Bioorganometallic Chemistry. 7. A Novel, Linear, Two-Coordinate Rh(I) Anionic Amide Complex Formed by the Reaction of the Nucleobase, 1-Methylthymine, with the $[(Cp^*Rh)_2(\mu\text{-}OH)_3]^+$ Cation at pH 10: Molecular Recognition and Electrostatic Interaction within an Organometallic Hydrophobic Cavity

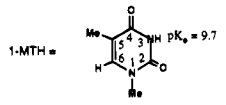
Hong Chen,[1a] Marilyn M. Olmstead,[1b]
Marcos F. Maestre,[1a] and Richard H. Fish*,[1a]

Lawrence Berkeley National Laboratory
University of California, Berkeley, California 94720
Department of Chemistry, University of California
Davis, California 95616

Received June 8, 1995

Molecular recognition is the foundation of many important biological processes, especially those that involve enzyme-catalyzed chemical reactions, as well as the interaction of a specific sequence of nucleobases with drugs, spectroscopic probes, and cleavage agents, which also may contain metal ions.[2] Recently, we were able to characterize several (η^5-pentamethylcyclopentadienyl)rhodium (Cp*Rh)−cyclic trimer structures[3] with 9-methyladenine, 9-ethylhypoxanthine, adenosine, adenosine 3′-, methyl-5′-, and 5′-monophosphates and, in this process, discovered the first examples of molecular recognition by several bioorganometallic Cp*Rh−cyclic trimer nucleobase, nucleoside, and nucleotide hosts with aromatic amino acid guests in H_2O at pH 7.0.[3e]

We now extend our bioorganometallic/molecular recognition studies to the nucleobase 1-methylthymine (1-MTH) and



describe the synthesis and structural characterization of the *first example of a novel, linear, two-coordinate Rh(I) anionic amide complex* $[Rh(\eta^1,N^3\text{-}1\text{-}MT)_2]^-$ (1-MT$^-$ was deprotonated at N3) (**1**), from the reaction of 1-MTH with *in situ* generated $[(Cp^*Rh)_2(\mu\text{-}OH)_3]^+$ (**2**) performed at pH 10. This unusual coordination around the Rh(I) complex is presumed to be stabilized by three factors: an organometallic hydrophobic cavity, generated from 1.5 molecules of **2**,[4] to provide the interaction of two 1-MT ligands with the adjacent Cp* groups by a classical $\pi-\pi$ molecular recognition process; an electrostatic interaction of anionic **1** with cationic **2**; and a possible shielding of the Rh(I) center to nucleophilic attack by four sets of oxygen lone pair electrons contained in the 1-MT ligands.

Reaction of $[Cp^*Rh(H_2O)_3](OTf)_2$ (**3**) with 1 equiv of 1-MTH in H_2O (degassed once) at pH 10 afforded a yellow solution;

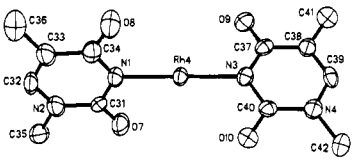


Figure 1. Structure of **1**. Selected bond lengths (Å) and angles (deg): Rh4−N3, 2.087(7); Rh4−N1, 2.095(7); N3−C37, 1.371(12); N3−C40, 1.363(11); N1−C31, 1.375(13); N1−C34, 1.340(13); O9−C37, 1.223(11); O10−C40, 1.257(11); O7−C31, 1.234(13); O8−C34, 1.249(13); N1−Rh4−N3, 178.2(3); C34−N1−Rh4, 118.9(7); C31−N1−Rh4, 117.4(7); C34−N1−C31, 123.3(8); C37−N3−Rh4, 118.6(6); C40−N3−Rh4, 119.4(6); C40−N3−C37, 122.0(7). The C=O groups of the two 1-MT$^-$ ligands are at a distance to Rh4 of 3.072, 3.075, 3.073, and 3.093 Å for O7, O8, O9, and O10, respectively. Please note that the atom numbering schemes for the structure of 1-MTH and the structure of **1** are different.

the rapid formation of **2** from **3** at pH 10 has recently been extensively studied.[5] After being stirred at 25 °C overnight and at 60 °C for 2 h to drive the reaction mixture to completion, the solution turned orange, and upon reducing the volume of this reaction mixture, complex **1** was crystallized with 1.5 equiv of **2** at 4 °C to form the adduct $[\mathbf{1}_2{\cdot}\mathbf{2}_3](OH)$ as orange plates (20%).[6] A small amount (<5%) of the complex **2**, whose structure had been reported previously,[4] was also crystallized separately as yellow needles.

