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Asymmetric Photocycloadditions with an Optically Active Allenylsilane: Trimethylsilyl as a Removable Stereocontrolling Group for the Enantioselective Synthesis of *exo*-Methylenecyclobutanes

Mary S. Shepard and Erick M. Carreira*

Contribution from the Arnold and Mabel Beckman Laboratory of Chemical Synthesis, Division of Chemistry and Chemical Engineering, California Institute of Technology, Pasadena, California 91125

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Abstract: Allenylsilanes undergo enantioselective intramolecular photocycloaddition reactions with enones and enoates to give adducts in 76−99% enantiomeric excess and 67−90% yield. The silyl-substituted *exo*-methylenecyclobutane products undergo protodesilylation to give the parent unsubstituted *exo*-methylenecyclobutane. Optically active allenylsilanes may thus be used in enantioselective photocycloadditions in which the silyl moiety functions as a removable stereochemical controlling group.

Introduction

The [2+2] photocycloaddition reaction of alkenes is an important and powerful synthetic transformation for the construction of complex molecules.[1] The synthetic potential of this reaction is formidable; in a single step a ring system is produced along with two new C−C bonds and up to four stereogenic centers. As an added benefit, the strained four-membered ring products readily undergo ring-expansion reactions, providing access to additional structures.[2,3] Elegant applications of such processes have been reported in which stereoselective [2+2] cycloadditions afford key synthetic intermediates that are otherwise not readily accessed.[1,4,5]

Two general strategies may be identified for control of relative and absolute asymmetric induction in intramolecular photocycloaddition reactions. These may be classified according to the position of the stereochemical controlling group in relation to the reacting partners and the cyclic adducts. The first type of intramolecular diastereoselective photocycloaddition reactions includes substrates in which the stereochemical controlling

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(1) (a) Crimmins, M. T. *Chem. Rev.* **1988**, *88*, 1453. (b) Crimmins, M. T.; Reinhold, T. L. *Organic Reactions*; Wiley: New York, 1993; Vol. 44, p 297. (c) Winkler, J. D.; Bowen, C. M.; Liotta, F. *Chem. Rev.* **1995**, *95*, 2003. (d) Schreiber, S. L. *Science* **1985**, *227*, 857. (e) Wiesner, K. *Tetrahedron* **1975**, *31*, 1655.

(2) Bellus, D.; Ernst, B. *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 797.

(3) For selected, recent elegant examples of fragmentation and ring-enlargement reactions of substituted cyclobutanes, see: (a) Crimmins, M. T.; Huang, S.; Guise-Zawacki, L. E. *Tetrahedron Lett.* **1996**, *37*, 6519. (b) Rawal, V. H.; Dufour, C.; Iwasa, S. *Tetrahedron Lett.* **1995**, *36*, 19. (c) Winkler, J. D.; Siegel, M. G.; Stelmach, J. E. *Tetrahedron Lett.* **1993**, *34*, 6509. (d) Kraus, G. A.; Zheng, D. *Synlett* **1993**, 71. (e) Crimmins, M. T.; Dudek, C. M.; Cheung, A. W.-H. *Tetrahedron Lett.* **1992**, *33*, 181. (f) Baker, W. R.; Senter, P. D.; Coates, R. M. *J. Chem. Soc., Chem. Commun.* **1980**, 1011.

(4) (a) Rawal, V. H.; Fabre, A.; Iwasa, S. *Tetrahedron Lett.* **1995**, *36*, 6851. (b) Crimmins, M. T.; Jung, D. K.; Gray, J. L. *J. Am. Chem. Soc.* **1993**, *115*, 3146. (c) Winkler, J. D.; Scott, R. D.; Williard, P. G. *J. Am. Chem. Soc.* **1990**, *112*, 8971. (d) Pirrung, M. C.; Thomson, S. A. *J. Org. Chem.* **1988**, *53*, 227. (e) Winkler, J. D.; Hershberger, P. M.; Springer, J. P. *Tetrahedron Lett.* **1986**, *27*, 5177. (f) Crimmins, M. T.; DeLoach, J. A. *J. Am. Chem. Soc.* **1986**, *108*, 800. (g) Smith, A. B.; Sulikowski, G. A.; Sulikowski, M. M.; Fujimoto, K. *J. Am. Chem. Soc.* **1992**, *114*, 2567. (h) Rawal, V. H.; Eschbach, A.; Dufour, C.; Iwasa, S. *Pure Appl. Chem.* **1996**, *68*, 675. (i) Pirrung, M. C. *J. Am. Chem. Soc.* **1979**, *101*, 7130.

(5) Meyers, A. I.; Fleming, S. A. *J. Am. Chem. Soc.* **1986**, *108*, 306.

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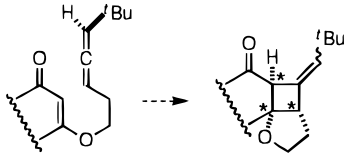
group, or stereogenic center, resides in the tether interconnecting the reacting partners.[4f] Since the resident stereogenic center is incorporated within one of the newly formed rings in the product, these cycloaddition reactions are characterized by intraannular chirality transfer.[6] The second type of intramolecular diastereoselective photocycloaddition reactions is exemplified by substrates in which the stereochemical controlling group resides outside of the newly formed rings in the product; these reactions are characterized by extraannular chirality transfer. Diastereoselective [2+2] photocycloadditions have been reported using either of these approaches.[4] However, in general, the conformational and stereoelectronic constraints accompanying ring formation resulting from intraannular chirality transfer afford greater control in reaction diastereoselectivity.

The strategies that have been employed in asymmetric photocycloaddition reactions of monosubstituted allenes and enones parallel those described in olefin−enone cycloaddition reactions involving extraannular and intraannular chirality transfer.[4d] However, the use of 1,3-disubstituted allenes affords the opportunity to develop a novel class of [2+2] cycloaddition reactions with the chiral allene itself serving as the stereocontrolling group. In contrast to photoadditions involving extraannular and intraannular chirality transfer, the stereocontrolling group in such allene−enone photocycloadditions is absent in the product.[7] In the course of the [2+2] cycloaddition reaction, the stereogenic centers of the product are established at the expense of the axial asymmetry of the allene. We have been interested in developing this complementary cycloaddition strategy into a useful method for the asymmetric synthesis of complex ring systems.

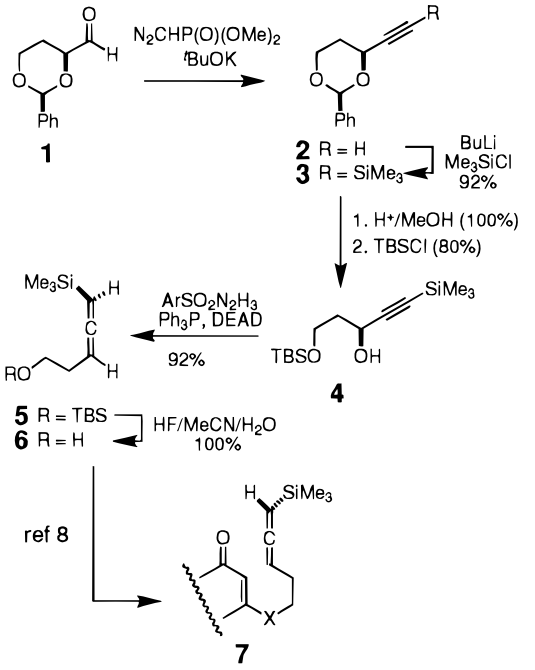
We have reported the intramolecular cycloadditions of optically active *tert*-butyl-substituted allenes with enones and enoates to give photoadducts in excellent yields and up to 99% asymmetric induction (eq 1).[8] Although the products were formed with high enantioselectivities, the bulky *tert*-butyl substituent is a limitation to the synthetic elaboration of these products. Thus, the synthetic utility of the enantioselective allene−enone photocycloaddition reaction would benefit from the development of a family of optically active allenes with a controlling group analogous to the *tert*-butyl moiety which could be removed following enantioselective photocycloaddition.

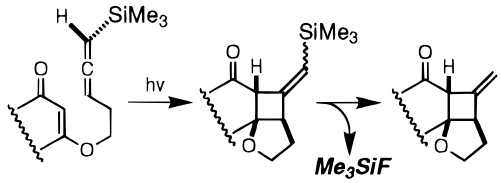


(1)

In this paper we disclose the synthesis of optically active allenylsilanes and their use in enantioselective intramolecular photocycloadditions. The tethered, optically active allenylsilanes undergo intramolecular [2+2] photocycloadditions with enones and enoates to give cyclobutane adducts in 76−99% enantiomeric excess (ee) and 67−90% yield. Importantly, the trimethylsilyl-substituted *exo*-methylenecyclobutanes undergo protodesilylation to give the corresponding unsubstituted photoadducts. Thus, the optically active allenylsilanes may be used in enantioselective photocycloadditions with the trimethylsilyl moiety functioning as a removable stereochemical controlling group (eq 2).

Scheme 1





(2)

Results

The requisite optically active silylallene **6** was readily prepared in multigram quantities from aldehyde **1**, itself synthesized from inexpensive, commercially available (*S*)-(−)-malic acid (Scheme 1).[9] Treatment of aldehyde **1** with the Gilbert−Seyferth reagent (THF, −78 °C) afforded acetylene **2**.[10] Deprotonation of **2** (*n*-BuLi, THF) followed by addition of Me_3SiCl afforded the silylalkyne **3** (92%). Hydrolysis of the benzylidene acetal (MeOH, TsOH) followed by selective monosilylation of the isolated diol yielded alcohol **4** (80%, two steps). The stereoselective conversion of this optically active propargyl alcohol to the desired allenylsilane was effected using reaction methodology recently reported by Myers.[11] Thus, treatment of **4** with [(*o*-nitrophenyl)sulfonyl]hydrazine under Mitsunobu conditions (−15 °C, Ph_3P, $EtO_2CN{=}NCO_2Et$) afforded an intermediate alkylhydrazine which upon warming (23 °C) gave allene **5** in 92% yield. Optically active allenylsilane−alcohol **6** was obtained quantitatively upon hydrolysis of the *O*-silyl ether protecting group (HF/CH_3CN, H_2O). Subsequent attachment of **6** to the α,β-unsaturated carbonyl compounds was accomplished following procedures described previously.[8] Although the conversion of optically active propargyl alcohols analogous to **4** to the corresponding allenes has been shown to occur stereospecifically,[11] we checked that allene **6** had been produced with complete induction by gas chromato-

(6) This nomenclature parallels that which has been used in auxiliary-based enolate alkylation reactions; see: Evans, D. A. In *Asymmetric Synthesis*; Morrison, J. D., Ed.; Stereodifferentiating Addition Reactions Part B; Wiley: New York, 1984; Vol. 3, Chapter 1.

