68081-49-2; **48**, 68127-30-0; **49**, 68081-37-8; ethyl propiolate, 623-47-2; *tert*-butyldimethylsilyl chloride, 18162-48-6; cyclopentanone, 120-92-3; 2-methylcyclopentanone, 1120-72-5; 2,2,4-trimethylcyclopentanone, 28056-54-4; cyclohexanone, 108-94-1; cycloheptanone, 502-42-1; cyclooctanone, 502-49-8; cyclododecanone, 830-13-7; 2-octanone, 111-13-7; 4-heptanone, 123-19-3; camphor, 76-22-2; methyl 1-methyl-2-oxocycloheptanecarboxylate, 68081-50-5.

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[2 + 2] Cycloadditions of Silyl Enol Ethers and Dimethyl Acetylenedicarboxylate, Dimethyl Fumarate, and Methyl Crotonate

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[2 + 2] cycloadditions of silyl enol ethers with dimethyl acetylenedicarboxylate, dimethyl fumarate, and methyl crotonate using titanium tetrachloride catalysis are reported. The cyclobutene adducts undergo a two-carbon ring expansion during acid hydrolysis.

We have shown previously that silyl enol ethers undergo [2 + 2] cycloaddition with ethyl propiolate under titanium tetrachloride catalysis and that in the case of cyclic enol ethers the derived silyloxycyclobutenes can be opened to afford two-carbon ring-expanded products.[2] We now report that a similar cycloaddition–ring expansion can also be accomplished with dimethyl acetylene dicarboxylate. Furthermore, we have found that certain α,β-unsaturated esters will also undergo cycloaddition with silyl enol ethers to afford cyclobutane adducts.

The results of the $TiCl_4$-catalyzed cycloaddition of trimethylsilyl (Me_3Si) and *tert*-butyldimethylsilyl ($BuMe_2Si$) enol ethers with dimethyl acetylenedicarboxylate are listed in Table I. Typically, the reaction is carried out by addition of the silyl ether to a −78 °C CH_2Cl_2 solution of $TiCl_4$ (1 equiv) and dimethylacetylenedicarboxylate (1.5 equiv). The reaction is virtually instantaneous, and after several minutes at −78 °C the product is isolated by ether extraction. The $BuMe_2Si$ group is relatively stable to the reaction conditions and is retained in the cycloadduct, whereas the Me_3Si group is usually cleaved. Since the Me_3Si group is also rapidly cleaved from the starting enol ether, the yields are significantly better with the corresponding $BuMe_2Si$ ethers. However, some cleavage of the $BuMe_2Si$ enol ether does occur, and the yields are generally lower than in the corresponding cycloadditions with ethyl propiolate.[3]

Also listed in Table I are the products from the aqueous acetic acid hydrolysis of the cycloadducts. Silyl ethers **9** and **14** are converted to the known ring expansion products **10**[4] and **15**,[4e] which have been prepared previously from the corresponding enamines. Compound **15** results from decarboxylation of **12**,[4c,e] which is the direct product from Me_3Si ether **11**. The cycloadduct from the silyloxycyclooctene **16** opens at room temperature to afford cyclodecadiene **17**, which is converted by hydrolysis to the known keto diester **18**.[4c,e]

The bicyclo[3.2.0]heptenyl alcohols **2** and **7** are stable under the hydrolysis conditions. Treatment with sodium hydride in *tert*-butyl alcohol (or THF) affords the cleavage products **19** (57%) and **20** (40%) rather than ring-expanded materials.[5] The formation of **19** and **20** may involve Michael addition of alkoxide at C-6 followed by fragmentation of the $C_{1,7}$ bond with loss of alkoxide to generate the β,γ-unsaturated isomer which isomerizes to the observed product.[6]

Cycloadditions with dimethyl fumarate (**21**) and methyl crotonate (**23**) were also investigated, and modest yields of cyclobutane adducts **22** and **24** and **25** were obtained (yields