Figure 1 shows the X-ray crystal structure of the anionic component, **1**, and *a key feature is the unexpected linear, N1−Rh4−N3 grouping, with a bond angle of 178.2(3)°, and a near-staggered (98.8°) configuration of two thymine planes with respect to one another.*[7] Similar stoichiometry and metrical parameters are seen in $Hg(1\text{-}MT)_2$,[8] but the two thymine planes of **1** are eclipsed, as required by its inversion symmetry. The perpendicular geometry of the two thymine rings gives rise to an interesting stacking arrangement where the two thymine planes are π-stacked to either a Cp* ring (three such interactions) or to a centrosymmetrically related thymine ring of another anion of **1** which, among other things, allows the Rh4 center to be shielded by a hydrophobic cavity generated from the five Cp* Me hydrogens (Rh4···H distances range from 2.93 to 3.16 Å).

Shielding by the carbonyl oxygen lone pair electrons of the 1-MT ligands may also be of some importance; however, the four carbonyl oxygen atoms are hydrogen-bonded to H_2O molecules, and none of these interactions all near the Rh4 atom.[9] Moreover, the distances between the least-squared adjacent planes of the Cp* groups and the 1-MT ligands range from 3.45 to 3.58 Å, and the angles from 0.0 to 2.9°, which agrees well with the reported value of 3.35 Å by Loeb and co-workers for a $\pi-\pi$ guanine−aromatic ring molecular recognition interaction.[10a] A view of this unique set of π-stacking arrangements is presented in Figure 2.

(1) University of California: (a) Berkeley, (b) Davis.

(2) (a) Sherman, S.; Lippard, S. J. *Chem. Rev.* **1987**, *87*, 1153. (b) Kuo, L. Y.; Kanatzidis, M. G.; Sabat, M.; Tipton, A. L.; Marks, T. J. *J. Am. Chem. Soc.* **1991**, *113*, 9027. (c) Dervan, P. B. *Science* **1986**, *232*, 464. (d) Turro, N. J.; Barton, J. K.; Tomalia, D. A. *Acc. Chem. Res.* **1991**, *24*, 332. (e) Burrows, C. J.; Rokita, S. E. *Acc. Chem. Res.* **1994**, *27*, 295. (f) Li, Z. W.; Taube, H. *Science* **1992**, *256*, 210. (g) Cowan, J. A. *Inorganic Biochemistry*; VCH: New York, 1993.

(3) (a) Smith, D. P.; Baralt, E.; Morales, B.; Olmstead, M. M.; Maestre, M. F.; Fish, R. H. *J. Am. Chem. Soc.* **1992**, *114*, 10647. (b) Smith, D. P.; Olmstead, M. M.; Noll, B. C.; Maestre, M. F.; Fish, R. H. *Organometallics* **1993**, *12*, 593. (c) Smith, D. P.; Kohen, E.; Maestre, M. F.; Fish, R. H. *Inorg. Chem.* **1993**, *32*, 4119. (d) Smith, D. P.; Griffin, M. T.; Olmstead, M. M.; Maestre, M. F.; Fish, R. H. *Inorg. Chem.* **1993**, *32*, 4677. (e) Chen, H.; Maestre, M. F.; Fish, R. H. *J. Am. Chem. Soc.* **1995**, *117*, 3631. (f) Chen, H.; Olmstead, M. M.; Smith, D. P.; Maestre, M. F.; Fish, R. H. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 1514.

(4) Notton, A.; Bailey, P. M.; Maitlis, P. M. *J. Chem. Soc., Dalton Trans.* **1981**, 1997.