(7) This is an example of chirality transfer that has been termed by Mislow as self-immolative; see: Mislow, K. *Introduction to Stereochemistry*; Benjamin: New York, 1965; p 131.

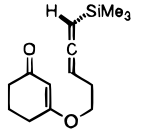
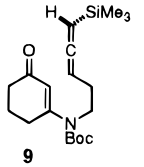
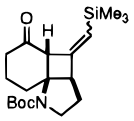
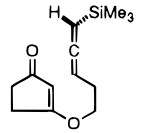
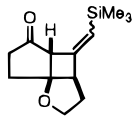
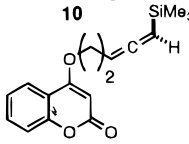
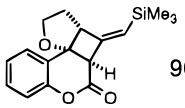
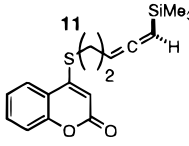
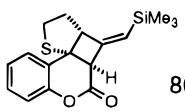
(8) Carreira, E. M.; Hastings, C. A.; Shepard, M. S.; Yerkey, L. A.; Millward, D. B. *J. Am. Chem. Soc.* **1994**, *116*, 6622.

(9) For the preparation of aldehyde **1**, see: Pawlak, J.; Nakanishi, K.; Iwashita, T.; Borowski, E. *J. Org. Chem.* **1987**, *52*, 2896.

(10) (a) Gilbert, J. C.; Weerasooriya, U. *J. Org. Chem.* **1982**, *47*, 1837. (b) Seyferth, D.; Marmor, R. S.; Hilbert, P. *J. Org. Chem.* **1971**, *36*, 1379.

(11) Myers, A. G.; Zheng, B. *J. Am. Chem. Soc.* **1996**, *118*, 4492.

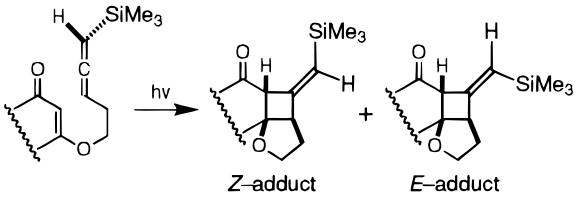
Table 1. Photocycloaddition of Optically Active Silyl-Substituted Allenes

Entry	Photosubstrate	Photoadduct	Yield[a]	ee[d]
1	 8	 13	86%[b]	86% (E)[e] 92% (Z)
2	 9	 14	77%[b]	85% (E)[f]
3	 10	 15	67%[b]	78% (E)[g] 76% (Z)
4	 11	 16	90%[c]	>99%[h]
5	 12	 17	80%[c]	89%[h]

[a] Isolated yields of both diastereomers after purification by chromatography on silica gel. [b] 2−1.5:1 ratio of olefin diastereomers observed. [c] Isolated as a single alkene diastereomer. [d] In all cases, the optical purity was established by comparison to authentic racemic mixtures. The % ee's were determined as follows: [e] Reduction of **13** to the corresponding alcohol and analysis by GC on a Cyclodex-B chiral column. [f] Reduction of **14** to the corresponding alcohol, preparation of the (*S*)-MTPA ester, and analysis by ^{1}H NMR. [g] Direct analysis of the adducts by GC on a Cyclodex-B chiral column. [h] Reduction of **16** and **17** to the corresponding phenol−alcohols, preparation of the bis[(*S*)-MTPA esters], and analysis by ^{19}F NMR.

graphic analysis using a Cyclodex-B chiral column and comparison to authentic racemic material.

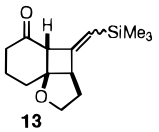
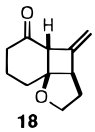
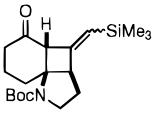
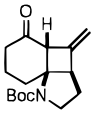
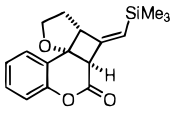
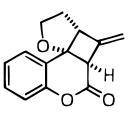
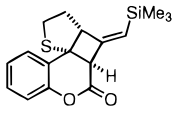
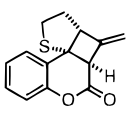
All photocycloaddition reactions were performed in cyclohexane at ambient temperature with a Hanovia 450 W Hg medium-pressure UV lamp in a water-cooled quartz immersion apparatus through a Pyrex filter (eq 3). As shown in Table 1,



(3)

the photoadducts were isolated in 67−90% yield. In analogy to observations made in our previously reported investigation involving *tert*-butyl-substituted allenes, the coumarin-derived adducts (entry 4, **16**; entry 5, **17**) were formed as single alkene diastereomers as determined by ^{1}H NMR spectroscopy. Enones **8**−**10** gave the substituted *exo*-methylenecyclobutane products as a 2−1.5:1 mixture of alkene *E* and *Z* diastereomers which could be readily separated by chromatography on silica gel. Although for the purposes of this investigation the formation of such alkene diastereomers is inconsequential, we determined

Table 2. Protodesilylation of Silyl-Substituted Photoadducts

Entry	Photoadduct	Product	Yield[a]
1[b]	 13	 18	70%
2[b]	 14	 19	67%
3	 16	 20	60%
4	 17	 21	60%

[a] Yields correspond to isolated material after purification by chromatography on silica gel. [b] Reaction was performed on the mixture of alkene diastereomers (2−1.5:1) isolated from the photocycloaddition reaction.

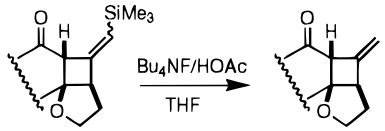
the optical purity of each diastereomer individually as shown in Table 1.[12]

The stereochemical induction in these reactions ranged from 76 to 99% ee.[13] The determination of asymmetric induction of the products necessitated the development of several different protocols, since in only one case (entry 3) was it possible to assay directly the optical purity by GC on a Cyclodex-B chiral column. The stereoisomeric purity of **13** (entry 1) was established upon reduction of the ketone ($NaBH_4$, MeOH) and analysis of the alcohol product by gas chromatography. For adduct **14** (entry 2) the enantioselectivity was assayed upon reduction of the ketone ($NaBH_4$, MeOH), conversion of the isolated secondary alcohol to the corresponding (*S*)-MTPA ester, and analysis by ^{1}H NMR spectroscopy. For the coumarin-derived products **16** and **17** reduction to the phenol−alcohol and preparation of the bis[(*S*)-MTPA esters] permitted the extent of asymmetric induction to be determined in the product by ^{19}F NMR spectroscopy.

Having prepared the optically active photoadducts, we sought reaction conditions that would excise the trimethylsilyl group. In this regard, it was desirable to find protodesilylation conditions to effect removal of the trimethylsilyl moiety without compromising the *exo*-methylenecyclobutane ring. Under a variety of different conditions, such as Bu_4NF/THF, K_2CO_3/MeOH, and KF/MeOH, we observed extensive decomposition of the starting materials, giving highly polar products. When HF·py was employed, unreacted starting material was reisolated. However, use of Bu_4NF buffered with glacial acetic acid in THF at 23 °C proved sufficiently mild, allowing for isolation of the *exo*-methylenecyclobutanes **18**−**21** in good yields (eq 4 and Table 2). The protodesilylation reactions were performed on

(12) The optical purity of **14*Z*** could not be determined accurately as a consequence of carbamate rotamers. The ^{1}H and ^{19}F NMR resonances for the derived (*S*)-MTPA ester were poorly resolved to give an estimated 80−85% ee in the product.

(13) The absolute stereochemistry of the adducts is presumed to parallel that previously reported for the *tert*-butyl-substituted allenes, for which X-ray crystallographic analysis of an appropriate derivative was possible (ref 8). To date, we have been unable to obtain crystalline material of adducts **13**−**17** and their derivatives.

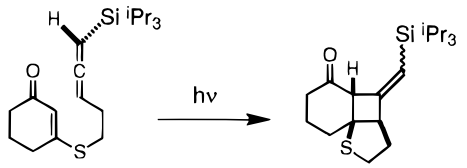


(4)

the mixture of alkene diastereomers isolated from the photocycloadditions. It should be noted that the *E*-substituted diastereomers were routinely observed to undergo protodesilylation at a faster rate than the more sterically encumbered *Z*-substituted adducts.