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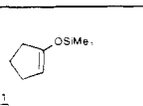
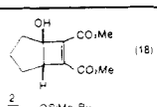
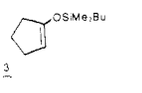
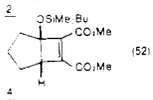
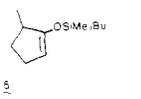
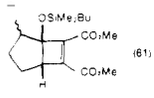
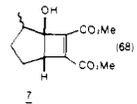
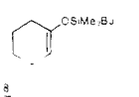
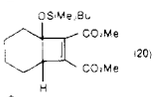
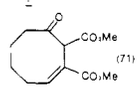
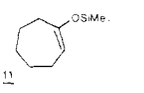
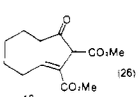
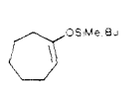
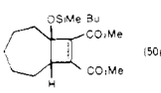
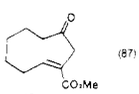
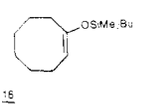
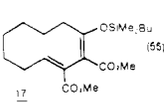
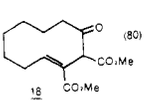
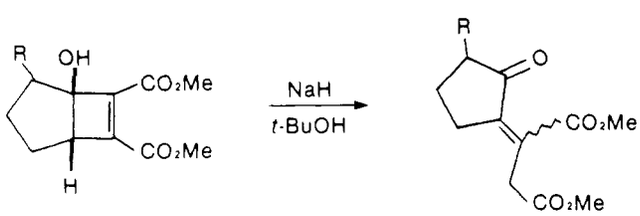
TABLE I
CYCLOADDITION OF SILYL ENOL ETHERS AND DIMETHYL ACETYLENE DICARBOXYLATE

SILYL ETHER	CYCLOADDUCT (% YIELD)[a]	HYDROLYSIS PRODUCT[b]
 1	 2 (18)	
 3	 4 (52)	
 5	 6 (61)	 7 (68)
 8	 9 (20)	 10 (71)
 11		 12 (26)
 13	 14 (50)	 15 (87)
 16	 17 (55)	 18 (80)

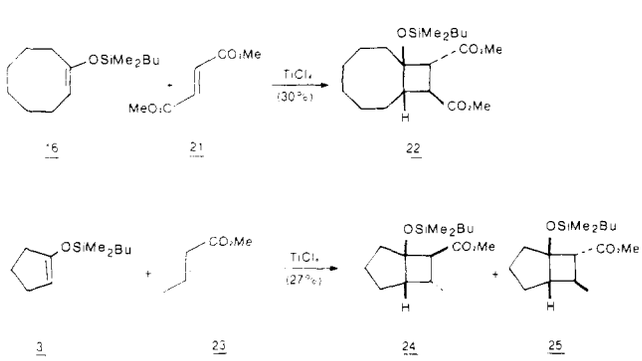
[a] Isolated by silica gel chromatography. None of the yields have been optimized. [b] Acetic acid–THF–H_2O, reflux.



2 R = H
7 R = CH_3

19 R = H
20 R = CH_3

not optimized). The stereochemistry of these products was determined by NMR spectroscopy (cf. Experimental Section). Mukaiyama has obtained Michael adducts from reaction of Me_3Si enol ethers with unsaturated esters.[7] Our results suggest that if the Mukaiyama reaction also involves a [2 + 2] cycloaddition, the Me_3Si group is cleaved from the cy-



cloadduct and cyclobutane opening then leads to the observed Michael product. Alternatively, the Michael products may result from $TiCl_4$-mediated conversion of the silyl enol ether to the enolate followed by Michael addition.[8]

Experimental Section

Infrared (IR) spectra were recorded on a Perkin-Elmer 137 spectrometer. Nuclear magnetic resonance (NMR) spectra were obtained with Varian A-60 and HA-100 instruments with an Me_4Si internal standard in CCl_4 solution unless otherwise stated. Combustion analyses were performed by our microanalytical laboratory and the microanalytical laboratory, Department of Chemistry, Stanford University.

