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Substituent and Solvent Effects on the Photosensitized Oxygenation of 5,6-Dihydro-1,4-oxathiins. Intramolecular Oxygen Transfer vs Normal Cleavage of the Dioxetane Intermediates

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The reaction of singlet oxygen with variously substituted oxathiins **1** affords dicarbonyl compounds **4** and/or ketosulfoxides **7** and **8** depending on the nature of the substituent at C3 and on the reaction conditions. The normal fragmentation of dioxetanes **2** to **4** competes with an intramolecular oxygen transfer to ring sulfur, which leads to **7** and **8**, presumably via the labile epoxides **5**. This new pathway is promoted by electron-withdrawing groups at C3 and, for unsubstituted and monosubstituted amide derivatives **1h** and **1i**, respectively, by the solvent basicity. Chemical experiments support the intermediacy of epoxides **5** for **7**, whereas they are not conclusive for **8**. However, the formation of the latter compounds appears to be favored by polar solvents and cation-stabilizing groups at C2 as phenyl or methyl, and these observations may be well accounted for by the suggested pathway from **5** through charged species as **E**. Direct oxidation by singlet oxygen to sulfur is unsignificant, except for the amide series and for **1g** or when the oxygenation is carried out in methanol.

Introduction

Alkenes are among the most reactive substrates for singlet oxygen leading to dioxetanes or, in the presence of allylic hydrogens, to ene-adducts.[1] The presence of a heteroatom at the double bond can favor the dioxetane mode and influence the thermal stability of the peroxidic intermediate.[2] Thus, the reaction of singlet oxygen with sulfur-containing olefins normally leads to oxygenated products whose origins may be attributed to a dioxetane intermediate.[3] In line with this assumption, the expected dicarbonyl compound **4a** is obtained via the thermally unstable dioxetane **2a** in the dye-sensitized photooxygenation in CH_2Cl_2 of a S,O-substituted alkene, namely, 2,3-diphenyl-5,6-dihydro-1,4-oxathiin (**1a**) (Scheme 1).[2b] We subsequently found that under the same conditions, only **1b** gives the dicarbonyl compound **4b**, whereas the presence of an electron-withdrawing group at C-3 of the 1,4-oxathiin system in derivatives **1c**−**e** induces the exclusive and highly stereoselective formation of the ketosulfoxides **7c**−**e** and **8c**−**e** (Scheme 1).[5] We explained this unexpected product pattern via the rearrangement of the related dioxetanes **2c**−**e** into the undetected sulfoxide epoxides **5c**−**e**.[5] Although similar intramolecular rearrangement is hitherto unreported, the capability of dioxetanes to give oxygen transfer to sulfides is documented,[1b,6] and it is also reported that the reaction in some cases can lead to epoxidic compounds[6a,b] or rearrangement products.[6c] None of the sulfoxides **6b**−**d** were found, although oxidation of the sulfur atom is known to occur, albeit rarely, in the reaction of $^1O_2$ with vinyl sulfides.[4] On the other hand, it is also reported that oxygenation of sulfides to sulfoxides by singlet oxygen is slow and reversible in aprotic solvents, whereas it increases in efficiency at low temperatures or, mainly, in alcohols (especially in MeOH).[7]

To gain further mechanistic insight, we thoroughly investigated the dye-sensitized photooxygenation of a series of 5,6-dihydro-1,4-oxathiins, **1b**−**e** and suitable **1f**−**k**. This topic appears to be of interest in the field of

(1) (a) Foote, C. S.; Clennan, E. L. In *Active Oxygen in Chemistry*; Foote, C. S., Valentine, J. S., Greenberg, A., Liebman, J. F., Eds.; Chapman and Hall: London, 1995; p 105. (b) *Singlet Oxygen*; Frimer, A. A., Ed.; CRC Press: Boca Raton, FL, 1985; Vol. II. (c) Schaap, A. P.; Zaklika, K. A. In *Singlet Oxygen*; Wasserman, H. H., Murray, R. W., Eds.; Academic Press: New York, 1979; p 234.

(2) See, for example: (a) Gollnick, K.; Knutzen-Mies, K. *J. Org. Chem.* **1991**, *56*, 4027. (b) Handley, R. S.; Stern, A. J.; Schaap, A. P. *Tetrahedron Lett.* **1985**, *26*, 3183. (c) Geller, G. G.; Foote, C. S.; Pechman, D. B. *Tetrahedron Lett.* **1983**, 673. (d) Adam, W.; Encarnacion, L. A. A. *Chem. Ber.* **1982**, *115*, 2592.

(3) Sulfur-substituted dioxetanes are much more thermally unstable than the O-analogues, and in many cases, their formation has been postulated on the basis of the characteristic C−C bond cleavage products; some examples have been also reported involving C−S bond cleavages.[4] It has been suggested that the greater thermal instability of sulfur-substituted dioxetanes compared to that of oxygen-substituted derivatives could be due to the decreased rigidity of the sulfur heterocycles as a consequence of the larger atomic radius of sulfur compared to that of oxygen.[2a]

(4) Ando, W.; Takata, T. In *Singlet Oxygen*; Frimer, A. A., Ed.; CRC Press: Boca Raton, FL, 1985; Vol. III, Part 2.

(5) Part of this work has been reported in a preliminary form: Cermola, F.; De Lorenzo, F.; Giordano, F.; Graziano, M. L.; Iesce, M. R.; Palumbo, G. *Org. Lett.* **2000**, *2*, 1205.

(6) See, for example: (a) Adam, W.; Heil, M. *J. Am. Chem. Soc.* **1992**, *114*, 5591. (b) Campbell, B. S.; Denney, D. B.; Denney, D. Z.; Shih, L. S. *J. Am. Chem. Soc.* **1975**, *97*, 3850. (c) Wasserman, H. H.; Saito, I. *J. Am. Chem. Soc.* **1975**, *97*, 905.

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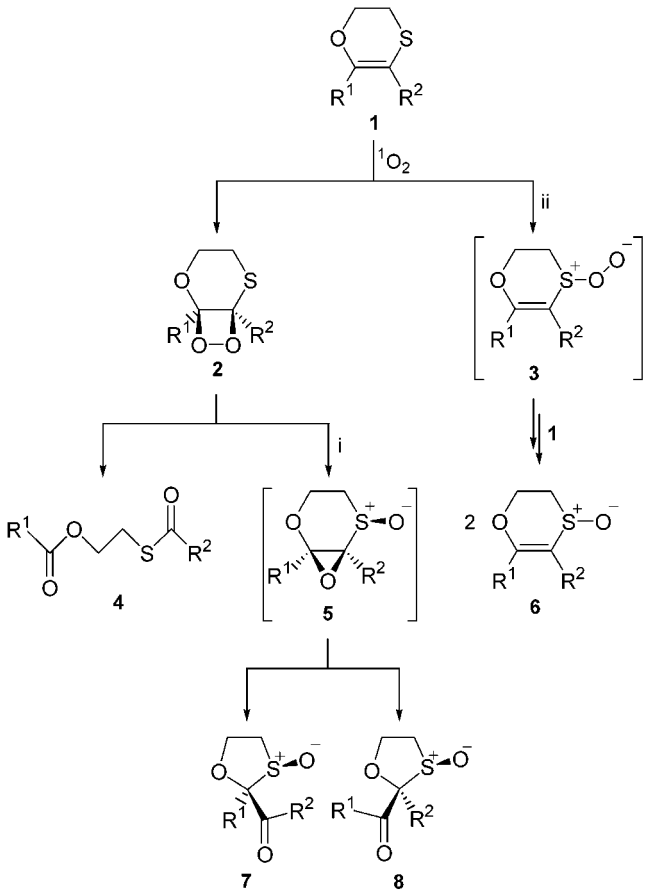
SCHEME 1



i; only for R^2 = Electron-withdrawing group
ii; for **1f-k** or in MeOH

a; $R^1 = R^2 =$ Ph
b; R^1 = Ph, R^2 = Me
c; R^1 = Me, $R^2 = CO_2Me$
d; R^1 = Me, R^2 = COMe
e; R^1 = Ph, $R^2 = CO_2Et$
f; R^1 = H, $R^2 = CO_2Me$
g; $R^1 = R^2 = CO_2Me$
h; R^1 = Me, $R^2 = CONH_2$
i; R^1 = Me, R^2 = CONHPh
j; R^1 = Me, R^2 = CON(Me)Ph
k; R^1 = Me, $R^2 = CONMe_2$

singlet oxygen reactivity toward heterosubstituted olefins. It also offers information on the action of light and oxygen mediated by dye-sensitizers on the 1,4-oxathiin system present in compounds that are important for their antifungal (**1i** is known as carboxin)[8a,b] or anti-HIV activity.[8c]