Discussion

The use of an allenylsilane in [2+2] cycloadditions considerably expands the scope of products that may be accessed via enantioselective allene−enone synthetic photochemistry. When compared to the *tert*-butyl-substituted allenes we have previously described and studied, the trimethylsilyl-substituted counterparts provide adducts with slightly diminished levels of induction. This observation is consistent with the effective size of the stereochemical controlling groups (Me_3C- versus Me_3Si-) on the allene terminus and its ability to block one of the allene diastereofaces. Although the van der Waals radius of Me_3Si- is larger than that of Me_3C-, the longer Si−C bond (1.81 Å) versus C−C bond (1.54 Å) attenuates the effectiveness of the former as a blocking group.[14] In this regard, we have observed higher levels of asymmetric induction when an optically active triisopropylsilyl-substituted allene is employed in intramolecular [2+2] photocycloaddition reactions (eq 5).[15]



(5)

>99% enantioselectivity

The working model which accounts for the transfer of asymmetry during the cycloaddition reaction parallels the Becker model we have previously invoked (Figure 1). The regiochemistry of the initial bond formation uniformly follows Hammond's and Srinivasan's "rule of five".[16] Formation of **23**, including a C(α)-radical, is consistent with Winkler's observations in related olefin−enone cycloadditions.[17] The observation of high optical activity in the photoadducts suggests a mechanism in which the stereochemistry of the products is established kinetically upon addition of the enone excited state to the least hindered allene face (**7** → **22** → **23**, Figure 1). Importantly, within the lifetime of the putative 1,4-biradical intermediate **23**, C−C bond rotation and inversion of the vinyl radical occurs[18] with

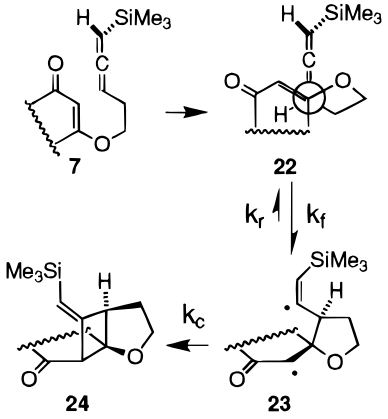


Figure 1. Working model for the enantioselective photocycloadditions.

consequent loss of olefin geometry in reaction products such as **13**, **14**, and **15** (Table 1).[19,20] Interestingly, the coumarin substrates gave photoproducts as single alkene diastereomers. This result can be understood when it is considered that for these cases the resulting 1,4-biradical intermediate is buttressed by peri-interactions with the adjacent aromatic ring. We have proposed that such steric interactions considerably constrain the conformation of the 1,4-biradical and lead to rapid collapse to products.[8] The observation of asymmetric induction for the cycloadditions reported herein is consistent with a mechanism in which ring closure by the 1,4-biradical **23** is faster than retroaddition, k_c(**23**→**24**) ≫ k_r(**23**→**22**).[21,22] In this regard, the lifetime of 1,4-biradicals analogous to **23** can vary from 15 to 900 ns.[23] The inversion barriers for vinyl and methylvinyl radicals have been determined by ESR spectroscopy to be in the range 2−3 kcal/mol, giving rise to bent conformations possessing lifetimes with upper and lower limits of 10^{-8} and 10^{-10} s.[18,24,25] Additionally, the barrier to rotation about the C−C single bond in the methylvinyl radical ($H_2C{=}CMe$) has been observed to be 1300 cal/mol, giving lifetimes of 2×10^{-10} s for the conformational rotamers. Thus, the reversible formation of the 1,4-biradical **23** may be excluded for substrates giving products with high enantioselectivities. Given the lifetimes for bond rotation and vinyl radical inversion in relation to the lifetime of 1,4-biradicals, reversible formation of **23** would likely result in loss of allene enantiopurity. Supporting experimental data for this hypothesis may be found in studies we have

(14) This same effect is manifest in the observed *A* values for $-CMe_3$ ($-\Delta G° = 4.7$ kcal/mol) when compared to $-SiMe_3$ ($-\Delta G° = 2.5$ kcal/mol). See: Eliel, E. L.; Wilen, S. H. *Stereochemistry of Organic Compounds*; Wiley: New York, 1994; Chapter 11, p 695.

(15) Although the triisopropyl-substituted allenes typically gave products with higher levels of induction than the corresponding trimethylsilyl-substituted allenes, the desilylation of these photoadducts proceeded in diminished yields. We are currently investigating this novel class of allenes, and their synthetic chemistry which will be the subject of future work in our laboratories.

(16) (a) Liu, R. S. H.; Hammond, G. S. *J. Am. Chem. Soc.* **1967**, *89*, 4936. (b) Srinivasan, R.; Carlough, K. H. *J. Am. Chem. Soc.* **1967**, *89*, 4932. (c) For recent investigations which provide verification to the rule of five, see: Maradyn, D. J.; Weedon, A. C. *J. Am. Chem. Soc.* **1995**, *117*, 5359.

(17) Winkler, J. D.; Shao, B. *Tetrahedron Lett.* **1993**, *34*, 3355.

(18) (a) Fessenden, R. W.; Schuler, R. H. *J. Chem. Phys.* **1963**, *39*, 2147. (b) Kochi, J. K. *Adv. Free Radical Chem.* **1975**, *5*, 189.

(19) For mechanistic investigations of alkene−enone photocycloadditions, see: (a) Andrew, D.; Weedon, A. C. *J. Am. Chem. Soc.* **1995**, *117*, 5647. (b) Haddad, N.; Abramovich, Z. *J. Org. Chem.* **1995**, *60*, 6883. For computational studies, see: (c) Broeker, J. L.; Eksterowicz, J. E.; Belk, A. J.; Houk, K. N. *J. Am. Chem. Soc.* **1995**, *117*, 1847.

(20) For a [2+2] photocycloaddition reaction of an alkene with an enone which intercepts the 1,4-biradical, see: Becker, D.; Morlender, N.; Haddad, N. *Tetrahedron Lett.* **1995**, *36*, 1921.

(21) For an example in which retroaddition competes with ring closure, see: (a) McCullough, J. J.; Ramachandran, B. R.; Snyder, F. F.; Taylor, G. N. *J. Am. Chem. Soc.* **1975**, *97*, 6767. (b) Hastings, D. J.; Weedon, A. C. *J. Am. Chem. Soc.* **1991**, *113*, 8525. (c) Maradyn, D. J.; Sydnes, L. K.; Weedon, A. C. *Tetrahedron Lett.* **1993**, *34*, 2413. (d) Rudolph, A.; Weedon, A. C. *Can. J. Chem.* **1990**, *68*, 1590.

(22) For recent theoretical discussion of allene−enone photocycloadditions, see: Froese, R. D. J.; Lange, G. L.; Goddard, J. D. *J. Am. Chem. Soc.* **1996**, *61*, 952.

(23) Schuster, D. I.; Lem, G.; Kaprinidis, N. A. *Chem. Rev.* **1993**, *93*, 3.

(24) (a) Fossey, J.; Lefort, D.; Sorba, J. *Free Radicals in Organic Chemistry*; Wiley: Chichester, 1995; Chapter 3. (b) Lowry, T. H.; Richardson, K. S. *Mechanism and Theory in Organic Chemistry*; Harper Collins: New York, 1987; Chapter 9.

(25) In elegant mechanistic work, Weedon has reported trapping the triplet 1,4-biradical intermediates in allene−enone photocycloadditions; see ref 21c. The conditions of the trapping experiment (H_2Se) are analogous to those previously employed by these researchers in trapping the corresponding 1,4-biradical intermediate produced in alkene−enone photocycloadition reactions.[19a]

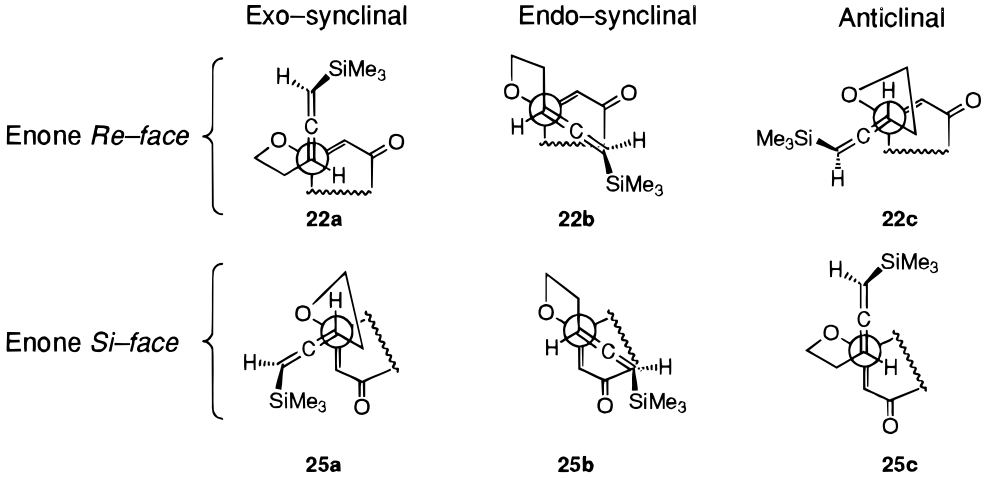


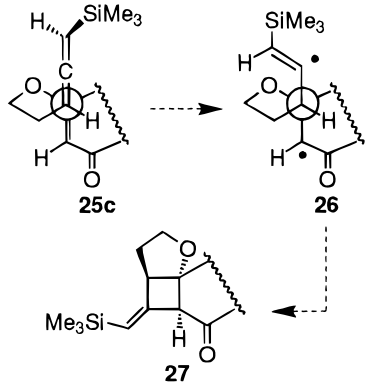
Figure 2. Transition-state models for the addition of allene and enone.

previously reported involving the intramolecular [2+2] photocycloaddition reaction of a tethered optically active allene with cyclopentenone, a class of substrates routinely giving the lowest levels of asymmetric induction. We have observed that interruption of the reaction at various stages of conversion and analysis of the recovered starting material affords allene with diminished levels of optical purity.[8]

Although allene regioselectivity and face selectivity may be understood on the basis of well-known kinetic and steric preferences in related photochemical processes, the origins of the enone face selectivity (*Si* versus *Re*) are not clear. Shown in Figure 2 are the possible arrangements between allene and enone C═C bonds (two synclinal and one anticlinal) to be considered for the attack of the allene on each of the diastereofaces of the enone. Although a more detailed analysis awaits additional data on the nature of transition states for such [2+2] photocycloaddition reactions, we have chosen to consider idealized staggered orientations which minimize nonbonded steric interactions between the substituents on the two sp^2-hybridized carbons.[26] Examination of molecular models permits conformers **22c** and **25a** to be excluded since the ethylene tether interconnecting the enone and allene must incur significant angular deformation in such arrangements. In structures **22b** and **25b** the tethered allene is disposed synclinal to the enone C═C and endo to the preexisting ring. In both of these arrangements, the distal allenyl C−H points directly toward the cyclic enone, resulting in steric interactions with the ring. Importantly, these interactions are absent in **22a** and **25c**. Differing only in the relative orientation of the enone and allene C═C (synclinal **22a** versus anticlinal **25c**), these two structures possess otherwise similar nonbonded interactions and are thus difficult to differentiate. The stereochemistry of the products that we have routinely obtained in allene−enone cycloadditions is only consistent with the reaction proceeding through structure **22a**. Structure **25c** would yield diastereomeric product **27**, possessing a trans-fused 4−5 ring system (Scheme 2) which we have not observed in the photocycloaddition reactions performed to date.[27,28]

The energetic difference between **22a** and **25c** likely results from a combination of subtle effects which dictate the orientation of the allene and enone during the formation of 1,4-biradical intermediate **23**. An inherent kinetic preference for the synclinal

Scheme 2



arrangement **22a** over the anticlinal arrangement **25c** may result from stabilizing secondary orbital interactions between the nascent singly occupied orbitals on the central allene carbon and the enone α-position.[29] It is also possible that a bias for synclinal orientation may be established in the formation of an exciplex prior to carbon−carbon bond formation. In the more commonly employed stereoselective, synthetic reactions involving ground-state polar intermediates, numerous steric, inductive, and stereoelectronic effects have been documented to bias the stereochemical outcome in the products in substantial ways. By contrast, a detailed understanding of similar effects in stereoselective synthetic photochemistry is still lacking, and thus additional mechanistic investigations of this fundamental process are warranted.