(5) Eisen, M. S.; Haskel, A.; Chen, H.; Olmstead, M. M.; Smith, D. P.; Maestre, M. F.; Fish, R. H. *Organometallics* **1995**, *14*, 2806.

(6) Elemental analysis for the vacuum dried sample, $[\mathbf{1}_2{\cdot}\mathbf{2}_3](OH){\cdot}10.5H_2O$ ($C_{84}H_{128}N_8O_{18}Rh_8{\cdot}10.5H_2O$). Calcd: C, 39.5; H, 5.84; N, 4.39. Found: C, 39.3; H, 5.65; N, 4.55. ^1H NMR spectrum of the adduct $[\mathbf{1}_2{\cdot}\mathbf{2}_3](OH)$ in CD_3OD at 25 °C (400 MHz): δ 7.24 (s, 1H, C6-H), 3.29 (s, 3H, N1-Me), 1.85 (s, 3H, C5-Me), 1.62 (s, 22.5H, Cp*).

(7) The adduct $[\mathbf{1}_2{\cdot}\mathbf{2}_3](OH){\cdot}46.5H_2O$ ($C_{84}H_{227}N_8O_{64.5}Rh_8$, FW = 3205.52) was crystallized from its aqueous solution (pH 10) at 4 °C in the monoclinic space group $P2_1/c$ with a = 17.427(8) b = 13.403(5) Å, c = 32.436(10) Å, β = 107.52(3)°, Z = 4, V = 7225(5) Å^3, ϱ_{calcd} = 1.47 g cm^{-3}, Mo Kα radiation, 130 K, Siemens R3m/v diffractometer equipped with an Enraf-Nonius low-temperature apparatus, ω scans, 12 706 measured reflections, of which 12 699 unique data were used for refinement (based on F^2 SHELXL-93). The structure was solved by direct methods, and an absorption correction (XABS2) was applied. w$R2$ = 0.2242; $R1$ based on 8258 reflections with $I > 2\sigma(I)$ = 0.0651. The large final R factors are due to the disorder in the 1-MT group and the half molecule of $[(Cp^*Rh)_2(\mu\text{-}OH)_3]^+$ that contains Rh(3) (see supporting information).

(8) Kosturko, L. D.; Folzer, C.; Stewart, R. F. *Biochemistry* **1974**, *13*, 3949.

(9) Raudaschl-Sieber, G.; Lippert, B. *Inorg. Chem.* **1985**, *24*, 2426.

0002-7863/95/1517-9097$09.00/0

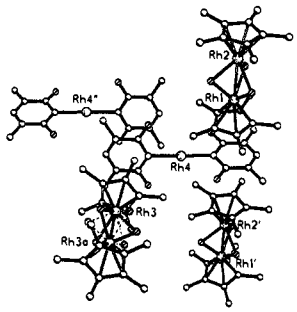


Figure 2. Structure of $[\mathbf{1}_2{\cdot}\mathbf{2}_3]^+$ and the π-stacking arrangement.

While the formula $[\mathbf{1}_2{\cdot}\mathbf{2}_3](OH)$ dictates one OH^- to balance the overall charge and is consistent with the previously reported complexes, **2** and its Ir analog, which are isolated at high pH,[4,11] it is our supposition, in this particular case, that the electrostatic interaction between $\mathbf{1}^-$ and $\mathbf{2}^+$ further stabilizes adduct formation. The total absence of EPR signals at 77 K verified the diamagnetic nature of the presumed Rh(I) center. More importantly, the ^1H NMR spectrum of $[\mathbf{1}_2{\cdot}\mathbf{2}_3](OH)$ in CD_3OD exhibited *upfield* shifts of 0.15 ppm for the thymine's ring proton (C6-H), consistent with classical $\pi-\pi$ interactions[3e,10] between the parallel 1-MT ligands and the adjacent Cp* groups, and supports the existence of the adduct in solution.[6] An ^1H NMR study (CD_3OD) of the concentration dependency of the upfield chemical shifts of C6-H revealed only slight changes (0.03 ppm) and further supports the presumed $\pi-\pi$ interactions in solution (supporting information).