Results and Discussion

Tetraphenylporphyrin-sensitized photooxygenation of **1b**−**k** was carried out at −20 °C in CH_2Cl_2. The reaction products, which were generally isolated by preparative TLC, are shown in Scheme 1 and Table 1. For all of them, satisfactory spectroscopic data were obtained. The structures of **7c** and of **8c**, the latter as a 2,4-dinitrophenylhydrazone derivative, had been previously determined by X-ray crystallography, which had evidenced the cis relationship between the sulfoxide oxygen and the newly formed carbonyl function.[5] Since compounds **7j** and **8j** afforded suitable crystals, a second opportunity was therefore provided to confirm the stereochemical trend (Figures 1 and 2). The crystallographic determination also accounted for the anomalous upfield values of the Me singlets (δ 1.28 and 1.41) in the ^{1}H NMR of ketosulfoxides **7j** and **8j** if compared with those of the other **7** (δ 1.7−1.9) and **8** (δ 2.3−2.5). In fact, it shows that for both compounds, the methyl groups are found above the ring current of phenyl and are affected by its strong diamagnetic effect.

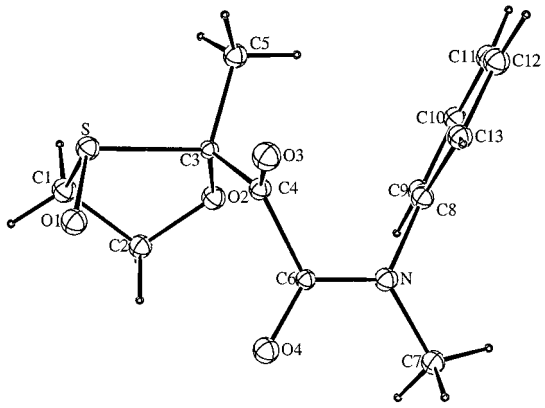


FIGURE 1. ORTEP graphical representation of **7j**.

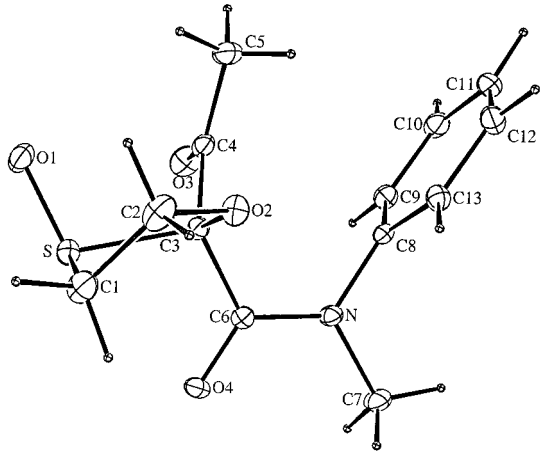


FIGURE 2. ORTEP graphical representation of **8j**.

Table 1 reports the relative amounts of all the products formed, which were spectroscopically deduced by ^{1}H NMR of the crude reaction mixtures. In this Table, the yields of pure isolated compounds are also reported; these are lower than those determined by ^{1}H NMR since all products, except sulfoxides **6**, partly decompose on contact with the chromatographic adsorbent. Neither traces of the stereomers of **7** and **8** or products from ene-reactions were ever found in the mixtures of **1b**−**d**,**h**−**k** despite the presence of allylic hydrogens.

(7) It has been shown that the initial persulfoxide in an aprotic solvent is converted to a thiadioxirane and in MeOH to a hydroperoxy methoxy sulfide (or to H-bonding stabilized persulfoxide), both of which promptly oxidize another molecule of substrate to give two molecules of sulfoxides: (a) Clennan, E. L.; Greer, A. *J. Org. Chem.* **1996**, *61*, 4793. (b) Liang, J.-J,; Gu, C.-L.; Kacher, M. L.; Foote, C. S. *J. Am. Chem. Soc.* **1983**, *105*, 4717.

(8) (a) Cook, M. J. In *Comprehensive Heterocyclic Chemistry*; Boulton, A. J., McKillop, A., Eds.; Pergamon Press: Oxford, 1984; Vol. 3, p 994. (b) Guillaumet, G. In *Comprehensive Heterocyclic Chemistry II*; Katritzky, A. R., Rees, C. W., Eds.; Elsevier Science: Oxford, 1996; Vol. 6, p 447. (c) Borkow, G.; Barnard, J.; Nguyen, T. M.; Belmonte, A.; Wainberg, M. A.; Parniak, M. A. *J. Virol.* **1997**, *71*, 3023.

TABLE 1. TPP-Sensitized Photooxygenation of 1b−k in CH_2Cl_2[a]

substrate	*t* (min)	R^1	R^2	product distribution % [%][b] 4	7	8	6
1b[c]	180	Ph	Me	100 [90]			
1c[c]	90	Me	CO_2Me		64 [47]	36 [23]	
1d[c]	90	Me	COMe		75[d]	25[d]	
1e[c]	90	Ph	CO_2Et		35 [15][e]	65 [30]	
1f	120	H	CO_2Me		>95[d]		<5 [3]
1g	210	CO_2Me	CO_2Me		82[d,f]		18 [10]
1h	180	Me	$CONH_2$	60 [31]	14 [8]	10 [9]	16 [11]
1i	150	Me	CONHPh	50 [29]	5 [4]		45 [34]
1j	150	Me	CON(Me)Ph	8 [5]	68 [60]	21 [15]	3 [2]
1k	180	Me	$CONMe_2$	80 [58]	7 [5]		13 [11]

[a] Solution = 0.02 M; −20 °C (0 °C for **1h** due to its low solubility). [b] Product ratios that have been determined by ^{1}H NMR spectra of crude reaction mixtures are an average of 2 or 3 determinations and are good to ±2−5%. No other products are present. In brackets, yields of pure products isolated by preparative TLC are reported; they are lower than those deduced spectroscopically due to the partial decomposition of all products, except sulfoxides **6**, during the silica gel chromatography. [c] From ref 5. [d] Not isolated. [e] With a purity of 70%. [f] **7g**≡**8g**.

TABLE 2. Product Distribution (%)[a] in Photooxygenation of 1b,c,i under Different Conditions[b]

entry	oxathiin	solvent	*t* (min)	*T* (°C)	4	7	8	6
a	**1b**	CH_2Cl_2	180	−20	100			
b	**1b**	CH_2Cl_2	240	−20	98			2
c	**1b**	MeOH	270	−40	55			45
e	**1c**	CCl_4	150	−20		80	20	
f	**1c**	CH_2Cl_2	90	−20		64	36	
g	**1c**	CH_2Cl_2	90	−70		63	35	2
h	**1c**	CH_2Cl_2	120	−20		64	34	2
i	**1c**	Acetone	180	−20		68	32	
j	**1c**	MeCN	90	−20		60	40	
k	**1c**	MeOH	180	−20		2	5	93
l	**1c**	MeOH	180	−40				100
m	**1i**	CH_2Cl_2	150	−20	50	5		45
n	**1i**	MeCN	90	−20	44	30	10	16
o	**1i**	Acetone	210	−20	16	54	14	16
p	**1i**	DMF-d_7	420	−20		78	15	7
q	**1i**	MeOH	210	−20	65	4		31

[a] Product ratios that have been determined by ^{1}H NMR spectra of crude reaction mixtures are an average of 2 or 3 determinations and are good to ±2−5%. [b] A 0.02 M solution was used except for entries b and h, for which 0.1 M solutions were used.