The successful development of the protodesilylation reaction conditions required careful optimization and examination of numerous fluoride sources. Importantly, the optimal conditions necessitated the use of fluoride buffered with acetic acid. Under basic conditions (Bu_4NF/THF, K_2CO_3/MeOH, and KF/MeOH) we observed extensive decomposition of the starting materials with the formation of highly polar products. We speculate that under these basic conditions Grob fragmentation takes place to give an enolate that subsequently undergoes β-elimination (Scheme 3); the 2-en-5-ynone so produced would be expected

(26) Houk, K. N.; Paddon-Row, M. N; Rondan, N. G.; Wu, Y.-D.; Brown, F. K.; Spellmeyer, D. C.; Metz, J. T.; Li, Y.; Loncharich, R. J. *Science* **1986**, *231*, 1108.

(27) For a discussion of the relative orientation between alkene and enone, and the resulting consequences in the stereochemistry of the photoadducts, see ref 19.

(28) It is important to note that formation of the first spirocyclic ring from **22a** and **25c**, for example, is an exothermic process and likely proceeds through an early transition state that should not resemble the cis- or trans-fused, 4−5 ring systems present in the ultimate products **24** and **27**, respectively.

(29) Similar issues in the addition of allylmetal reagents to aldehydes have been discussed. For a leading reference, see: Keck, G. E.; Dougherty, S. M.; Savin, K. A. *J. Am. Chem. Soc.* **1995**, *117*, 6210.

Scheme 3

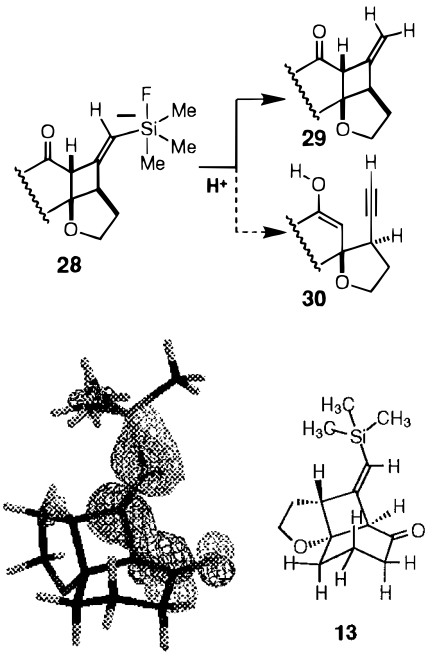
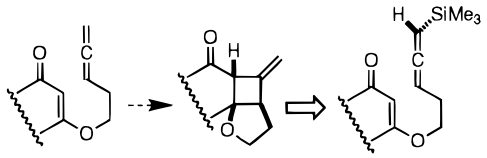


Figure 3. Computationally minimized structure of **13** with graphical representation of the calculated LUMO.

to decompose extensively under the reaction conditions.[30] In this regard, the use of added acetic acid as a buffer in the protodesilylation reaction ensures that the putative vinylsiliconate **28** rapidly protonates to afford the observed product **29** at the expense of fragmentation leading to decomposition.[31,32]

It is remarkable that protodesilylation of the silyl-substituted *exo*-methylenecyclobutanes can compete effectively with ring fragmentation. Analysis of the computationally-minimized molecular model of photoadduct **13** reveals an ideal stereoelectronic alignment among the exocyclic C−Si bond, the cyclobutyl C−C bond, and the carbonyl antibonding orbital (Figure 3).[33] Moreover, calculation and inspection of the LUMO orbital in **13** using semiempirical methods (AM1) reveal that this antibonding orbital has considerable contributions from the adjacent cyclobutyl C−C and C−Si bonds.

To the best of our knowledge, the results described herein represent the first example of asymmetric photocycloadditions involving chiral, optically active allenylsilanes. In combination with the photocycloaddition of Si-tethered alkenes and enones described by Crimmins[34] and the photoremovable silyl protecting group developed by Pirrung,[35] the methodology we delineate further expands the use of silanes in synthetic photochemistry. The sequential intramolecular photocyclization of allenylsilanes with enones and protodesilylation of the trimethylsilyl-substituted products provide access to optically active *exo*-methylenecyclobutanes incorporating complex fused ring systems. The products obtained from such a two-step procedure are formally the photoadducts of enantioselective photocycloadditions of achiral monosubstituted allenes with enones, a synthetic transformation which lacks precedence (eq 6).



(6)

Conclusion

We have demonstrated that optically active allenylsilanes will undergo intramolecular [2+2] photocycloadditions with enones and enoates to give cyclobutane products in high enantioselectivity. Importantly, this represents the first use of allenylsilanes as substrates in [2+2] photocycloadditions. Additionally, conditions have been developed which effect protodesilylation of these adducts, thereby affording the unsubstituted *exo*-methylenecyclobutanes. The salient features of this process include (1) an optically active allenylsilane which is easily prepared, (2) compatibility of the allenylsilane with the photoreaction conditions, and (3) the ease with which the trimethylsilyl controlling group is excised from the reaction products. The methodology described herein should prove useful in the preparation of fused ring systems that are not otherwise readily synthesized in optically active form.

Experimental Section

General Procedures. All reagents were commercially obtained except where noted. Where appropriate, reagents were purified prior to use. All nonaqueous reactions were performed using oven-dried glassware under an atmosphere of dry nitrogen. Air- and moisture-sensitive liquids and solutions were transferred *via* syringe or stainless steel cannula. Organic solutions were concentrated by rotary evaporation below 35 °C at ~25 mmHg (water aspirator). Photoreactions were performed in Pyrex flasks (λ > 293 nm) using a Hanovia 450 W Hg medium-pressure UV lamp in a water-cooled quartz immersion apparatus as the light source. Diethyl ether and tetrahydrofuran (THF) were distilled from sodium−benzophenone ketyl prior to use. Dichloromethane, pyridine, and triethylamine were distilled from calcium hydride prior to use. Dimethyl sulfoxide (DMSO) and *N*,*N*-dimethylformamide (DMF) were distilled under reduced pressure from calcium hydride and stored over 4 Å molecular sieves. Methanol was distilled from magnesium methoxide prior to use. Spectroscopy grade cyclohexane was used in photoreactions. Chromatographic purification of products was accomplished using forced flow chromatography on EM Science Geduran silica gel 60 according to the method of Still.[36] Thin-layer chromatography was performed on EM Reagents 0.25 mm silica gel 60F plates (230−400 mesh). Visualization of the developed chromatogram was performed by fluorescence quenching, ethanolic *p*-anisaldehyde stain, or aqueous ceric ammonium molybdate (CAM) stain.

NMR spectra were recorded on a Bruker AM-500 operating at 500 and 470 MHz for ^{1}H and ^{19}F, respectively, or a General Electric QE Plus operating at 300 and 75 MHz for ^{1}H and ^{13}C, respectively. Data for ^{1}H are reported as follows: chemical shift (δ, ppm), multiplicity (s, singlet; d, doublet; t, triplet; q, quartet; m, multiplet), integration, and coupling constant (*J*, Hz). IR spectra were recorded on a Perkin-Elmer Paragon 1000 FTIR spectrometer using NaCl salt plates and are reported in terms of frequency of absorption (ν, cm^{-1}). Optical rotations were determined on a JASCO DIP-1000 digital polarimeter operating at the sodium D line and are reported as follows: $[\alpha]_{Na}$, concentration (g/100 mL), and solvent. Gas chromatographic analyses were performed on a Hewlett-Packard 6890 gas chromatograph with a flame ionization detector and a 30 m J&W Cyclodex-B capillary column. High-resolution mass spectra were obtained from the Mass Spectrometry Laboratory, Division of Chemistry and Chemical Engineering, California Institute of Technology.

(30) Wovkulich, P. M. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon: Oxford, 1991; Vol. 1.

(31) For an excellent leading reference concerning siliconates, see: Chuit, C.; Corriu, R. J. P.; Reye, C.; Young, J. C. *Chem. Rev.* **1993**, *93*, 1371.

(32) For the facile Lewis acid mediated Grob fragmentation of fused 4−6 ring systems with an exocyclic Me_3SiCH_2 moiety, see: Ochiai, M.; Arimoto, M.; Fujita, E. *J. Chem. Soc., Chem. Commun.* **1981**, 460.

(33) The calculation of the LUMO of **13** was performed using AM1 semiempirical methods supported by the Spartan molecular modeling package available from Wavefunction, Inc., Irvine, CA.

(34) Crimmins, M. T.; Guise, L. E. *Tetrahedron Lett.* **1994**, *35*, 1657.