It is interesting to note that two-coordinate, open-shell (d^0-d^9) transition metal amide complexes are a very esoteric class of molecules.[12] In fact, the small number of well-characterized examples are restricted to the first row metals, Cr→Ni, and all of these compounds were isolated from strictly anhydrous and anaerobic conditions by using sterically and electronically demanding ligands;[12,13] *until now, the second and third row transition metal analogs were virtually unknown.* Moreover, the Rh(I) center of **1** is highly coordinatively unsaturated, since the overall electron count is 12 (8 from Rh(I) d^8 and 4 from two 1-MT ligands). This is reminiscent of the above-mentioned Cr→Ni (d^4-d^8) series of two coordinate amide structures that have electron counts from 8 to 12 electrons around the metal centers.[12]

In the case of the $[Rh(\eta^1,N^3\text{-1-MT})_2]^-$ component, **1**, the 1-MT ligand is not bulky; therefore, the unusual local environment generated by cationic **2** is essential for the stabilization of the linear two-coordination of **1**. The role of the Cp* groups of **2**, in the stabilization of **1**, was supported by a control experiment that featured the reaction of the Rh^{3+} aqua cation, obtained *in situ* from $RhCl_3{\cdot}3H_2O$ and 3 equiv of AgOTf in H_2O, with 2 equiv of 1-MTH at pH 10 to afford a yellow precipitate, which was consistent with $Rh(OH)_3$ by elemental analysis; no indication of the formation of **1** was found.[14]

The mechanism for the formation of $[\mathbf{1}_2{\cdot}\mathbf{2}_3](OH)$ can be tentatively rationalized by the following observations. The distillate of the reaction mixture was analyzed by GC/MS techniques[15] and provided information that Cp*OH[16] was formed (m/z = 151 and 135 for $[M-H]^+$ and $[M-OH]^+$) during the reaction, clear evidence for the loss of the Cp* ligand from Rh^{3+}. Thus, we speculate the reductive elimination of Cp*OH from the putative mononuclear $[Cp^*Rh(1\text{-MT})_2(OH)]^-$ complex provided **1**. This former complex, $[Cp^*Rh(1\text{-MT})_2(OH)]^-$, was thought to form via nucleophilic substitution of 1-MT^- ($pK_a = 9.7$)[17] on the plausible and similarly precedented intermediate *trans*-$[Cp^*Rh(\mu\text{-OH})(\eta^1,N^3\text{-1-MT})]_2$, the presumed initial product from the reaction of 1-MT^- with **2**.[3b,f]

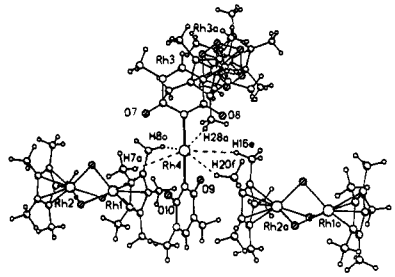


Figure 3. Hydrophobic cavity with possible weak Rh···H agostic interactions and steric shielding effects.

Thus, in this logical sequence of plausible reactions, **1** was trapped in a cavity formed by the π-donating Cp* groups of **2** (scheme in the supporting information). While reductive elimination of the very inert Cp* ligand from the coordination sphere of a Rh^{3+} metal center is a rare occurrence, it has been observed in a facile reaction of $Cp^*RhH_3(SiEt_3)$ with excess Me_3P to provide Cp*H and a Rh(I) complex.[18]

Although the Rh4···H distances of 2.93−3.16 Å are slightly long for any dominant agostic interactions,[19] it is reasonable to speculate that weak Rh4···H interactions/steric shielding effects may also be of some importance in the stabilization/protection of complex **1** (Figure 3). Future experiments with $[\mathbf{1}_2{\cdot}\mathbf{2}_3](OH)$ will be concentrated on its reactions with small molecules such as CH_4, CO, and H_2, with the focus on the coordinatively unsaturated Rh(I) center in order to provide evidence for potential chemical reactivity by this novel molecule. It is interesting to note that the Cp*Ir-1-MT analog was also synthesized using the same procedure.