As shown in Table 1, product distribution dramatically depends on the nature of the substituents at the double bond. The selective formation of the expected compound **4b** was observed only for arylmethyl-substituted **1b** since ketosulfoxides **7** and **8** were competitive in the presence of an electron-withdrawing group at C-3. In actual fact, the higher the electrophilic nature

(−CO−, −COO > CON−), the more selective the formation of **7** and **8**. However, in the series of amides, particularly for **1h** and **1i**, the electronic nature of the substituent does not appear to be the sole factor. Indeed, while the major product from amide **1i** is the dicarbonyl compound **4i**, the substitution of the NH hydrogen with methyl (series **j**) leads to the highly selective formation of **7j** and **8j**. This suggests that the presence of an active NH moiety may play a role in the reaction of **1i** and, hence, of **1h**. Sulfoxides **6** were obtained from the electron-poor dicarbomethoxy derivative **1g** and from amides **1h**−**k**, particularly from **1h** and **1i**.

Mechanistic Probes. *Reaction Conditions (Concentration, Temperature, Solvent Effects).* We chose compounds **1b**, **1c**, and **1i** as representative derivatives and oxygenated them under different conditions (Table 2). No effect of concentration or of solvent was observed from **1b** except for the reaction in MeOH, which led to compound **4b** and, also, to sulfoxide **6b**. Instead, a slight increment in **8c** vs **7c** was observed by enhancing solvent polarity (cf. reactions in CCl_4 and MeCN). For the amide **1i**, the ratio of ketosulfoxides **7i** and **8i** to compound **4i** appeared to increase when the solvent basicity was increased [on the basis of the β scale of HBA (hydrogen-bond acceptor) basicities acetonitrile < acetone < dimethylformamide].[9] As expected, the use of methanol as an oxygenating solvent significantly favored the formation of sulfoxides **6** (entries c,k, and l) especially at low temperatures (entry l) according to the above data.[7] Notable is the absence of alcohol adducts for all three oxathiins. This solvent is used in the oxygenation of olefins, especially electron-rich derivatives, to intercept ionic intermediates sometimes invoked as precursors of dioxetanes, which conversely do not add alcohol.[10]

Intermediates. Experiments were carried out to detect the dioxetanes **2b**,**c**,**i** at low temperatures by oxygenating at −70 °C in $CDCl_3$/$CFCl_3$ and monitoring the reaction mixtures by means of NMR spectroscopy. This proved to be successful only for **2b**,**c**, whereas no transient was detected starting from **1i**. The dioxetane **2b**, exhibiting the characteristic dioxetanyl carbons at δ 93.6 and 111.6, was stable enough to react with triphenylphosphine (PPh_3) at −70 °C, albeit partially. The reaction leads to the ketosulfide **10b** with concomitant formation of phosphine oxide (Ph_3PO), and low-temperature NMR analysis showed that this occurs via a labile intermediate to which, on the basis of a significant Me signal at a high field (δ 1.36)[11] and literature data,[12] we assigned the structure of epoxide **9b** (Scheme 2). To our knowledge, epoxides fused to the oxathiane ring such as **9** are

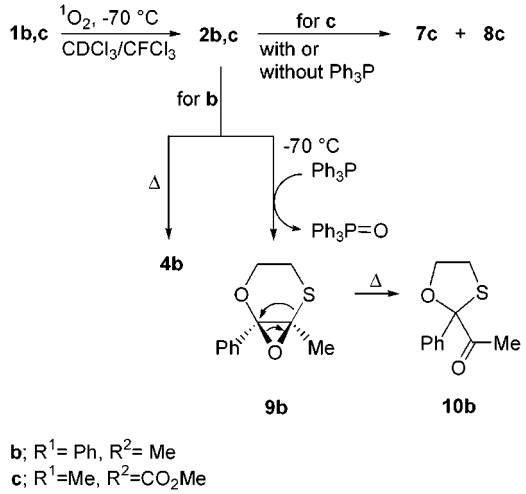
(9) Acetonitrile has β = 0.31, acetone β = 0.48, and dimethylformamide β = 0.69: Kamlet, M. J.; Abboud, J.-L. M., Abraham, M. H.; Taft, R. W. *J. Org. Chem.* **1983**, *48*, 2877.

(10) See, for example: (a) Gorman, A. A.; Gould, I. R.; Hamblett, I. *J. Am. Chem. Soc.* **1982**, *104*, 7098. (b) Asveld, E. W. H.; Kellogg, R. M. *J. Am. Chem. Soc.* **1980**, *102*, 3644. (c) Jefford, C. W.; Rimbault, C. G. *J. Am. Chem. Soc.* **1978**, *100*, 295.

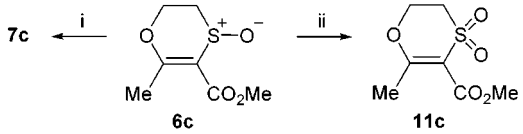
(11) Batterham, T. J. *NMR Spectra of Simple Heterocycles*; Wiley: New York, 1973; p 367.

(12) It is reported that treatment of dioxetanes with PPh_3 leads to epoxides. See, for example: (a) Adam, W.; Heil, M.; Mosandl, T.; Saha-Moller, R. C. In *Organic Peroxides*; Ando, W., Ed.; Wiley: Chichester, U.K., 1992; p 234. (b) Baumstark, A. L. In *Singlet Oxygen*; Frimer, A. A., Ed.; CRC Press: Boca Raton, FL, 1985; Vol. II, p 19. (c) Baumstark, A. L.; McCloskey, C. J.; Williams, T. E.; Chrisope, D. R. *J. Org. Chem.* **1980**, *45*, 3593.

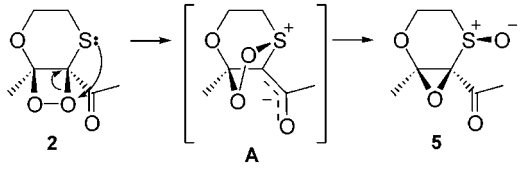
SCHEME 2



SCHEME 3



SCHEME 4

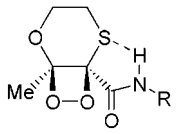


unreported, but the thermal instability of condensed epoxides is well-known and leads to carbonyl compounds.[13] The higher nucleophilicity of sulfur in comparison to that of oxygen can account for the selective formation of **10b** via 1,2-migration of the sulfide moiety.[14]

NMR analysis of the reaction mixture from **1c** highlighted the formation of a highly unstable intermediate to which we tentatively assigned the structure **2c** on the basis of ^{1}H NMR resonances and, in particular, that of Me (δ 1.76), which matched those reported for methyl groups at a bridgehead in fused dioxetanes.[15] **2c** rapidly decomposed to **7c** and **8c**, and attempts to trap it with PPh_3 failed. During the conversion, no epoxide **5c** (nor any other intermediate) was detected by varying the probe temperature from −70 to −10 °C. It was likely that the sulfoxide epoxide **5c** was so labile that it remained undetected. We therefore decided to verify the intermediacy of **5c** chemically by epoxidizing the related sulfoxide **6c**. The use of standard protocols as with peroxy acids, dimethyldioxirane,[16a] or methyltrioxorhenium/H_2O_2[16b] led quantitatively to sulfone **11c** via sulfur oxidation (Scheme 3). A more satisfying approach proved to be the treatment with NaOO-*t*-Bu, which was recently used to epoxidate vinylsulfoxides.[17] The reaction starting from **6c** afforded a mixture of products, including ketosulfoxide **7c**, which was identified and separated in a 10% yield (Scheme 3). Neither spectroscopic nor chromatographic methods detected **8c** either when the reaction was carried out at room temperature or lower, and control experiments showed that **8c** decomposes under the epoxidation conditions.

Mechanism. Scheme 1 reports a plausible interpretation of all the results. Products **1** react with $^1O_2$ leading, through a [2 + 2] cycloaddition, to unstable dioxetanes **2**, which undergo different rearrangements depending on the substituents and/or the solvent. The presence of an electron-withdrawing group prevents the usual C−C bond fragmentation, which leads to **4** in that it increases electron demand on the peroxide O−O bond. Thus, an intramolecular nucleophilic attack of sulfur at the peroxidic oxygen can occur with the formation of epoxides **5**, likely via the well-stabilized intermediates **A** (or transition states) (Scheme 4). Due to the H-bond formation between NH and S as shown in **B** (Figure 3), the sulfur attack for **2h**,**i** appears to be difficult, and consequently, it mainly occurs in basic solvents such as acetone or DMF (Table 2).