General Cycloaddition Procedure. Dimethyl 1-(*tert*-Butyldimethylsilyloxy)cyclodeca-1,3-diene-2,3-dicarboxylate (17). A solution of silyl ether **16** (2.26 g, 9.4 mmol) in 20 mL of CH_2Cl_2 was added dropwise to a −78 °C solution of dimethyl acetylenedicarboxylate (2.13 g, 15 mmol) and $TiCl_4$ (1.90 g, 10 mmol) in 25 mL of CH_2Cl_2. After an additional 10 min at −78 °C, the mixture was diluted with ether, washed with water and brine, dried, and evaporated. Chromatography on silica gel (25% ether–hexane) afforded 1.97 g of crystalline **17**. An analytical sample was obtained by recrystallization from pentane at −78 °C: mp 78.5–80.0 °C; IR (CCl_4) 1710, 1570, 1540, 1190 cm^{-1}; ^1H NMR δ 0.20 (s, 3), 0.23 (s, 3), 0.92 (s, 9), 3.51 (s, 3), 3.62 (s, 3), 5.96 (m, 1); UV (hexane) λ_{max} 230 nm (ε 12 700). Anal. Calcd for $C_{20}H_{34}O_5Si$: C, 62.79; H, 8.96. Found: C, 63.05; H, 9.17.

Cycloadducts **4, 6, 9, 14,** and **17** were characterized by their IR and NMR spectra and were converted directly to the hydrolysis products.

General Hydrolysis Conditions. Dimethyl 1-Oxocyclodec-3-ene-2,3-dicarboxylate (18). Silyl ether **17** (1.71 g, 4.5 mmol) was refluxed for 2 h in 4 mL of acetic acid and 4 mL of THF containing 2 mL of water. Ether extraction and silica gel chromatography afforded 952 mg (80%) of **18** which had IR and ^1H NMR spectra in accord with those reported in the literature.[4c,e] Compounds **10**,[4a,e] **12**,[4c,e] and **15**[4e] also had spectra (IR, NMR) in agreement with those in the literature.

Formation of 19 and 20. Cycloaddition of enol ether **1** and dimethyl acetylenedicarboxylate gave alcohol **2** in 18% yield: IR (film) 3400, 1710, 1640, 1280, 1150 cm^{-1}; ^1H NMR δ 1.67 (m, 6), 3.08 (m, 1), 3.82 (s, 6). Anal. Calcd for $C_{11}H_{14}O_5$: C, 58.40; H, 6.24. Found: C, 58.58; H, 6.31.

Alcohol **2** (455 mg, 2 mmol) in 25 mL of *tert*-butyl alcohol was treated with sodium hydride (2 mmol) at 15 °C. After 10 min, several drops of acetic acid were added and the product was isolated with ether. Chromatography on silica gel (50% ether–hexane) gave 258 mg (57%) of **19** as a light yellow oil: IR (film) 1735, 1700, 1620, 1200, 990 cm^{-1}; ^1H NMR δ 2.00 (m, 2), 2.40 (m, 2), 3.16 (triplet of triplets, 2, J = 1, 6 Hz), 3.72 (s, 3), 3.83 (s, 3), 4.08 (t, 2, J = 1 Hz). Anal. Calcd for $C_{11}H_{14}O_5$: C, 58.40; H, 6.24. Found: C, 58.43; H, 6.32.

Under similar conditions, alcohol **7** gave **20** (40% yield): IR (film) 1735, 1700, 1620, 1200 cm^{-1}; ^1H NMR δ 1.13 (d, 3, J = 6 Hz), 2.33 (m, 4), 3.06 (m, 2), 3.68 (s, 3), 3.80 (s, 3), 4.06 (t, 2, J = 1 Hz).

Although both **19** and **20** appear to be single isomers, their stereochemistry has not been determined.

Dimethyl 1-(*tert*-Butyldimethylsilyloxy)bicyclo[6.2.0]deca-9,10-dicarboxylate (22). Reaction of silyl ether **16** with dimethyl fumarate under the above general conditions afforded **22** (30% yield) as a colorless oil after chromatography on silica gel (20% ether–hexane): IR (film) 1735, 1220, 1160, 1070, 840, 770 cm^{-1}; ^1H NMR δ 0.13 (s, 3), 0.20 (s, 3), 0.92 (s, 9), 2.20 (m, 1, H-8), 2.55 (dd, 1, J = 9, 9 Hz, H-9), 3.54 (d, 1, J = 9 Hz, H-10), 3.68 (s, 6). Anal. Calcd for $C_{20}H_{36}O_5Si$: C, 62.46; H, 9.44. Found: C, 62.38; H, 9.68.