(35) Pirrung, M. C.; Lee, Y. R. *J. Org. Chem.* **1993**, *58*, 6961.

(36) Still, W. C.; Kahn, M.; Mitra, A. *J. Org. Chem.* **1978**, *43*, 2923.

Terminal Alkyne 2. A 1.0 M solution of KO^{t}Bu (48 mL, 48 mmol, 1.0 equiv) in THF was diluted with 100 mL of THF and cooled to −78 °C. A solution of dimethyl (diazomethyl)phosphonate (7.2 g, 48 mmol, 1.0 equiv) in 50 mL of THF was added dropwise over 10 min *via* cannula. After stirring at −78 °C for 25 min, a solution of the crude aldehyde **1** (48 mmol, 1.0 equiv) in 90 mL of THF was transferred *via* cannula whereupon effervescence occurred. The reaction mixture was stirred at −78 °C for 10 h and then at 23 °C for an additional 2 h. The mixture was poured into 500 mL of H_2O and extracted with 3 × 250 mL of CH_2Cl_2. The combined organic extracts were washed with 500 mL of saturated aqueous NaCl, dried over anhydrous Na_2SO_4, and concentrated *in vacuo*. Purification of the residue by chromatography on silica gel (gradient elution, 5% Et_2O in pentane to 10% Et_2O in pentane) afforded 4.1 g (45%) of alkyne **2**: TLC $R_f = 0.22$ (5% Et_2O in pentane); $[\alpha]_{Na}$ −31.2° ($c = 0.50$, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 300 MHz) δ 7.52−7.48 (m, 2H), 7.40−7.33 (m, 3H), 5.51 (s, 1H), 4.67 (dt, 1H, $J = 11.6$, 2.3 Hz), 4.28 (ddd, 1H, $J = 11.7$, 5.1, 1.1 Hz), 3.97 (td, 1H, $J = 12$, 2.5 Hz), 2.54 (d, 1H, $J = 2.1$ Hz), 2.27 (m, 1H), 1.79 (dm, 1H, $J = 12.9$ Hz); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 138, 129, 128, 126, 102, 82, 74, 67.2, 66.6, 32; IR (thin film) ν 3287, 3066, 3036, 2967, 2931, 2858, 2126; HRMS (FAB$^+$) calcd for $C_{12}H_{13}O_2^+$ (MH^+) 189.0916, found 189.0917.

Silylalkyne 3. To a solution of **2** (0.81 g, 4.3 mmol, 1.0 equiv) in 43 mL of THF at 0 °C was added a 1.6 M solution of ^{n}BuLi (4.0 mL, 6.5 mmol, 1.5 equiv) in hexane. The mixture was stirred at 0 °C for 15 min before chlorotrimethylsilane (1.1 mL, 8.6 mmol, 2.0 equiv) was added. After 15 min the reaction was poured into 75 mL of H_2O and 50 mL of Et_2O. The organic layer was collected, and the aqueous layer was extracted with 2 × 50 mL of Et_2O. The combined organic extracts were washed with 50 mL of saturated aqueous NaCl, dried over anhydrous Na_2SO_4, and concentrated *in vacuo*. Purification of the residue by chromatography on silica gel (4% EtOAc in hexanes) yielded 1.0 g (92%) of a white crystalline solid: mp 59−62 °C (hexanes/EtOAc); TLC $R_f = 0.71$ (4:1 hexanes/EtOAc); $[\alpha]_{Na}$ −40.1° ($c = 1.0$, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 300 MHz) δ 7.53−7.50 (m, 2H), 7.40−7.33 (m, 3H), 5.49 (s, 1H), 4.66 (dd, 1H, $J = 11.5$, 2.5 Hz), 4.26 (dm, 1H, $J = 12$ Hz), 3.95 (td, 1H, $J = 12.1$, 2.4 Hz), 2.27−2.19 (m, 1H), 1.77 (dq, 1H, $J = 13.6$, 2.0 Hz), 0.18 (s, 9H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 138, 129, 128, 126, 103, 102, 90, 68, 67, 32, −0.2; IR (thin film) ν 3068, 3037, 2963, 2853, 2187; HRMS (FAB$^+$) calcd for $C_{15}H_{21}O_2Si^+$ (MH^+) 261.1311, found 261.1316.

Alkynediol. To a solution of **3** (1.0 g, 3.8 mmol, 1.0 equiv) in 16 mL of MeOH was added 7 mg (0.04 mmol, 1 mol%) of *p*-toluenesulfonic acid monohydrate. The reaction was stirred at 23 °C for 70 min and then was poured into 25 mL of saturated aqueous $NaHCO_3$ and 15 mL of Et_2O. The organic layer was collected, and the aqueous layer was extracted exhaustively with CH_2Cl_2. The combined organic layers were washed with saturated aqueous NaCl, dried over anhydrous Na_2SO_4, and concentrated *in vacuo*. Purification of the residue by chromatography on silica gel (2:1 hexanes/EtOAc and then 1:1 hexanes/EtOAc) provided 0.66 g (100%) of the diol: TLC $R_f = 0.21$ (2:1 hexanes/EtOAc); $[\alpha]_{Na}$ −30.8° ($c = 1.0$, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 300 MHz) δ 4.62 (dd, 1H, $J = 6.7$, 5.0 Hz), 4.01−3.93 (m, 1H), 3.87−3.80 (m, 1H), 2.82 (br s, 2H), 2.04−1.92 (m, 2H), 0.16 (s, 9H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 106, 90, 62, 60, 39, −0.2; IR (thin film) ν 3317 (br), 2959, 2173; HRMS (EI$^+$) calcd for $C_8H_{15}O_2Si$ (M − 1) 171.0841, found 171.0834.

Propargyl Alcohol 4. To 560 mg of the diol (3.3 mmol, 1.0 equiv) in 30 mL of CH_2Cl_2 at 0 °C were added triethylamine (680 μL, 4.9 mmol, 1.5 equiv), ^{t}BuMe$_2$SiCl (540 mg, 3.6 mmol, 1.1 equiv), and 4-(*N*,*N*-dimethylamino)pyridine (20 mg, 0.16 mmol, 0.05 equiv) successively. The reaction mixture was allowed to warm slowly to 23 °C over 4.5 h and then was poured into 50 mL of H_2O. The organic layer was washed with 25 mL of 1.0 M aqueous KH_2PO_4, and then with 25 mL of saturated aqueous NaCl. The combined aqueous washes were extracted with 35 mL of Et_2O. The combined organic layers were dried over anhydrous Na_2SO_4 and concentrated *in vacuo*. Purification of the residue by chromatography on silica gel (6% EtOAc in hexanes) afforded 740 mg (80%) of alcohol **4**: TLC $R_f = 0.78$ (2:1 hexanes/EtOAc); $[\alpha]_{Na}$ −41.5° ($c = 1.0$, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 300 MHz) δ 4.61 (m, 1H), 4.06−4.04 (m, 1H), 3.86−3.81 (m, 1H), 3.4 (br s, 1H), 1.99−1.97 (m, 1H), 1.88−1.87 (m, 1H), 0.90 (s, 9H), 0.17 (s, 9H), 0.09 (s, 3H), 0.08 (s, 3H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 106, 89, 62, 61, 39, 26, 18, −0.1, −5.5; IR (thin film) ν 3418 (br), 2958, 2930, 2859, 2172; HRMS (FAB$^+$) calcd for $C_{14}H_{31}O_2Si_2^+$ (MH^+) 287.1863, found 287.1851.

Allene 5. To triphenylphosphine (0.93 g, 3.5 mmol, 1.3 equiv) in 10 mL of THF at −15 °C was added diethyl azodicarboxylate (0.56 mL, 3.5 mmol, 1.3 equiv) dropwise. After 5 min a solution of propargyl alcohol **4** (0.78 g, 2.7 mmol, 1.0 equiv) in 10 mL of THF was added dropwise *via* cannula over 10 min. The mixture was stirred at −15 °C for an additional 10 min before a solution of [(*o*-nitrophenyl)-sulfonyl]hydrazine (0.77 g, 3.5 mmol, 1.3 equiv) in 10 mL of THF was added dropwise *via* cannula over 10 min. The resultant orange solution was stirred at −15 °C for 30 min and then was allowed to warm slowly to 23 °C over 23 h. The reaction mixture was concentrated *in vacuo*, and the residue was purified by chromatography on silica gel (pentane) to afford 0.67 g (92%) of allene **5**: TLC $R_f =$ 0.91 (4:1 hexanes/EtOAc); $[\alpha]_{Na}$ +76.7° ($c = 1.0$, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 300 MHz) δ 4.90−4.87 (m, 1H), 4.77 (q, 1H, $J = 7.0$ Hz), 3.63 (t, 2H, $J = 7.3$ Hz), 2.23−2.14 (m, 2H), 0.90 (s, 9H), 0.09 (s, 9H), 0.06 (s, 6H); ^{13}C NMR δ 210, 82, 80, 63, 32, 26, 18, −0.9, −5.2; IR (thin film) ν 2957, 2930, 2859, 1939 (s).

Allenyl Alcohol 6. To 0.74 g of **5** (2.7 mmol, 1.0 equiv) was added a solution of HF (95:5:1.5 CH_3CN/48% HF/H_2O, 2.7 mL). After stirring at 23 °C for 30 min, the reaction mixture was loaded directly onto a column of silica gel and subjected to chromatography (4:1 pentane/Et_2O) to afford 0.43 g (100%) of allenyl alcohol **6**: TLC $R_f =$ 0.48 (3:1 hexanes/EtOAc); $[\alpha]_{Na}$ +87.8° ($c = 1.0$, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 300 MHz) δ 4.98−4.93 (m, 1H), 4.76 (q, 1H, $J = 6.9$ Hz), 3.66 (td, 2H, $J = 6.3$, 1.6 Hz), 2.26−2.18 (m, 2H), 1.8 (br s, 1H), 0.09 (s, 9H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 210, 83, 79, 62, 31, −1.0; IR (thin film) ν 3316 (br), 2956, 2898, 1939 (s).