On the basis of common proposals for $^1O_2$−olefin reactions, it is also possible to suppose that dioxetanes **2** and epoxides **5** are formed through parallel rather than sequential paths and, in particular, that epoxides **5** are formed via zwitterionic intermediates such as perepoxides **C** or charge-transfer complexes such as **D** (Scheme 5).[10,18] Some comments, however, have to be made: (i) zwitterionic intermediates are formed with olefins that can stabilize a cationic center,[18a] so oxathiin **1b** would be expected to give the anomalous product pattern more easily than **1c**−**k**; (ii) no methanol-trapped products were found in the oxygenations performed in this solvent;[10] (iii) perepoxides are oxidants toward electrophilic agents such as sulfoxides[19a] or sulfenate and sulfinate esters,[19b] while the sulfide moiety in the oxathiane ring is a nucleophilic site; (iv) no product of bis sulfur oxidation was ever found in any reaction mixture, nor sulfone **11c** when in an appropriate experiment **1c** was oxygenated in the presence of sulfoxide **6c**; and (v) in the presence of a less polar intermediate (or transition state) it appears hard to



B

2h; R = H
2i; R = Ph

FIGURE 3.

(13) See, for example: (a) Adam, W.; Hadjiarapoglou, L.; Wang, X. *Tetrahedron Lett.* **1991**, *32*, 1295. (b) Baylon, C.; Hanna, I. *Tetrahedron Lett.* **1995**, *36*, 6475. (c) Katritzky, A. R.; Xie, L., Serdyuk, L. *J. Org. Chem.* **1996**, *61*, 7564.

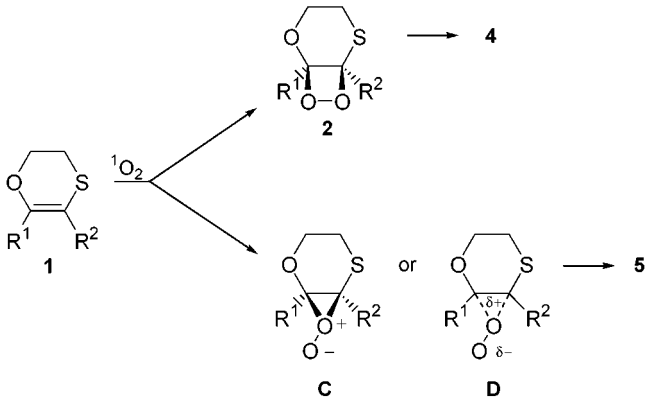
(14) March, J. *Advanced Organic Chemistry*; Wiley: New York, 1992. p 349.

(15) Adam, W.; Ahrweiler, M.; Sauter, M. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 80. Gollnick, K.; Knutzen-Mies, K. *J. Org. Chem.* **1991**, *56*, 4017. Burns, P. A.; Foote, C. S. *J. Am. Chem. Soc.* **1974**, *96*, 4339.

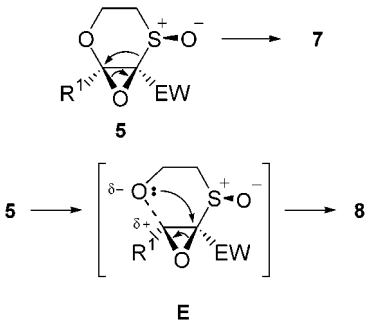
(16) (a) Singh, M.; Murray, R. W. *J. Org. Chem.* **1992**, *57*, 4263. (b) Adam, W.; Mitchell, C. M. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 533.

(17) Fernandez de la Pradilla, R.; Castro, S.; Manzano, P.; Martin-Ortega, M.; Priego, J.; Viso, A.; Rodriguez, A.; Fonseca, I. *J. Org. Chem.* **1998**, *63*, 4954.

SCHEME 5



SCHEME 6



explain the strong dependence of the reaction course on electronic factors. Moreover, as required by the alternative paths depicted in Scheme 5, the structure of epoxide **5c** should be assigned to the labile intermediate spectroscopically detected in the oxygenation of **1c** rather than that of dioxetane **2c**. Neverthless, the resonance at δ 1.76 appears too far downfield for a Me linked at a strained epoxide ring, for which values in the δ range 1.30−1.60 would be expected.[11,12c] We therefore feel that our results are best accommodated by the proposed mechanism, shown in Scheme 4, which, for **5**, involves electrophilic oxygen transfer from the peroxide moiety of dioxetanes **2** to the nucleophilic sulfide site.[20]

Whatever the origin of epoxides **5**, the formation of the ketosulfoxides **7** and **8** can be rationalized via 1,2-migration of the sulfinyl[21] and alkoxy groups,[13] respectively (Scheme 6). The stereochemical trend observed is consistent with the stereoelectronic constraints in a cyclic system involving the overlap of the migrating bond with the backside of the epoxidic C−O bond. The generally low ratio of **8** to **7** may be enhanced by the presence of a phenyl group at C-2, and it is significant that the ratio increases in the same series on going from **1f** (R^1 = H; 0:100) to **1c** (R^1 = Me; 1:2) to **1e** (R^1 = Ph; 2:1) (Table 1). This result, together with the increment, albeit slight, of **8** to increasing solvent polarity, suggests that a highly polarized transition state (or a charged species) such as **E** (Scheme 6) could be involved in its formation since the trend observed is consistent with the cation-stabilizing effect of a phenyl group at C-2 vs that of a 2-Me or 2-H.[22] Chemical experiments that support the intermediacy of the undetected epoxides **5** for ketosulfoxides **7** are not conclusive for **8**; so, it remains unclear whether **8** may derive from different routes.

The formation of sulfoxides **6** in methanol (Table 2, entries c, k, and l) can be easily rationalized on the basis of mechanistic studies of Clennan and Foote[7] via H-bonding stabilization of the initial persulfoxide **3** or formation of an alcohol adduct **12** (Scheme 7). It is more difficult to explain the presence of sulfoxides **6** in aprotic CH_2Cl_2, albeit in low yields, only in the amide series and in **1g** (Table 1). For the latter, it is likely that the ring sulfur is partly attacked by the electrophilic singlet oxygen due to the increasing electron-demand at the double bond, whereas in the series of amides, processes involving energy or electron transfer[23] and/or, for **1h**,**i**, intermolecular H-bonding stabilization can be invoked. In any case, the persulfoxide **3** would be the primary intermediate and lead to sulfoxides **6** as reported (Scheme 7).[7]

Conclusion

As reported for vinyl sulfides,[4] it is the olefinic part that is easily oxidized in singlet oxygen oxygenation of oxathiins **1**. No ene products or derived compounds were found in the reaction mixtures, whereas the oxidation of ring sulfur can also occur under certain conditions. Both pathways have been observed in vinyl sulfides, albeit to a lesser extent, so that it is likely that the strong preference of oxathiins **1** for the dioxetane mode lies in the mesomeric effect of both sulfur and oxygen, which even overcomes the presence of two electron-withdrawing groups. The theoretical calculations,[24] reported in Table 3, are consistent with this and show that the HOMO energy in all the derivatives **1** is always higher than that of tetramethylethylene, which is known to react with singlet oxygen.[1c] It is noteworthy that the HOMO electronic distribution is not remarkably different in the series considered above.

This investigation highlights new aspects of the reactivity of singlet oxygen toward electron-rich heterosubstituted alkenes through the unprecedented diastereoselective formation of ketosulfoxides **7** and **8** and confirms the role of this species as a versatile, mild, green oxidant. It was in fact shown that singlet oxygen can attack the

(18) See for example: (a) Clennan, E. L.; L'Esperance, R. P. *J. Am. Chem. Soc.* **1985**, *107*, 5178. (b) Manring, L. E.; Foote, C. S. *J. Am. Chem. Soc.* **1983**, *105*, 4710.

(19) (a) Schaap, A. P.; Recher, S. G.; Faler, G. R.; Villasenor, S. R. *J. Am. Chem. Soc.* **1983**, *105*, 1691. (b) Clennan, E. L.; Chen, M.-F.; Xu, G. *Tetrahedron Lett.* **1996**, *37*, 2911.

(20) An unusual O−O bond cleavage competing with normal fragmentation of some dioxetanes has been recently explained by way of an intramolecular nucleophilic attack of nitrogen at O−O: Matsumoto, M.; Murakami, H.; Watanabe, N. *Chem. Commun.* **1998**, 2319.

(21) Rearrangement of α,β-epoxy sulfoxides to β-carbonyl sulfoxides is reported: Braverman, S. In *The Chemistry of Sulphones and Sulphoxides*; Patai, S., Rappoport, Z., Stirling, C., Eds.; Wiley: New York, 1988; p 744.

