of rare nucleotides are present which are distributed mainly in the loop regions of the familiar cloverleaf model. These nucleosides probably have a structural or functional role or both. We now wish to report the molecular conformation of dihydrouridine (Fig. 1) which occurs solely in the dihydrouridine loop of tRNA. The number of dihydrouridines in the loop varies from one to five in the known tRNA's.

Dihydrouridine, $C_9H_{14}N_2O_6$ (Sigma), was crystallized from aqueous ethanol solution by D. Rohrer. Photographic investigation showed that the crystals belong to the orthorhombic system with the space group $P2_12_12_1$. The unit cell dimensions measured on a diffractometer are a = 8.131 Å, b = 11.766 Å, and c = 23.016 Å. Although the experimental density was not available, the calculated density (1.538 g cm^{-3}) for two molecules in the asymmetric unit was in the vicinity of that found for other nucleoside crystals. The crystal

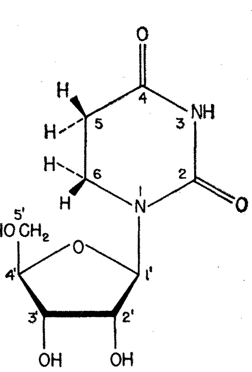

Fig. 1. Chemical structure of dihydrouridine.

structure determination not only confirmed the presence of two molecules of dihydrouridine, but also showed the presence of one water of crystallization in the asymmetric unit. Therefore, there are 35 nonhydrogen atoms and 30 hydrogen atoms in the asymmetric unit.

Approximately 2100 reflections were recorded on a four-circle automated diffractometer operating in the θ-2θ scan mode. Of these about 1900 were considered significantly above background and were used in the structure analysis. The crystal structure was solved by a combination of Patterson search method and the tangent formula (*2*). The structure was refined by the method of full-matrix least-squares to the present agreement index

$$R = \Sigma \mid \mid F_0 \mid - \mid F_c \mid \mid / \Sigma \mid F_0 \mid = 0.056$$

where F_0 and F_c are, respectively, the observed and calculated structure factors.

Dihydrouridine is the only nucleic acid constituent with a puckered base. It is particularly interesting that our study has shown that the conformations of the two molecules (A and B) in the asymmetric unit are different (Fig. 2, left). The bases themselves show approximately opposite (enantiomeric) conformations (Fig. 2, right); atoms C(5) and C(6) demonstrate the greatest deviations, and in opposite directions, from the plane through the six ring atoms. The overall shape of the bases may be described as a twist, half-chair conformation which is similar to that observed for the base (dihydrouracil) itself (*3*).

The glycosidic torsion angle, as defined by Sundaralingam (*1*), is 65.5° in molecule A and 57.1° in molecule B. This angle describes the stereochemical relation of the base with respect to the carbohydrate moiety. Even though the C(5)–C(6) bond is saturated, the conformation is still in the preferred *anti* range found for the common (planar) pyrimidine nucleosides.

The furanoside ring conformations are essentially the same in both molecules. When described as an envelope (E) form, that is, with respect to the best four-atom least-squares plane, the conformations are C(2′)-*endo*. However, the conformation when described with respect to next best four-atom plane is C(1′)-*exo*. This is an unusual conformation for the sugar. Whenever the plane through the "best four-atom plane" shows significant deviations from planarity, the furanoside ring is said to occur in a twist (*T*) form. In describ-