Allenyl Mesylate. To allenyl alcohol **6** (160 mg, 1.0 mmol, 1.0 equiv) in 4 mL of CH_2Cl_2 at 0 °C was added 210 μL (1.5 mmol, 1.5 equiv) of triethylamine followed by 94 μL (1.2 mmol, 1.2 equiv) of methanesulfonyl chloride. The reaction mixture was stirred at 0 °C for 30 min and then was poured into 20 mL of pH 7 phosphate buffer. The aqueous layer was extracted with 3 × 10 mL of Et_2O, and the combined organic layers were washed with 15 mL of saturated aqueous NaCl, dried over anhydrous Na_2SO_4, and concentrated *in vacuo*. The resultant oil was purified by chromatography on silica gel (1:1 CH_2Cl_2/hexanes) to afford 0.23 g (97%) of the mesylate: TLC $R_f = 0.71$ (5:1 CH_2Cl_2/hexanes); ^{1}H NMR ($CDCl_3$, 300 MHz) δ 5.00 (dt, 1H, $J =$ 6.7, 3.6 Hz), 4.76 (q, 1H, $J = 6.9$ Hz), 4.24 (t, 2H, $J = 6.8$ Hz), 3.02 (s, 3H), 2.46−2.38 (m, 2H), 0.11 (s, 9H).

Photosubstrate 8. To a solution of **6** (130 mg, 0.80 mmol, 1.0 equiv) in 8 mL of THF was added 120 mg of 1,3-cyclohexanedione (1.0 mmol, 1.3 equiv), 270 mg of triphenylphosphine (1.0 mmol, 1.3 equiv), and 170 μL of diethyl azodicarboxylate (1.0 mmol, 1.3 equiv). The mixture was stirred at 23 °C for 20 min, concentrated *in vacuo*, and subjected to chromatography on silica gel (4:1 hexanes/EtOAc) to afford 170 mg (84%) of **8**: TLC $R_f = 0.15$ (4:1 hexanes/EtOAc); $[\alpha]_{Na}$ +69.2° ($c = 1.0$, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 300 MHz) δ 5.30 (s, 1H), 4.9 (m, 1H), 4.74 (q, 1H, $J = 6.8$ Hz), 3.82 (t, 2H, $J = 6.6$ Hz), 2.27−2.38 (m, 6H), 1.9 (m, 2H), 0.46 (s, 9H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 210, 199, 178, 103, 84, 79, 68, 37, 29, 27, 21, −1.1; IR (thin film) ν 3072 (w), 2953, 2896, 1940 (s), 1667 (s), 1606 (s); HRMS (FAB$^+$) calcd for $C_{14}H_{22}O_2Si$ 250.1389, found 250.1391.

Photoadduct 13. A solution of **8** (99% ee, 150 mg, 0.59 mmol) in 80 mL of cyclohexane was deoxygenated by nitrogen sparge for 10 min. The flask was sealed, and the solution was irradiated for 90 min. The resultant yellow solution was concentrated *in vacuo* and purified by chromatography on silica gel (gradient elution, 8:1 hexanes/EtOAc to 4:1 hexanes/EtOAc) to give 71 mg of the (*Z*)-olefin and 55 mg of the (*E*)-olefin (86%). **13*Z***: TLC $R_f = 0.42$ (4:1 hexanes/EtOAc); $[\alpha]_{Na}$ = +135° ($c = 0.5$, C_6D_6); ^{1}H NMR (C_6D_6, 300 MHz) δ 5.53 (t, 1H, $J = 2.4$ Hz), 3.9 (m, 1H), 3.7 (m, 1H), 3.52 (t, 1H, $J = 3.2$ Hz), 2.9 (m, 1H), 2.2 (dt, 1H, $J = 16.9$, 4.0 Hz), 1.8−1.2 (m, 7H), 0.32 (s, 9H); ^{13}C NMR (C_6D_6 , 75 MHz) δ 206, 153, 127, 86, 67, 62, 54, 40, 33, 32, 20, −0.4; IR (thin film) ν 2948, 2864, 1709, 1643. **13*E***: TLC $R_f =$ 0.32 (4:1 hexanes/EtOAc); $[\alpha]_{Na}$ = +13.4° ($c = 0.1$, cyclohexane); ^{1}H NMR (C_6D_6, 300 MHz) δ 5.87 (t, 1H, $J = 2$ Hz), 3.8 (m, 1H), 3.6 (m, 1H), 3.53 (t, 1H, $J = 3$ Hz), 2.98 (dm, 1H, $J = 9$ Hz), 2.23 (dt, 1H, J

= 18.1, 3.6 Hz), 1.79−1.33 (m, 7H), 0.30 (s, 9H); ^{13}C NMR (C_6D_6, 75 MHz) δ 205, 151, 124, 84, 67, 62, 53, 39, 33, 32, 20, −0.4; IR (thin film) ν 2952, 2865, 1701 (s), 1637.

Analysis of Asymmetric Induction in Photoadduct 13. A sample of **13*Z*** (1 mg, 4 μmol, 1 equiv) in 0.5 mL of MeOH at 23 °C was treated with 2 mg (50 μmol, 50 equiv) of $NaBH_4$. After stirring for 12 h, the mixture was quenched with 2 drops of pH 7 phosphate buffer and concentrated *in vacuo*. The resultant residue was purified by chromatography on silica gel (4:1 hexanes/EtOAc). The epimer with an R_f of 0.39 (4:1 hexanes/EtOAc) was isolated and subjected to GC analysis (170 °C; retention time 18.7 min (minor), 19.4 min (major)), indicating 92% enantiomeric excess.

A sample of **13*E*** (1 mg, 4 μmol, 1 equiv) in 0.5 mL of MeOH at 23 °C was treated with 2 mg (50 μmol, 50 equiv) of $NaBH_4$. After stirring for 12 h, the mixture was quenched with 2 drops of pH 7 phosphate buffer and concentrated *in vacuo*. The resultant residue was purified by chromatography on silica gel (4:1 hexanes/EtOAc). The epimer with an R_f of 0.17 (4:1 hexanes/EtOAc) was isolated and subjected to GC analysis (170 °C; retention time 25.8 min (minor), 27.2 min (major)), indicating 86% enantiomeric excess.

***exo*-Methylenecyclobutane 18.** To a mixture of olefin isomers **13** (8.0 mg, 32 μmol, 1.0 equiv) in 0.5 mL of THF was added 0.35 mL of TBAF/AcOH (0.1 M/0.05 M in THF, 35 μmol/17 μmol, 1.1/0.55 equiv). The reaction mixture was stirred at 23 °C for 60 min and then was poured into pH 7 phosphate buffer. The aqueous layer was extracted 3× with Et_2O, and the combined organic layers were washed with saturated aqueous NaCl, dried over anhydrous Na_2SO_4, and concentrated *in vacuo*. The residue was purified by chromatography on silica gel (2% MeOH in 9:1 hexanes/EtOAc) to afford 4.0 mg (70%) of terminal olefin **18**: TLC R_f = 0.47 (2:1 hexanes/EtOAc); $[\alpha]_{Na}$ = +7.8° (c = 0.05, cyclohexane); ^{1}H NMR (C_6D_6, 300 MHz) δ 5.28 (m, 1H), 4.79 (m, 1H), 3.8 (m, 1H), 3.6 (m, 1H), 3.40 (t, 1H, J = 3.0 Hz), 2.8 (m, 1H), 2.22 (dm, 1H, J = 17.9 Hz), 1.75−1.27 (m, 7H); IR (thin film) ν 3075 (w), 2943, 2862, 1702 (s), 1669.

Photosubstrate 9. A 60% dispersion of NaH in mineral oil (10 mg, 0.26 mmol, 1.2 equiv) was weighed into a flask, washed with hexanes, and dried under vacuum. An atmosphere of nitrogen was restored, 1.5 mL of DMF was added, and the mixture was cooled to 0 °C. The Boc-protected 3-amino-2-cyclohexenone (prepared from the known enaminone[37]) (54 mg, 0.26 mmol, 1.2 equiv) was added, and stirring was continued at 0 °C for 15 min and then at 23 °C for 90 min. A solution of the allenyl mesylate (50 mg, 0.21 mmol, 1.0 equiv) in 0.5 mL of DMF was added *via* cannula. The reaction was heated to 100 °C for 5 h, cooled to 23 °C, and poured into H_2O, saturated aqueous NaCl, and Et_2O. The aqueous layer was extracted with Et_2O, and the combined organic layers were washed with saturated aqueous NaCl, dried over anhydrous Na_2SO_4, and concentrated *in vacuo*. The residue was purified by chromatography on silica gel (14% EtOAc in hexanes) to afford 14 mg (18%) of the desired product **9**: TLC R_f = 0.22 (3:1 hexanes/EtOAc); $[\alpha]_{Na}$ +102° (c = 0.5, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 300 MHz) δ 5.72 (s, 1H), 4.94 (m, 1H), 4.71 (q, 1H, J = 6.9 Hz), 3.60 (m, 2H), 2.72 (t, 2H, J = 6.0 Hz), 2.38 (t, 2H, J = 6.6 Hz), 2.23 (m, 2H), 1.98 (m, 2H), 1.50 (s, 9H), 0.09 (s, 9H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 210, 200, 163, 153, 115, 83, 82, 80, 49, 37, 31, 28, 27, 23, −1.0; IR (thin film) ν 2956, 1938, 1715, 1665; HRMS (FAB^+) calcd for $C_{19}H_{32}NO_3Si^+$ (MH^+) 350.2151, found 350.2158.