(22) This type of rearrangement becomes competitive due to the low nucleophilicity of the sulfinyl group [e.g., if compared with that of a sulfide group (cf. rearrangement in **9b** shown in Scheme 2)]. The rearrangement should be induced by the presence of a strong electron deficiency at the migrating terminus and favoured by cation-stabilizing groups at the migrating origin and by polar solvents. See: ref 14, p 1053.

(23) Ref 4, p 101.

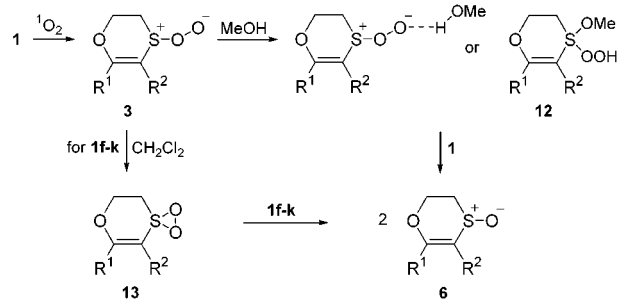
(24) Theoretical calculations using the AM1 method (Dewar, M. J. S.; Zeobish, E. G.; Healy, E. F.; Stewart, J. J. P. *J. Am. Chem. Soc.* **1985**, *107*, 3092) were performed with the Hyperchem 6.0 program.

TABLE 3. HOMO Energy[a] of Oxathiins 1b−k by AM1 Calculations

1b	1c	1d	1e	1f	1g	1h	1i	1j	1k	tetramethylethylene
−8.0	−8.2	−8.3	−8.2	−8.4	−8.7	−8.3	−8.4	−8.3	−8.2	−9.0

[a] Values in eV.

SCHEME 7



double bond of the oxathiin system or sulfur atom depending on the reaction conditions, whereas other oxidants such as peroxy acids, dimethyldioxirane, or methyltrioxorhenium/H_2O_2 only give oxidation at the sulfur site.

Experimental Section

General Methods. Melting points are uncorrected. IR spectra were recorded with chloroform as the solvent. ^{1}H and ^{13}C NMR spectra were run in $CDCl_3$ at 400 or 200 MHz and 100 or 50 MHz, respectively. Chemical shifts are reported in parts per million referenced to TMS. DEPT techniques were employed to determine the multiplicity in the ^{13}C NMR spectra. Low-resolution electron impact mass spectra were obtained operating at 70 eV on a GCMS. TLC was performed on silica gel layers. Reagent-grade commercially available reagents and solvents were used. The solvents used for the reactions were dried.

Compounds **1b**,[25] **1c** [mp 58−60 °C (lit.[26] 58−60 °C)], **1d**,[27] **1e** [mp 119−121 °C (lit.[28] 121 °C)], **1h** [mp 172−174 °C (lit.[29] 172−174 °C)], **1i** [mp 93−95 °C (lit.[30] 94−95 °C)], and the new **1k** were prepared following a literature procedure[30] by *N*-bromosuccinimide-promoted ring expansion of the related 1,3-oxathiolanes; the latter were synthesized in good yields through the standard protocol by refluxing the corresponding carbonyl compounds and 2-mercaptoethanol in the presence of PTSA.[26] Compound **1j**[31] was obtained by methylation of amide **1i** with BuLi/MeI. Compound **1f** was prepared as reported for **1g** [mp 42−44 °C (lit.[32] 42.5−43.5 °C)] by Cl_2-ring expansion of the related oxathiolane obtained almost quantitatively by adding methyl propiolate to 2-mercaptoethanol followed by treatment with NaH.[32] All the oxathiins prepared afforded spectral data consistent with their assigned structures; in particular, the proton spectra show two characteristic[31] multiplets (AA′XX′ system) due to the two methylenes in the ranges δ 2.90−3.10 (CH_2S) and 4.30−4.50 (CH_2O).

Methyl 5,6-Dihydro-1,4-oxathiine-3-carboxylate (1f): yield 8%; oil; IR ($CHCl_3$) 1735, 1640 cm^{-1}; ^{1}H NMR δ 2.96 (m, 2 H), 3.76 (s, 3 H), 4.33 (m, 2 H), 7.73 (s, 1 H); ^{13}C NMR δ 23.9 (t), 52.1 (q,), 66.2 (t), 101.2 (s), 150.5 (d), 165.5 (s); MS *m*/*z* 160 (M^+), 128 ($M^+ - 32$), 101 ($M^+ - 59$).

***N*,*N*,2-Trimethyl-5,6-dihydro-1,4-oxathiine-3-carboxamide (1k):** yield 50%; oil; IR ($CHCl_3$) 1625 cm^{-1}; ^{1}H NMR δ 1.80 (s, 3 H), 3.01 (m) and 3.10 (brs) (together 8 H), 4.34 (m, 2 H); ^{13}C NMR δ 18.9 (q), 24.6 (t), 34.8 (q), 38.3 (q), 65.6 (t), 97.1 (s), 145.5 (s), 167.8 (s); MS *m*/*z* 188 (MH^+), 159 ($M^+ - 28$), 143 ($M^+ - 44$).

General Procedure of Photooxygenation. Each 0.02 M solution of **1b−k** (0.5 mmol) in dry CH_2Cl_2 in the presence of tetraphenylporphirin (1.8×10^{-3} mmol) was irradiated at −20 °C with a halogen lamp (650 W). During irradiation, dry oxygen was bubbled through the solution. When the reaction was complete (^{1}H NMR), removal of the solvent gave a residue that was chromatographed on TLC [silica gel, EtOAc except for **1k** (1:9 light petroleum/EtOAc)].

Starting from **1b**, purification gave **2-(acetylthio)ethyl benzoate (4b)**:[33] yield 90%; oil; IR ($CHCl_3$) 1718, 1696 cm^{-1}; ^{1}H NMR δ 2.37 (s, 3 H), 3.29 (t, J = 6.5 Hz, 2 H), 4.44 (t, J = 6.5 Hz, 2 H), 7.40−8.10 (m, 5 H); ^{13}C NMR δ 28.0 (t), 30.5 (q), 63.2 (t), 128.4 (d), 129.7 (d), 129.9 (s), 133.1 (d), 166.2 (s), 194.8 (s); MS *m*/*z* 225 (MH^+), 182 ($M^+ - 42$), 105.

Starting from **1c**, separation led, with decreasing R_f values, to **8c**[5] and **7c** [mp 126−128 °C (lit.[5] 126−128 °C)] in 23 and 47% yields, respectively.

Starting from **1d**, all attempts to isolate **7d** and **8d** by TLC failed since they decompose on contact with chromatographic adsorbents; therefore, the yield and spectral data refer to the crude oxygenation mixture. **1-[(2*S**,3*R**)-2-Methyl-3-oxido-1,3-oxathiolan-2-yl]propane-1,2-dione (7d) and 1-(2-acetyl-3-oxido-1,3-oxathiolan-2-yl)ethanone (8d):** yield 85% with a purity of 90%; (* refers to the minor **7d**) ^{1}H NMR δ 1.86 (s, 3 H), 2.26* (s, 3 H), 2.36 (s) and 2.39* (s) (together 6 H), 2.75−3.35 (m, 4 H), 4.45−5.05 (m, 4 H); ^{13}C NMR δ 20.8 (q), 24.2 (q), 27.0* (q), 28.8* (q), 52.9 (t), 53.0* (t), 69.6 (t), 71.8* (t), 108.7 (s), 116.1* (s), 193.1 (s), 195.2 (s), 199.3* (s), 199.8* (s).