Methyl 1-(*tert*-Butyldimethylsilyloxy)-6-methylbicyclo[3.2.0]hepta-7-carboxylate (24 and 25). Reaction of silyl ether **3** with methyl crotonate afforded cycloadducts **24** and **25** (27% yield) in a 60:40 ratio. The two isomers were separated by chromatography on silica gel (5% ether–hexane). **24:** IR (film) 1735, 1220, 845, 770 cm^{-1}; ^1H NMR δ 0.83 (s, 9), 0.88 (d, 3, J = 5 Hz), 2.42 (m, 1), 2.45 (d, 1, J = 9 Hz, H-7), 3.50 (m, 1), 3.62 (s, 3). **25:** IR (film) 1735, 1220, 845, 770 cm^{-1}; ^1H NMR δ 0.86 (s, 9), 1.12 (d, 3, J = 6 Hz), 2.00 (m, 2, H-5,6), 2.74 (d, 1, J = 8 Hz, H-7), 3.64 (s, 3). Anal. (of the isomeric mixture) Calcd for $C_{16}H_{30}O_3Si$: C, 64.38; H, 10.13. Found: C, 64.71; H, 10.35.

Registry No.—1, 19980-43-9; **2**, 68151-55-3; **3**, 68081-15-2; **4**, 68151-56-4; **5**, 68081-16-3; **6**, 68151-57-5; **7**, 68151-61-1; **8**, 62791-22-4; **9**, 68151-58-6; **10**, 68151-62-2; **11**, 22081-48-7; **12**, 68151-63-3; **13**, 68-081-19-6; **14**, 68151-59-7; **15**, 42205-59-4; **16**, 67788-03-8; **17**, 68151-60-0; **18**, 68151-64-4; **19**, 68151-65-5; **20**, 68151-66-6; **21**, 624-49-7; **22**, 68151-67-7; **23**, 623-43-8; **24**, 68151-68-8; **25**, 68199-21-3; dimethyl acetylenedicarboxylate, 762-42-5.

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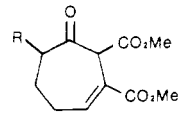
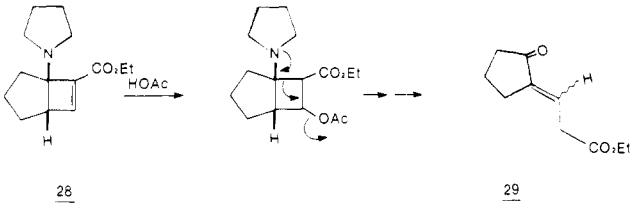
(1) Syntex Postdoctoral Fellow, 1977–1978.
(2) R. D. Clark and K. G. Untch, *J. Org. Chem.*, companion paper, this issue.
(3) Side products from the reaction are recovered ketone and 10–20% carbon silylated ketone.
(4) (a) G. A. Berchtold and G. F. Uhlig, *J. Org. Chem.*, **28**, 1459 (1963); (b) K. C. Brannock, R. D. Burpitt, V. Goodlett, and J. G. Thweatt, *ibid.*, **28**, 1464 (1963); (c) L. A. Paquette and R. W. Begland, *J. Am. Chem. Soc.*, **88**, 4685 (1966); (d) C. F. Huebner, L. Dorfman, M. Robison, E. Donoghue, W. Pierson, and P. Strachan, *J. Org. Chem.*, **28**, 3134 (1963); (e) J. A. Hirsch and F. J. Cross, *ibid.*, **36**, 955 (1971).
(5) Compounds **2** and **7** are apparently very sensitive to subtle changes in reaction conditions. In one instance, treatment of **7** with NaH in *tert*-butyl alcohol did afford the ring expansion product **26** in moderate yield with no detectable amount (TLC) of **20** present. However, this result could not be reproduced subsequently in several attempts. Furthermore, even more puzzling, a sample of **2** stored at room temperature for two weeks rearranged cleanly to **27**.



26 R = CH_3
27 R = H

(6) A similar product was obtained from the corresponding bicyclo[3.2.0]-heptenylpyrrolidinyl compound **28** in ref 4d upon treatment with acetic acid. Our explanation involving initial Michael addition to the cyclobutenyl ester (of acetate in this case) followed by fragmentive elimination may also be invoked to explain formation of this product. This mechanism is also consistent with the finding that **29** was not obtained upon treatment of **28** with aqueous hydrochloric acid since irreversable protonation of the nitrogen rules out the fragmentation.