Photoadduct 14. A solution of **9** (99% ee, 26 mg, 74 μmol) in 15 mL of cyclohexane was deoxygenated by nitrogen sparge for 5 min. The flask was sealed, and the mixture was irradiated for 5 min. The resultant yellow solution was concentrated *in vacuo* and purified by chromatography on silica gel (12% EtOAc in hexanes) to give 7 mg of the (*Z*)-olefin and 13 mg of the (*E*)-olefin (77%). **14*Z***: TLC R_f = 0.62 (3:1 hexanes/EtOAc); $[\alpha]_{Na}$ +250° (c = 0.29, cyclohexane); ^{1}H NMR (C_6D_6, 300 MHz) (peaks are broadened due to rotamers) δ 5.5 (br s, 1H), 3.9−3.4 (m, 3H), 2.9 (m, 1H), 2.6 (m, 1H), 2.3−2.0 (m, 3H), 1.4 (m, 13H), 0.32 (s, 9H); ^{13}C NMR (C_6D_6, 75 MHz) (some peaks are broadened due to rotamers) δ 206, 176, 125, 79, 61, 60, 54, 53, 48.3, 47.7, 41, 30, 28.9, 28.5, 27, 22, 21, −0.4; IR (thin film) ν 2951, 1694 (s); HRMS (FAB^+) calcd for $C_{19}H_{31}NO_3Si$ 349.2073, found 349.2072. **14*E***: TLC R_f = 0.55 (3:1 hexanes/EtOAc); $[\alpha]_{Na}$ +150° (c = 0.5, cyclohexane); ^{1}H NMR (C_6D_6, 300 MHz) (peaks are broadened due to rotamers) δ 5.7 (m, 1H), 3.9 (m, 1H), 3.6 (m, 1H), 3.1 (m, 1H), 2.9 (m, 1H), 2.35 (d, 1H, J = 18 Hz), 2.0 (m, 1H), 1.6 (m, 2H), 1.4 (m, 13H), 0.00 (s, 9H); ^{13}C NMR (C_6D_6, 75 MHz) (some peaks are broadened due to rotamers) δ 205, 154, 124, 102, 80, 77, 63, 54, 49, 39, 31, 28, 20, −0.5; IR (thin film) ν 2952, 2875, 1697 (s), 1638; HRMS (FAB^+) calcd for $C_{19}H_{31}NO_3Si$ 349.2073, found 349.2073.

Analysis of Asymmetric Induction in Photoadduct 14. A sample of **14*E*** (10 mg, 30 μmol, 1 equiv) in 1 mL of MeOH at 23 °C was treated with 2 mg (50 μmol, 2 equiv) of $NaBH_4$. After stirring for 2 h, the mixture was quenched with 3 drops of 1 M aqueous KH_2PO_4 and concentrated *in vacuo*. The resultant residue was purified by chromatography on silica gel (12% EtOAc in hexanes) to afford 1 mg of the minor alcohol epimer (R_f = 0.49, 3:1 hexanes/EtOAc). The alcohol (3 μmol) was dried by azeotropic removal of water with toluene and taken up in 0.2 mL of CH_2Cl_2. Triethylamine (20 μL, 140 μmol, 50 equiv) was added, followed by 4-(*N*,*N*-dimethylamino)pyridine (2.0 mg, 16 μmol, 5 equiv) and a solution of (*R*)-MTPA-Cl (0.1 M in CH_2Cl_2, 400 μL, 40 μmol, 13 equiv).[38] The reaction was stirred at 23 °C for 40 min and then was purified by chromatography on silica gel (10% EtOAc in hexanes). Integration of the ^{1}H NMR resonances ($CDCl_3$, 500 MHz) at δ 0.23 ppm (major) and δ 0.08 ppm (minor) indicated 85% enantiomeric excess.

***exo*-Methylenecyclobutane 19.** To vinylsilane **14** (7 mg, 20 μmol, 1.0 equiv) in 0.2 mL of THF was added 240 μL of TBAF/AcOH (0.1 M/5 μM in THF, 24 μmol/1.2 μmol, 1.2/0.06 equiv). The reaction mixture was stirred at 23 °C for 19 h and then was purified by chromatography on silica gel (15% EtOAc in hexanes) to afford 4 mg (67%) of terminal olefin **19**: TLC R_f = 0.42 (3:1 hexanes/EtOAc); $[\alpha]_{Na}$ +104° (c = 0.5, cyclohexane); ^{1}H NMR (C_6D_6, 300 MHz) (peaks are broadened due to rotamers) δ 5.3−5.2 (m, 1H), 4.8 (br s, 1H), 3.7 (m, 1H), 3.6−3.5 (m, 1H), 3.3 (m, 1H), 2.7 (m, 1H), 2.3 (m, 1H), 2.0 (m, 1H), 1.5−1.2 (m, 15H); ^{13}C NMR (C_6D_6, 75 MHz) (some peaks are broadened due to rotamers) δ 110, 59, 54, 51, 48, 40, 30, 29, 20, 14; IR (thin film) ν 3082 (w), 2929, 2875, 1695 (s); HRMS (FAB^+) calcd for $C_{16}H_{24}NO_3^+$ 287.1761, found 278.1756.

Photosubstrate 10. To a solution of **6** (16 mg, 0.10 mmol, 1.0 equiv) in 1 mL of THF was added 13 mg of 1,3-cyclopentanedione (0.13 mmol, 1.3 equiv), 34 mg of triphenylphosphine (0.13 mmol, 1.3 equiv), and 20 μL of diethyl azodicarboxylate (0.13 mmol, 1.3 equiv). The mixture was stirred at 23 °C for 30 min and then was concentrated *in vacuo* and purified by chromatography on silica gel (3:2 Et_2O/pentane and then 2:1 Et_2O/pentane) to afford 21 mg (88%) of the desired product **10**: TLC R_f = 0.08 (4:1 hexanes/EtOAc); $[\alpha]_{Na}$ +70° (c = 1.0, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 300 MHz) δ 5.29 (s, 1H), 4.98 (dt, 1H, J = 6.6, 3.7 Hz), 4.79 (q, 1H, J = 6.8 Hz), 3.99 (t, 2H, J = 6.7 Hz), 2.6 (m, 2H), 2.4 (m, 4H), 0.08 (s, 9H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 210, 206, 190, 105, 84, 79, 71, 34, 29, 27, −1.0; IR (thin film) ν 2954, 1939, 1705, 1682, 1593 (s); HRMS (FAB^+) calcd for $C_{13}H_{21}O_2Si^+$ 237.1311, found 237.1310.

Photoadduct 15. A solution of **10** (99% ee, 15 mg, 60 μmol) in 15 mL of cyclohexane was deoxygenated by nitrogen sparge for 10 min. The flask was sealed, and the mixture was irradiated for 30 min. The resultant yellow solution was concentrated *in vacuo* and purified by chromatography on silica gel (3:1 hexanes/EtOAc) to give 14 mg of an 11:7 mixture of (*Z*)- and (*E*)-olefins, respectively (67%). **15*Z***: TLC R_f = 0.68 (2:1 hexanes/EtOAc); $[\alpha]_{Na}$ +124° (c = 0.5, cyclohexane); ^{1}H NMR (C_6D_6, 300 MHz) δ 5.45 (t, 1H, J = 2 Hz), 3.86 (t, 1H, J = 8 Hz), 3.6 (m, 1H), 3.25 (br s, 1H), 2.91 (br d, 1H, J = 8 Hz), 2.1 (m, 2H), 1.96 (m, 1H), 1.7 (m, 1H), 1.4−1.6 (m, 2H), 0.27 (s, 9H); ^{13}C NMR (C_6D_6, 75 MHz) δ 211, 151, 126, 88, 69, 60, 55, 38, 33, 31, −0.6; IR (thin film) ν 2951, 2864, 1738 (s), 1642; HRMS (FAB^+) calcd for $C_{13}H_{21}O_2Si^+$ (MH^+) 237.1311, found 237.1308.

Analysis of Asymmetric Induction in Photoadduct 15. The mixture of **15*Z*** and **15*E*** was subjected to GC analysis (150 °C; retention time 24.8 min (minor *Z*), 25.3 min (major *Z*), 34.3 min (minor *E*), 34.8 min (major *E*)), which indicated 76% enantiomeric excess for the (*Z*)-olefin and 78% enantiomeric excess for the (*E*)-olefin.

Photosubstrate 11. To a solution of alcohol **6** (31 mg, 0.20 mmol, 1.0 equiv) in 2 mL of THF was added 43 mg of 4-hydroxycoumarin

(37) Baraldi, P. G.; Simoni, D.; Manfredini, S. *Synthesis* **1983**, 902.

(38) Dale, J. A.; Mosher, H. S. *J. Am. Chem. Soc.* **1973**, *95*, 512.

(0.27 mmol, 1.3 equiv), 70 mg of triphenylphosphine (0.27 mmol, 1.3 equiv), and 45 μL of diethyl azodicarboxylate (0.27 mmol, 1.3 equiv). The mixture was stirred at 23 °C for 30 min, concentrated *in vacuo*, and purified by chromatography on silica gel (6:1 hexanes/EtOAc) to afford 43 mg (72%) of white crystalline product **11**: mp 54−58 °C (hexanes/EtOAc); TLC $R_f = 0.31$ (3:1 hexanes/EtOAc); $[\alpha]_{Na}$ +87° (*c* = 1.0, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 300 MHz) δ 7.85−7.82 (m, 1H), 7.58−7.52 (m, 1H), 7.34−7.24 (m, 2H), 5.67 (s, 1H), 5.0 (m, 1H), 4.88 (q, 1H, *J* = 6.8 Hz), 4.17 (t, 2H, *J* = 6.6 Hz), 2.61−2.53 (m, 2H), 0.09 (s, 9H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 210, 166, 163, 153, 132, 124, 123, 117, 116, 90, 84, 79, 69, 27, −1.0; IR (thin film) ν 3041, 2956, 1940, 1743 (s), 1610; HRMS (FAB^+) calcd for $C_{17}H_{21}O_3Si^+$ 301.1247, found 301.1260.