Starting from **1e**, TLC chromatography led, with decreasing R_f values, to **ethyl (2*R**,3*R**)-2-benzoyl-1,3-oxathiolane-2-carboxylate 3-oxide (8e)**: yield 30%; oil; IR ($CHCl_3$) 1737, 1699, 1071 cm^{-1}; ^{1}H NMR δ 1.21 (t, J = 7.0 Hz, 3 H), 3.10−3.40 (m, 2 H), 4.25 (q, J = 7.0 Hz, 2 H), 4.87 (m, 1 H), 5.00 (m, 1 H), 7.40−8.10 (m, 5 H); ^{13}C NMR δ 13.8 (q), 52.1 (t), 63.5 (t), 72.4 (t), 112.2 (s), 128.5 (d), 129.6 (d), 133.9 (d), 135.5 (s), 165.4 (s), 189.1 (s); MS *m*/*z* 283 (MH^+), 209 ($M^+ - 73$), 177 ($M^+ - 105$), 105. **Ethyl [(2*S**,3*R**)-3-oxido-2-phenyl-1,3-oxathiolan-2-yl](oxo)acetate (7e)**: yield 15% with a purity of 70%. Selected signals: ^{1}H NMR δ 1.31 (t, J = 7.0 Hz, 3 H), 2.87 (m, 1 H), 3.21 (m, 1 H), 4.33 (q, J = 7.0 Hz, 2 H), 4.65 (m, 1 H), 5.00 (m, 1 H), 7.30−7.60 (m, 5 H); ^{13}C NMR δ 13.9 (q), 51.3 (t), 62.7 (t), 70.5 (t), 113.0 (s), 160.8 (s), 187.0 (s).

Starting from **1f**, TLC chromatography yielded only **methyl 5,6-dihydro-1,4-oxathiine-3-carboxylate 4-oxide (6f)**: yield 3%; viscous oil; IR ($CHCl_3$) 1717, 1595, 1035 cm^{-1}; ^{1}H NMR δ 2.71 (ddd, J = 14.7, 12.8, 3.9 Hz, 1 H), 3.05 (m, 1 H), 3.87 (s, 3 H), 4.47−4.75 (m, 2 H), 8.04 (s, 1 H); ^{13}C NMR δ 42.4 (t), 52.5 (q), 57.0 (t), 97.1 (s), 159.4 (s), 160.1 (d); MS *m*/*z* 176 (M^+),

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160 ($M^+ - 16$), 144 ($M^+ - 32$), 116 ($M^+ - 60$). **Methyl [(2*S**,3*R**)-3-oxido-1,3-oxathiolan-2-yl](oxo)acetate (7f)** decomposed on contact with the chromatographic adsorbent, so its spectroscopic data and yield were deduced from the crude oxygenation mixture: yield 75% (purity of 80%); ^{1}H NMR δ 2.85 (m, 1 H), 3.22 (m, 1 H), 3.95 (s, 3 H), 4.64 (m, 2 H), 6.44 (s, 1 H); ^{13}C NMR δ 53.5 (t), 54.1 (q), 70.0 (t), 99.6 (d), 162.0 (s), 185.0 (s).

Starting from **1g**, TLC chromatography yielded only **dimethyl 5,6-dihydro-1,4-oxathiine-2,3-dicarboxylate 4-oxide (6g)**: yield 10%; viscous oil; IR ($CHCl_3$) 1752, 1723, 1100 cm^{-1}; ^{1}H NMR δ 2.79 (ddd, J = 14.7, 13.7, 3.4 Hz, 1 H), 3.13 (m, 1 H), 3.87 (s, 3 H), 3.91 (s, 3 H), 4.62 (m, 1 H), 4.76 (m, 1 H);^{13}C NMR δ 43.1 (t), 52.9 (q), 53.6 (q), 58.0 (t), 109.5 (s), 159.6 (s), 162.2 (s), 163.1 (s); MS *m*/*z* 234 (M^+), 218 ($M^+ - 16$), 203 ($M^+ - 31$), 175 ($M^+ - 59$). **Methyl (2*R**,3*R**)-2-[methoxy(oxo)acetyl]-1,3-oxathiolane-2-carboxylate 3-oxide (7g≡8g)** decomposed on contact with the chromatographic adsorbents, so its spectroscopic data and yield were deduced from the crude oxygenation mixture: yield 70% (purity of 75%); ^{1}H NMR δ 2.95−3.15 (m),* 3.30 (m, 1 H), 3.80 (s, 3 H), 3.95 (s, 3 H), 4.70−4.95 (m, 2 H)*;^{13}C NMR δ 52.8 (q), 53.8 (t + q), 72.8 (t), 107.7 (s), 159.8 (s), 163.9 (s), 181.4 (s); [* indicates partial overlap to signals of **6g**].

Starting from **1h**, chromatography by TLC gave, with decreasing R_f values, **2-[(2-amino-2-oxoacetyl)thio]ethyl acetate (4h)**: yield 31%; mp 95−97 °C; IR ($CHCl_3$) 3464, 3394, 1745, 1687, 1568 cm^{-1}; ^{1}H NMR δ 2.07 (s, 3 H), 3.21 (t, J = 6.5 Hz, 2 H), 4.23 (t, J = 6.5 Hz, 2 H), 6.36 (br s, 1 H), 6.86 (br s, 1 H); ^{13}C NMR δ 20.7 (q), 27.9 (t), 61.9 (t), 160.3 (s), 170.7 (s), 190.4 (s); MS *m*/*z*: 192 (MH^+), 149 ($M^+ - 42$), 147 ($M^+ - 44$), 131 ($M^+ - 60$), 120 ($M^+ - 72$). **(2*R**,3*R**)-2-Acetyl-1,3-oxathiolane-2-carboxamide 3-oxide (8h)**: yield 9%; oil; IR ($CHCl_3$) 3486, 3398, 1714, 1601, 1076 cm^{-1}; ^{1}H NMR δ 2.46 (s, 3 H), 3.07 (m, 1 H), 3.32 (m, 1 H), 5.00 (m, 2 H), 5.71 (br s, 1 H), 7.02 (br s, 1 H); ^{13}C NMR δ 29.5 (q), 52.7 (t), 69.9 (t), 111.7 (s), 164.5 (s), 201.3 (s); MS *m*/*z* 192 (MH^+), 149 ($M^+ - 43$), 148 ($M^+ - 44$). **[(2*S**,3*R**)-2-(2-Methyl-3-oxido-1,3-oxathiolan-2-yl]-2-oxoacetamide (7h)**: yield 8%; oil; IR ($CHCl_3$) 3514, 3397, 1713, 1602, 1078 cm^{-1}; ^{1}H NMR δ 1.90 (s, 3 H), 2.82 (m, 1 H), 3.20 (m, 1 H), 4.53−4.72 (m, 2 H), 5.50 (br s, 1 H), 6.70 (br s, 1 H); ^{13}C NMR δ 20.7 (q), 52.8 (t), 69.9 (t), 108.3 (s), 160.9 (s), 192.4 (s); MS *m*/*z* 192 (MH^+), 163 ($M^+ - 28$), 119 ($M^+ - 72$). **2-Methyl-5,6-dihydro-1,4-oxathiine-3-carboxamide 4-oxide (6h)**: yield 11%; oil; IR ($CHCl_3$) 3499, 3378, 1673, 1041 cm^{-1}; ^{1}H NMR δ 2.37 (s, 3 H), 2.82 (ddd, J = 14.6, 12.7, 3.9 Hz, 1 H), 3.08 (m, 1 H), 4.40−4.65 (m, 2 H), 6.20 (br s, 2 H); ^{13}C NMR δ 20.8 (q), 43.3 (t), 56.8 (t), 110.0 (s), 166.9 (s), 167.1 (s); MS *m*/*z* 176 (MH^+), 159 ($M^+ - 16$), 131 ($M^+ - 44$).