28 **29**

(7) K. Narasaka, K. Soai, Y. Aikawa, and T. Mukaiyama, *Bull. Chem. Soc. Jpn.*, **49**, 779 (1976).
(8) We have been unable to obtain cycloadducts from reaction of silyl ethers with enones. In this case the products are mainly Michael adducts.

Intramolecular Dipolar Cycloaddition Reactions with Azomethine Ylides

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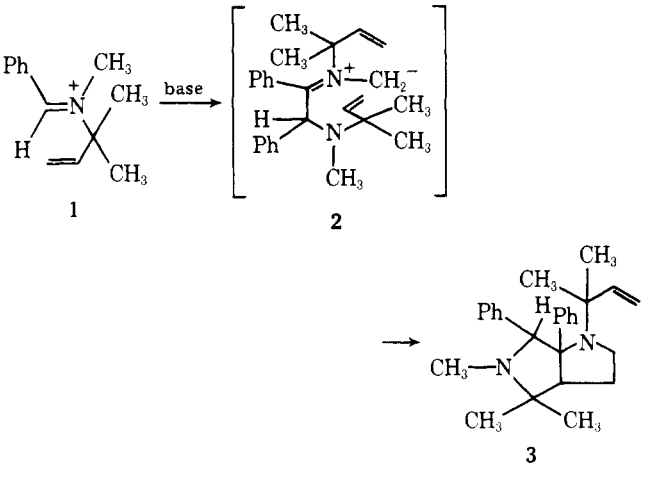
The intramolecular 1,3-dipolar cycloaddition reactions of several aziridine carboxylates containing a neighboring π bond were studied. The only reaction found to occur on thermolysis of *cis*- and *trans*-allyl 1-isopropyl-2-(*p*-biphenyl)-3-aziridinecarboxylate corresponds to isomerization about the three-membered ring. With this system, equilibration of the ring-opened azomethine ylides occurs at a faster rate than internal cycloaddition. Attachment of an electron-withdrawing carbomethoxy substituent to the double bond was found to significantly enhance the intramolecular dipolar cycloaddition rate. Isomerization of the less reactive *cis*-azomethine ylide to the trans form was still found to compete with the cycloaddition reaction. An additional system which was also studied involved the thermal chemistry of *cis*- and *trans*-methyl *N*-(4-carbomethoxy-3-butenyl)-2-(*p*-biphenyl)-3-aziridinecarboxylate. The azomethine ylides derived from these aziridines undergo regioselective cycloadditions which are compatible with the principles of frontier MO theory.

1,3-Dipoles bearing a functional group able to behave as a dipolarophile are extremely interesting substrates. In fact, the intramolecular cycloaddition reaction of a properly functionalized 1,3-dipole represents a general scheme for the synthesis of novel fused ring heterocycles.[1-3] Intramolecular dipolar cycloadditions have been carried out with nitrones,[4-10] diazoalkanes,[11-15] azides,[16-20] azomethine imines,[21,22] carbonyl oxides,[23] nitrile imines,[24,25] nitrile ylides,[26] and sydnones.[27] As part of a program directed toward a study of the scope and generality of intramolecular dipolar cycloaddition reactions, we had the occasion to prepare several aziridine carboxylates containing a π bond in close proximity to the three-membered heterocyclic ring. Reactions involving the thermal and photochemical cleavage of aziridines to azomethine ylides and their subsequent 1,3-dipolar additions to reactive carbon–carbon multiple bonds are well known.[28-36] Huisgen and coworkers have firmly established that the thermal ring cleavage of aziridines involves stereospecific, conrotatory ring opening.[37] On irradiation a disrotatory cleavage of the aziridine ring was observed.[37] Although the bimolecular cycloaddition reactions of the ring-opened valence tautomer of aziridines are well documented, there is only one example in the literature dealing with an intramolecular cycloaddition reaction of an azomethine ylide. Recently, Deyrup and co-workers reported that the reaction of the aldiminium salt **1** with base afforded dimer **3**.[38] The formation of **3** was suggested to arise via the cyclization of a transient 1,3-dipolar azomethine ylide **2**.



1 **2** **3**

In this paper, we wish to describe several of the features associated with the intramolecular dipolar cycloaddition reaction of azomethine ylides which possess a neighboring double bond.

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