Photoadduct 16. A solution of **11** (99% ee, 20 mg, 67 μmol) in 20 mL of cyclohexane was deoxygenated by nitrogen sparge for 10 min. The flask was sealed, and the mixture was irradiated for 120 min. The resultant yellow solution was concentrated *in vacuo* and purified by chromatography on silica gel (9:1 hexanes/EtOAc) to give 18 mg (90%) of the (*E*)-olefin **16** only: TLC $R_f = 0.58$ (3:1 hexanes/EtOAc); $[\alpha]_{Na}$ +157° (*c* = 0.5, $CHCl_3$); ^{1}H NMR (C_6D_6, 300 MHz) δ 7.34−7.31 (m, 1H), 6.87−6.78 (m, 3H), 6.16 (t, 1H, *J* = 2.5 Hz), 3.92 (td, 1H, *J* = 7.8, 1.4 Hz), 3.85 (t, 1H, *J* = 3.2 Hz), 3.64−3.55 (m, 1H), 3.27 (dm, 1H, *J* = 8.9 Hz), 1.78−1.64 (m, 1H), 1.52 (ddd, 1H, *J* = 12.5, 5.8, 1.5 Hz), −0.10 (s, 9H); ^{13}C NMR (C_6D_6 , 75 MHz) δ 163, 151, 148, 130, 127.5, 127.1, 125, 122, 118, 80, 68, 60, 53, 33, −0.6; IR (thin film) ν 3072 (w), 3041 (w), 2954, 2864, 1757 (s), 1646, 1618; HRMS (FAB^+) calcd for $C_{17}H_{20}O_3Si$ 300.1182, found 300.1196.

Analysis of Asymmetric Induction in Photoadduct 16. A sample of **16** (7 mg, 20 μmol, 1 equiv) in 0.3 mL of THF at 23 °C was treated with 30 μL (60 μmol, 3 equiv) of 2.0 M $LiBH_4$ in THF. After stirring at 23 °C for 12 h, the reaction was quenched cautiously with 1 M aqueous KH_2PO_4 and concentrated *in vacuo*. The residue was purified by chromatography on silica gel (4:1 hexanes/EtOAc) to afford 6 mg of the diol ($R_f = 0.33$, 3:1 hexanes/EtOAc). The alcohol (10 μmol) was dried by azeotropic removal of water with toluene and dissolved in 0.2 mL of CH_2Cl_2. Triethylamine (10 μL, 70 μmol, 7 equiv) was added, followed by 4-(*N*,*N*-dimethylamino)pyridine (2 mg, 20 μmol, 2 equiv) and a solution of (*R*)-MTPA-Cl (0.1 M in CH_2Cl_2, 200 μL, 20 μmol, 2 equiv). The reaction mixture was stirred at 23 °C for 25 min and was purified by chromatography on silica gel (15% EtOAc in hexanes). Integration of the ^{19}F NMR resonances ($CDCl_3$, 470 MHz) at δ −71.03 and −71.20 ppm (major) indicated 99% enantiomeric excess (minor diastereomer peaks at δ −70.96 and −71.22 ppm were not detected).

***exo*-Methylenecyclobutane 20.** To vinylsilane **16** (7 mg, 20 μmol, 1.0 equiv) in 0.6 mL of THF was added an excess of TBAF/AcOH (0.1 M/0.15 M in THF). The reaction mixture was stirred at 23 °C for 15 min and then was subjected to chromatography on silica gel (15% EtOAc in hexanes) to afford 3 mg (60%) of the desired terminal olefin: TLC $R_f = 0.43$ (25% EtOAc in hexanes); $[\alpha]_{Na}$ +158° (*c* = 0.5, cyclohexane); ^{1}H NMR (C_6D_6, 300 MHz) δ 7.26−7.23 (m, 1H), 6.88−6.79 (m, 3H), 5.39 (m, 1H), 4.73 (t, 1H, *J* = 2 Hz), 3.88 (t, 1H, *J* = 8.4 Hz), 3.69 (t, 1H, *J* = 3.1 Hz), 3.60−3.51 (m, 1H), 2.89 (dm, 1H, *J* = 8 Hz), 1.60−1.46 (m, 1H), 1.32 (dd, 1H, *J* = 12.5, 5.5 Hz); ^{13}C NMR (C_6D_6 , 75 MHz) δ 164, 151, 142, 130, 127, 125, 122, 117, 112, 80, 68, 58, 50, 32; IR (thin film) ν 3072, 2947, 2863, 1755 (s), 1675, 1612; HRMS (EI^+) calcd for $C_{14}H_{12}O_3$ 228.0786, found 228.0779.

Photosubstrate 12. A solution of **6** (25 mg, 0.16 mmol, 1.0 equiv) in 2.0 mL of THF was transferred *via* cannula to 4-mercaptocoumarin[39] (160 mg, 0.87 mmol, 5 equiv). Triphenylphosphine (55 mg, 0.21 mmol, 1.3 equiv) was added, followed by 33 μL (0.21 mmol, 1.3 equiv) of diethyl azodicarboxylate. The resultant mixture was stirred at 23 °C for 3 h and then was concentrated *in vacuo*. The residue was purified by flash chromatography on silica gel (7% EtOAc in hexanes) to yield 35 mg (69%) of **12**: TLC $R_f = 0.59$ (3:1 pentane/Et_2O); $[\alpha]_{Na}$ +94° (*c* = 1.0, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 300 MHz) δ 7.80−7.71 (m, 1H), 7.55−7.50 (m, 1H), 7.34−7.23 (m, 2H), 6.14 (s, 1H), 5.06 (m, 1H), 4.87 (q, 1H, *J* = 6.6 Hz), 3.07 (t, 2H, *J* = 7.3 Hz), 2.49−2.41 (m, 2H), 0.11(s, 9H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 209, 159, 156, 152, 132, 124.0, 123.8, 118, 117, 107, 85, 81, 31, 26, −0.9; IR (thin film) ν 3072 (w), 2956, 1938, 1718 (s); HRMS (FAB^+) calcd for $C_{17}H_{21}O_2SSi^+$ (MH^+) 317.1032, found 317.1028

Photoadduct 17. A solution of **12** (99% ee, 4.5 mg, 14 μmol, 1 equiv) in 5 mL of cyclohexane was deoxygenated by nitrogen sparge for 5 min. The reaction vessel was sealed, and the solution was irradiated for 25 min. After concentration *in vacuo* the residue was purified by chromatography on silica gel (3% EtOAc in hexanes) to afford 3.6 mg (80%) (*E*)-olefin **17**: TLC $R_f = 0.64$ (3:1 hexanes/EtOAc); $[\alpha]_{Na}$ +121° (*c* = 1.0, cyclohexane); ^{1}H NMR (C_6D_6, 300 MHz) δ 7.56 (dd, 1H, *J* = 5.6, 2.5 Hz), 6.83−6.75 (m, 3H), 6.05 (t, 1H, *J* = 2.5 Hz), 4.10 (t, 1H, *J* = 3.4 Hz), 3.53−3.48 (m, 1H), 2.83−2.74 (m, 1H), 2.67−2.61 (m, 1H), 1.89−1.82 (m, 2H), −0.15 (s, 9H); ^{13}C NMR (C_6D_6, 75 MHz) δ 163, 151, 149, 130, 129, 127, 125, 123, 118, 67, 57, 56, 39, 35, −0.6; IR (thin film) ν 3061 (w), 2952, 1758 (s), 1643; HRMS (FAB^+) calcd for $C_{17}H_{21}O_2SSi^+$ (MH^+) 317.1032, found 317.1022.

Analysis of Asymmetric Induction in Photoadduct 17. A sample of **17** (3.6 mg, 11 μmol, 1 equiv) in 0.5 mL of THF at 23 °C was treated with 30 μL (60 μmol, 5 equiv) of 2.0 M $LiBH_4$ in THF. After stirring at 23 °C for 1 h, the reaction was quenched cautiously with 3 drops of 1 M aqueous KH_2PO_4. The mixture was purified by chromatography on silica gel (3:1 hexanes/EtOAc) to afford 2 mg of the diol ($R_f = 0.22$, 3:1 hexanes/EtOAc). The alcohol (6 μmol) was dried by azeotropic removal of water with toluene and dissolved in 0.2 mL of CH_2Cl_2. Triethylamine (20 μL, 140 μmol, 23 equiv) was added, followed by 4-(*N*,*N*-dimethylamino)pyridine (2.0 mg, 16 μmol, 3 equiv) and a solution of (*R*)-MTPA-Cl (0.1 M in CH_2Cl_2, 300 μL, 30 μmol, 5 equiv). The mixture was stirred at 23 °C for 30 min and then was purified by chromatography on silica gel (9:1 hexanes/EtOAc). Integration of the ^{19}F NMR resonances ($CDCl_3$, 470 MHz) at δ −70.32 and −71.05 ppm (minor) and δ −70.45 and −70.95 ppm (major) indicated 89% enantiomeric excess.

***exo*-Methylenecyclobutane 21.** To **17** (7 mg, 20 μmol, 1.0 equiv) in 0.4 mL of THF was added 240 μL of TBAF/AcOH (0.1 M/0.15 M in THF, 24 μmol/36 μmol, 1.1/1.6 equiv). The mixture was stirred at 23 °C for 20 min and then was purified by chromatography on silica gel (5% EtOAc in hexanes) to afford 3 mg (60%) of terminal olefin **21**: TLC $R_f = 0.60$ (3:1 hexanes/EtOAc); $[\alpha]_{Na}$ +45° (*c* = 0.25, cyclohexane); ^{1}H NMR (C_6D_6, 300 MHz) δ 7.54−7.50 (m, 1H), 6.8 (m, 3H), 5.30 (m, 1H), 4.57 (m, 1H), 3.93 (q, 1H, *J* = 3.2 Hz), 3.06 (m, 1H), 2.82−2.72 (m, 1H), 2.58−2.51 (m, 1H), 1.61−1.54 (m, 2H); ^{13}C NMR (C_6D_6, 75 MHz) δ 163, 151, 143, 130, 129, 125, 123, 118, 112, 64, 57, 55, 37, 35; IR (thin film) ν 3071 (w), 2925, 2854, 1756 (s), 1675; HRMS (FAB^+) calcd for $C_{14}H_{13}O_2S^+$ (MH^+) 245.0636, found 245.0635.

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