Starting from **1i**, chromatography gave, with decreasing R_f values, **2-[(2-anilino-2-oxoacetyl)thio]ethyl acetate (4i)**: yield 29%; mp 82−83 °C; IR ($CHCl_3$) 3377, 1741, 1703, 1677 cm^{-1}; ^{1}H NMR δ 2.08 (s, 3 H), 3.26 (t, J = 6.3 Hz, 2 H), 4.27 (t, J = 6.3 Hz, 2 H), 7.10−7.70 (m, 5 H), 8.56 (br s, 1 H); ^{13}C NMR δ 20.7 (q), 28.0 (t), 61.8 (t), 119.9 (d), 125.6 (d), 129.2 (d), 135.7 (s), 155.8 (s), 170.6 (s), 191.6 (s); MS *m*/*z* 267 (M^+), 149 ($M^+ - 118$), 120, 119. **[(2*S**,3*R**)-2-Methyl-3-oxido-1,3-oxathiolan-2-yl]-2-oxo-*N*-phenylacetamide (7i)**: yield 4%; oil; IR ($CHCl_3$) 3380, 1732, 1697, 1078, 1054 cm^{-1}; ^{1}H NMR δ 1.93 (s, 3 H), 2.88 (m, 1 H), 3.23 (m, 1 H), 4.60 (m, 2 H), 7.00−7.70 (m, 5 H), 8.81 (br s, 1 H); ^{13}C NMR δ 20.8 (q), 52.7 (t), 69.9 (t), 108.4 (s), 120.1 (d), 125.3 (d), 129.0 (d), 136.0 (s), 156.6 (s), 193.0 (s); MS *m*/*z* 267 (M^+), 149 ($M^+ - 118$), 120. **2-Methyl-*N*-phenyl-5,6-dihydro-1,4-oxathiine-3-carboxamide 4-oxide (6i)**:[34] yield 34%; oil; IR ($CHCl_3$) 3349, 1721, 1673, 1079, 1039 cm^{-1}; ^{1}H NMR δ 2.38 (s, 3 H), 2.90 (ddd, J = 14.6, 13.5, 3.5 Hz, 1 H), 3.10 (m, 1 H), 4.52 (m, 2 H), 7.10−7.60 (m, 5 H), 8.35 (br s, 1 H); ^{13}C NMR δ 20.7 (q), 43.5 (t), 56.9 (t), 110.7 (s), 120.5 (d), 124.7 (d), 129.0 (d), 137.8 (s),163.6 (s), 166.6 (s); MS *m*/*z* 251 (M^+), 234 ($M^+ - 17$), 159 ($M^+ - 92$), 131.

(34) NMR data reported in ref 31 are in DMSO-d_6.

Starting from **1j**, chromatography gave, with decreasing R_f values, **2-({2-[methyl(phenyl)amino]-2-oxoacetyl}thio)-ethyl acetate (4j)**: yield 5%; oil; IR ($CHCl_3$) 1745, 1670 cm^{-1}; ^{1}H NMR δ 2.00 (s, 3 H), 3.04 (t, J = 6.4 Hz, 2 H), 3.37 (s, 3 H), 4.00 (t, J = 6.4 Hz, 2 H), 7.10−7.50 (m, 5 H); ^{13}C NMR δ 20.7 (q), 27.3 (t), 38.0 (q), 62.0 (t), 126.4 (d), 128.2 (d), 129.5 (d), 141.7 (s), 170.5 (s), 189.1 (s); MS *m*/*z* 281 (M^+), 221 ($M^+ - 60$), 163 ($M^+ - 118$). **(2*R**,3*R**)-2-Acetyl-*N*-methyl-*N*-phenyl-1,3-oxathiolane-2-carboxamide 3-oxide (8j)**: yield 15%; 131−133 °C; IR ($CHCl_3$) 1716, 1646, 1058, 1025 cm^{-1}; ^{1}H NMR δ 1.41 (s, 3 H), 3.11 (m, 1 H), 3.25 (s, 3 H), 3.52 (m, 1 H), 4.58 (m, 1 H), 4.95 (m, 1 H), 7.10−7.50 (m, 5 H); ^{13}C NMR δ 27.4 (q), 38.4 (q), 53.7 (t), 72.0 (t), 112.4 (s), 128.9 (d), 129.4 (d), 130.0 (d), 140.0(s), 156.8 (s), 202.6 (s); MS *m*/*z* 282 (MH^+), 239 ($M^+ - 42$), 146 ($M^+ - 135$), 134. ***N*-Methyl-2-[(2*S**,3*R**)-2-methyl-3-oxido-1,3-oxathiolan-2-yl]-2-oxo-*N*-phenylacetamide (7j)**: yield 60%; 136−138 °C; IR ($CHCl_3$) 1718, 1656, 1070, 1026 cm^{-1}; ^{1}H NMR δ 1.28 (s, 3 H), 2.88 (m, 1 H), 3.25 (m, 1 H), 3.38 (s, 3 H), 4.50−4.90 (m, 2 H), 7.20−7.50 (m, 5 H); ^{13}C NMR δ 21.0 (q), 36.6 (q), 52.2 (t), 71.3 (t), 109.0 (s), 127.4 (d), 128.3 (d), 129.5 (d), 140.8 (s), 164.8 (s), 194.1 (s); MS *m*/*z* 282 (MH^+), 147 ($M^+ - 134$), 134, 119; sulfoxide **6j** [yield 2%] was identified by comparing ^{1}H and ^{13}C NMR data with those reported.[31]

Starting from **1k**, chromatography gave, with decreasing R_f values, **2-{[2-(dimethylamino)-2-oxoacetyl]thio}ethyl acetate (4k)**: yield 58%; oil; IR ($CHCl_3$) 1739, 1674, 1653 cm^{-1}; ^{1}H NMR δ 2.07 (s, 3 H), 3.04 (s, 3 H), 3.18 (s) and 3.21 (t, J = 6.3 Hz) (together 5 H), 4.23 (t, J = 6.3 Hz, 2 H); ^{13}C NMR δ 22.7 (q), 29.6 (t), 38.2 (q), 39.3 (q), 64.2 (t), 164.0 (s), 172.7 (s), 192.6 (s); MS *m*/*z* 220 (MH^+), 160 ($M^+ - 59$). ***N*,*N*-Dimethyl-[(2*S**,3*R**)-2-methyl-3-oxido-1,3-oxathiolan-2-yl](oxo)acetamide (7k)**: yield 5%; oil; IR ($CHCl_3$) 1723, 1651, 1063, 1014 cm^{-1}; ^{1}H NMR δ 1.75 (s, 3 H), 3.02 (s), 3.05 (s), 3.04 (m) and 3.20 (m) (together 8 H), 4.62 (m, 1 H), 4.87 (m, 1 H); ^{13}C NMR δ 22.0 (q), 34.7 (q), 36.5 (q), 52.1 (t), 70.2 (t), 109.7 (s), 164.5 (s), 200.5 (s); MS *m*/*z* 220 (MH^+), 119. ***N*,*N*,2-Trimethyl-5,6-dihydro-1,4-oxathiine-3-carboxamide 4-oxide (6k)**: yield 11%; oil; IR ($CHCl_3$) 1625, 1041, 1019 cm^{-1}; ^{1}H NMR δ 1.98 (s, 3 H), 2.76 (ddd, J = 14.9, 10.2, 6.3 Hz, 1 H), 3.00 (m) and 3.11 (br s) (together 8 H), 4.55 (m, 2 H); ^{13}C NMR δ 19.4 (q), 36.6 (br q), 38.8 (br q), 43.4 (t), 56.6 (t), 111.3 (s), 157.9 (s), 166.6 (s); MS *m*/*z* 204 (MH^+), 186 ($M^+ - 17$), 159 ($M^+ - 44$), 131 ($M^+ - 72$).

Photooxygenation of 1b,c,i under Different Conditions. Reactions were carried out as described above using 0.25 mmol of the starting oxathiin **1**. When methanol, acetone, CH_3CN, or DMF-d_7 was used as the solvent, methylene blue was the sensitizer (2×10^{-3} mmol). Table 2 reports the various conditions used as well as the product distribution, which was deduced by ^{1}H NMR of each reaction mixture after removal of the solvent except for entry p. In this case, the reaction was carried out in DMF-d_7 and the mixture analyzed directly by comparing the spectrum with those of authentic samples in this solvent.

After the oxygenation of **1b** in methanol, TLC of the residue carried out as above gave, in addition to **4b** (yield 40%), **3-methyl-2-phenyl-5,6-dihydro-1,4-oxathiine 4-oxide (6b)**: yield 37%; oil; IR ($CHCl_3$) 1617, 1040, 1029 cm^{-1}; ^{1}H NMR δ 2.15 (s, 3 H), 2.93 (ddd, J = 12.1, 9.5, 3.4 Hz, 1 H), 3.10 (m, 1 H), 4.52 (m, 2 H), 7.41 (s, 5 H); ^{13}C NMR δ 16.6 (q), 45.0 (t), 57.1 (t), 108.9 (s), 128.3 (d), 128.9 (d), 129.8 (d), 134.2 (s), 154.4 (s); MS *m*/*z* 209 (MH^+), 192 ($M^+ - 16$), 191 ($M^+ - 17$).

After the oxygenation of **1c** in methanol at −40 °C, TLC of the residue carried out as above led to the sulfoxide **6c** [mp 80−82 °C (lit.[35] 81−82 °C)] in 87% yield.