Acknowledgment. The studies at LBNL were generously supported by NIH Grant A I 08427 to M.F.M., by LBNL Laboratory Directed Research and Development Funds to M.F.M. and R.H.F., and by the Department of Energy under Contract No. DE-ACO3-76SF00098.

Supporting Information Available: Structure determination summary notes; tables of crystal data, data collection, solution and refinement, atomic coordinates and equivalent isotropic displacement parameters, bond distances and angles, anisotropic displacement parameters, thermal parameters, H coordinates and isotropic displacement parameters; scheme for the formation of $[\mathbf{1}_2{\cdot}\mathbf{2}_3]^+$; and a plot of the concentration dependency of the ^1H NMR chemical shift of the C6-H proton of $[\mathbf{1}_2{\cdot}\mathbf{2}_3](OH)$ (29 pages); observed and calculated structure factors for $[\mathbf{1}_2{\cdot}\mathbf{2}_3](OH){\cdot}46{\cdot}5H_2O$ (29 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, can be ordered from the ACS, and can be downloaded from the Internet; see any current masthead page for ordering information and Internet access instructions.

JA9518641

(10) (a) Kickham, J. E.; Loeb, S. J.; Murphy, S. L. *J. Am. Chem. Soc.* **1993**, *115*, 7031 and references therein. (b) Zimmerman, S. C.; Wu, W.; Zeng, Z. *J. Am. Chem. Soc.* **1991**, *113*, 196. (c) Deslongchamps, G.; Galan, A.; de Mendoza, J.; Rebek, J., Jr. *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 61. (d) Lehn, J.-M. *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 90 and references therein.

(11) Dadci, L.; Elias, H.; Frey, U.; Hornig, A.; Koelle, U.; Merbach, A. E.; Paulus, H.; Schneider, J. S. *Inorg. Chem.* **1995**, *34*, 306.

(12) (a) Power, P. P. *Comments Inorg. Chem.* **1989**, *8*, 177 and references therein. (b) Bartlett, R. A.; Chen, H.; Power, P. P. *Angew. Chem., Int. Ed. Engl.* **1989**, *28*, 316. (c) Chen, H.; Bartlett, R. A.; Dias, H. V. R.; Olmstead, M. M.; Power, P. P. *J. Am. Chem. Soc.* **1989**, *111*, 4338. (d) Chen, H.; Bartlett, R. A.; Olmstead, M. M.; Power, P. P.; Shoner, S. C. *J. Am. Chem. Soc.* **1990**, *112*, 1048. (e) Bartlett, R. A.; Power, P. P. *J. Am. Chem. Soc.* **1987**, *109*, 7563. (f) Andersen, R. A.; Faegri, K., Jr.; Green, J. C.; Haaland, A.; Lappert, M. F.; Leung, W.-P.; Rypdal, K. *Inorg. Chem.* **1988**, *27*, 1782.

(13) Lappert, M. F.; Power, P. P.; Sanger, A. R.; Srivastava, R. C. *Metal and Metalloid Amides*; Ellis-Horwood: Chichester, 1980.

(14) Elemental analysis for $Rh(OH)_3{\cdot}1.2H_2O$. Calcd: Rh, 58.6; H, 3.08. Found: Rh, 58.1; H, 2.71.

(15) The reaction mixture was distilled at 50 °C in vacuo, and the distillate was passed through a C-18 cartridge; finally, the Cp*OH was eluted off the cartridge with a small amount of MeOH. This fraction was then subjected to GC/MS analysis.

(16) Macaulay, J. B.; Fallis, A. G. *J. Am. Chem. Soc.* **1990**, *112*, 1136.

(17) Saenger, W. *Principles of Nucleic Acid Structure*; Springer-Verlag: New York, 1983; p 111.

(18) Paneque, M.; Maitlis, P. M. *J. Chem. Soc., Chem. Commun.* **1989**, 105.

(19) (a) Yared, Y. W.; Miles, S. L.; Bau, R.; Reed, C. A. *J. Am. Chem. Soc.* **1977**, *99*, 7076. (b) Muir, K. W.; Ibers, J. A. *Inorg. Chem.* **1970**, *9*, 440.