Photooxygenation of **1i** at −20 °C in acetone and separation as above led, with a decreasing order of R_f values, to **4i** (yield 10%), a mixture of **7i** and **8i**, and **6i** (yield 14%). Subsequent TLC of the mixture using 1:9 methanol/$CHCl_3$ gave, with a

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decreasing order of R_f values, **8i** (yield 12%) and **7i** (yield 35%). **(2*R**,3*R**)-2-Acetyl-*N*-phenyl-1,3-oxathiolane-2-carboxamide 3-oxide (8i)**: mp 129−130 °C; IR ($CHCl_3$) 3395, 1714, 1693, 1077, 1022 cm^{-1}; ^1H NMR δ 2.54 (s, 3 H), 3.11 (m, 1 H), 3.32 (m, 1 H), 5.05 (m, 2 H), 7.10−7.60 (m, 5 H), 8.90 (br s, 1 H); ^{13}C NMR δ 29.8 (q), 52.8 (t), 73.2 (t), 113.2 (s), 120.0 (d), 125.5 (d), 129.3 (d), 136.3 (s), 160.3 (s), 191.3 (s); MS *m*/*z* 267 (M^+), 224 ($M^+ - 43$), 174 ($M^+ - 93$), 120.

Low-Temperature Photooxygenation of 1b,c,i. A solution of **1b** (0.25 mmol) in $CDCl_3/CFCl_3$ (2/1, 5 mL) was photooxygenated as above at −70 °C. After 3 h, NMR analysis of a sample recorded at this temperature showed the presence, in addition to a small amount of **4b** (<10%), **6-methyl-1-phenyl-2,7,8-trioxa-5-thiabicyclo[4.2.0]octane (2b)**. Selected signals: ^1H NMR (400 MHz, $CDCl_3/CFCl_3$) δ 1.44 (s, 3 H), 3.16 (m, 1 H), 3.38 (m, 1 H),* 4.40 (m, 1 H),* 5.19 (dt, J = 3.4, 11.7 Hz, 1 H), 7.40−7.70 (m, 5 H); ^{13}C NMR (100 MHz, $CDCl_3/CFCl_3$) δ 23.5 (t), 25.9 (q), 57.9 (t), 93.6 (s), 111.6 (s), 126.0 (d), 128.4 (d), 129.6 (d), 133.3 (s); [* indicates partial overlap to the triplets of **4b**]. A precooled solution of triphenylphosphine (PPh_3) (0.3 mmol) in $CDCl_3$ (1 mL) was then added to the remainder of the mixture, which then was examined via NMR at −70 °C. While the signals of **2b** disappeared, those of **4b** and **9b** increased, the latter changing in turn to **10b**. After 60 min, in addition to **4b**, only **10b** was present. Selected signals for **6-methyl-1-phenyl-2,7-dioxa-5-thiabicyclo[4.1.0]-heptane (9b)**: ^1H NMR (400 MHz, $CDCl_3/CFCl_3$) δ 1.36 (s, 3 H), 3.20 (m, 2 H)*, 4.30 (m, 2 H)*; [* indicates partial overlap to signals of the other products]. It was not possible to obtain a satisfactory ^{13}C NMR spectrum due to the low concentration of **9b**. **1-(2-Phenyl-1,3-oxathiolan-2-yl)ethanone (10b)** was isolated from the remainder of the mixture by preparative TLC (EtOAc as the eluent): yield 15%; oil; IR ($CHCl_3$) 1720 cm^{-1}; ^1H NMR ($CDCl_3$) δ 2.18 (s, 3 H), 3.15 (m, 2 H), 4.18−4.42 (m, 2 H), 7.30−7.60 (m, 5 H); ^{13}C NMR δ 24.8 (q), 34.0 (t), 72.2 (t), 100.0 (s), 126.8 (d), 128.4 (d), 128.7 (d), 138.5 (s), 202.9 (s); MS *m*/*z* 165 ($M^+ - 43$), 105.

A solution of **1c** in $CDCl_3/CFCl_3$ photooxygenated at −70 °C as **1b** was examined before the completion of the reaction and showed, in addition to **1c**, **7c** and **8c**, the presence of dioxetane **2c**: ^1H NMR (400 MHz, $CDCl_3/CFCl_3$) δ 1.76 (s, 3 H), 2.92 (m, 2 H)*, 3.96 (s, 3 H), 4.51 (m, 2 H)* [* indicates partial overlap to signals of other products].[5] The mixture was treated with PPh_3 and spectroscopically analyzed as above for series **b**. No transient was observed, and the final spectrum was similar to that obtained without PPh_3 showing only **7c** and **8c** in a ca. 2:1 molar ratio.

NMR analysis of the solution of **1i** oxygenated at −70 °C and spectroscopically examined as **1b** showed no transient, and the spectrum was similar to that obtained from the reaction at −20 °C.

Oxidation of Sulfoxide 6c: (a) Using NaOO-*t*-Bu.[17] A suspension of oil-free NaH (washed with hexane and dried) (50 mg, 2 mmol) in dry THF (20 mL) under an atmosphere of argon was cooled to 0 °C, and 0.4 mL (2 mmol) of *t*-BuOOH (solution 5.0 M in decane) was added. The resulting mixture was kept under stirring at 25 °C for 30 min and then cooled to 0 °C, and a solution of sulfoxide **6c**, previously dried over 4 Å sieves (95 mg, 0.5 mmol), in dry THF (10 mL), was added dropwise. The reaction mixture was stirred at 0 °C until sulfoxide **6c** disappearance, as monitored by TLC. The reaction was then quenched with a saturated solution of $Na_2S_2O_4$ (4 mL) and diluted with EtOAc (8 mL), and the layers were separated. The aqueous layer was extracted with EtOAc (3 × 4 mL), and the combined organic extracts were washed with brine and dried over anhydrous $MgSO_4$. After filtration, the solvent was removed under reduced pressure and the crude mixture was chromatographed on TLC, using EtOAc as the eluent, to give **7c** (10.3 mg, yield 10%) and unidentified products.

A mixture of **7c** and **8c** was treated and worked as **6c**. The NMR spectrum showed a mixture of products, among which only **7c** was identified and recovered by TLC.

(b) Using Dimethyldioxirane. A solution (5×10^{-2} M) of dimethyldioxirane in acetone (2 mL), prepared as reported,[16a] was added under stirring at room temperature to a solution of the sulfoxide **6c** (95 mg, 0.5 mmol) in dry acetone (2 mL). After 2 h, the solvent was removed and TLC (EtOAc as the eluent) gave pure **methyl 3-methyl-5,6-dihydro-1,4-oxathiine-3-carboxylate 4,4-dioxide (11c)**: 90 mg, yield 88%; mp 102−104 °C; IR ($CHCl_3$) 1723, 1323, 1302, 1133, 1091 cm^{-1}; ^1H NMR δ 2.39 (s, 3 H), 3.39 (m, 2 H), 3.88 (s, 3 H), 4.79 (m, 2 H); ^{13}C NMR δ 21.2 (q), 49.7 (t), 52.5 (q), 65.8 (t), 112.4 (s), 161.9 (s), 172.4 (s); MS *m*/*z* 206 (M^+).

(c) Using Methyltrioxorhenium/H_2O_2.[16b] A solution of methyltrioxorhenium (7 mg, 25 μmol) in $CHCl_3$ (5 mL) was mixed with the urea hydrogen peroxide adduct (470 mg, 5 mmol) and stirred under argon for 10 min. The sulfoxide **6c** (95 mg, 0.5 mmol) was added, and the suspension was stirred for 18 h at room temperature. After adding water (3 mL), extraction with CH_2Cl_2 and the usual workup gave sulfone **11c** (82 mg, yield 80%).

Photooxygenation of 1c in the Presence of Sulfoxide 6c. A solution of **1c** (0.25 mmol) and **6c** (0.25 mmol) in CH_2Cl_2 (5 mL) was photooxygenated at −20 °C as above. After 90 min, NMR analysis showed only the presence of **7c**, **8c**, and **6c** in a ca. 1:2:3 molar ratio. No trace of sulfone **11c** was detected either spectroscopically or by TLC.

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Supporting Information Available: ^1H NMR spectra of oxathiins **1b**−**e**,**g**,**h**. This material is available free of charge via the Internet at http://pubs.acs.org.

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