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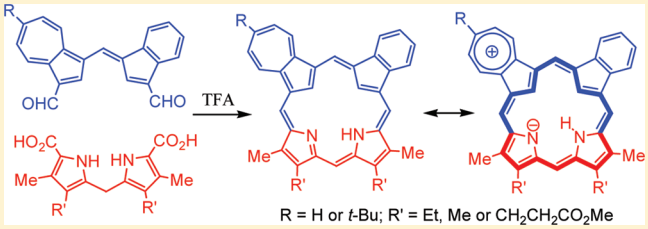
Preparation of Azulene-Derived Fulvenedialdehydes and Their Application to the Synthesis of Stable *adj*-Dicarbaporphyrinoids†

Timothy D. Lash,* Aaron D. Lammer, Aparna S. Idate, Denise A. Colby, and Kristen White

Department of Chemistry, Illinois State University, Normal, Illinois 61790-4160, United States

Supporting Information

ABSTRACT: A "2 + 2" strategy for synthesizing *adj*-dicarbaporphyrinoid systems has been developed. In a model study, an azulenylmethylpyrrole dialdehyde was condensed with a dipyrrylmethane in the presence of HCl, followed by oxidation with ferric chloride, to give a modest yield of an azuliporphyrin. Fulvene aldehydes were prepared by reacting an indene-derived enamine with azulene aldehydes in the presence of Bu_2BOTf, and azulene dialdehydes similarly reacted to give fulvene dialdehydes. The dialdehydes were condensed with dipyrrylmethanes in TFA/dichloromethane to afford good to excellent yields of dicarbaporphyrinoids with adjacent indene and azulene subunits. These 22-carbaazuliporphyrins exhibited significant diatropic character, and this property was magnified upon protonation. These characteristics are attributed to tropylium-containing resonance contributors that possess 18π electron delocalization pathways. Protonation studies demonstrated that *C*-protonation readily occurred at the interior indene carbon, but deuterium exchange also occurred at the internal azulene CH as well as at the *meso*-positions with TFA-*d*. Reaction of a carbaazuliporphyrin with silver(I) acetate in methanol or ethanol solutions also gave unusual nonaromatic dialkoxy derivatives.



INTRODUCTION

Carbaporphyrinoid systems, porphyrin analogues where one or more of the internal nitrogens are replaced by carbons, continue to attract a considerable amount of attention.[1−3] This is due in part to the unique properties exhibited by these macrocycles, which provide organized binding cavities that can afford unusual organometallic derivatives. Most of the research in this area has focused on monocarbaporphyrinoids, where only one carbon is present within the macrocyclic cavity. This work includes investigations on the so-called N-confused porphyrins **1**,[4] benzocarbaporphyrins **2**,[5] azuliporphyrins **3**,[6,7] tropiporphyrins,[8] carbachlorins,[9] benziporphyrins,[10−12] oxybenziporphyrins,[11,12] naphthiporphyrins,[13] O- and S-confused heteroporphyrins,[14] neo-confused porphyrins,[15] pyrazoloporphyrins,[16] and N-confused pyriporphyrins.[17] Most of these macrocyclic platforms have been shown to form stable organometallic complexes,[18,19] and unusual oxidation reactions have also been reported.[20,21] For instance, benzocarbaporphyrins **2** react with silver(I) acetate to give silver(III) derivatives **4** (Scheme 1),[18] and gold(III) complexes have also been reported.[18b] However, reaction of porphyrinoids **2** with ferric chloride and alcohols gave rise to regioselective oxidations that afforded unusual carbaporphyrin ketals **5** which exhibit strong absorptions in the far red (Scheme 1).[20] These polar oxidation products are promising photosensitizing agents and have been shown to be active agents in the treatment of leishmaniasis.[22] Azuliporphyrins **3** behave somewhat differently, acting as dianionic ligands and favoring the formation of nickel(II), palladium(II), and platinum(II) derivatives **6**.[19] Tetraarylazuliporphyrins **7** also undergo an oxidative metalation reaction with copper(II) salts to give nonaromatic coordination complexes **8** (Scheme 1).[21] Furthermore, azuliporphyrins undergo oxidative ring contractions with peroxides under alkaline conditions (e.g., with KOH-*t*-BuOOH) to afford benzocarbaporphyrins (Scheme 1).[23]

Investigations into dicarbaporphyrinoid systems have developed comparatively slowly. The first example of a dicarbaporphyrin **9** was obtained by reacting indane dialdehyde **10** with 3,4-diethylpyrrole in the presence of HBr, followed by oxidation with ferric chloride (Scheme 2).[24] This system is highly diatropic, and the proton NMR spectrum for **9** in $CDCl_3$ gave rise to upfield singlets for the internal CHs and NHs at −5.68 and −4.82 ppm, respectively, while the external *meso*-protons afforded a 4H singlet at 9.79 ppm.[24] Addition of TFA to solutions of **9** gave the related *C*-protonated cation $\mathbf{9H^+}$ and this retained diatropic character, showing the internal methylene unit as a 2H singlet at −4.34 ppm, while the remaining indene CH and the NHs gave resonances at −3.30 and −0.95 ppm, respectively.[24] Unfortunately, dicarbaporphyrin **9** proved to be somewhat unstable, and this has limited further investigations. Further examples of *opp*-dicarbaporphyrinoids have been reported, including the 23-carbaazuliporphyrin **11**[25] and the resorcinol-derived species **12**[26] (Scheme 3). Carbaazuliporphyrin **11**, which was also rather unstable, was prepared by treating azulitripyrrane **13** with TFA, followed by a

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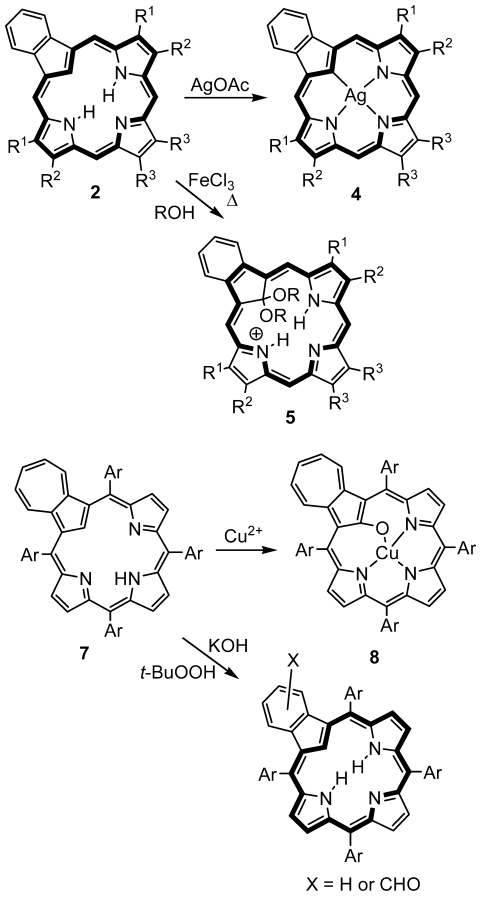
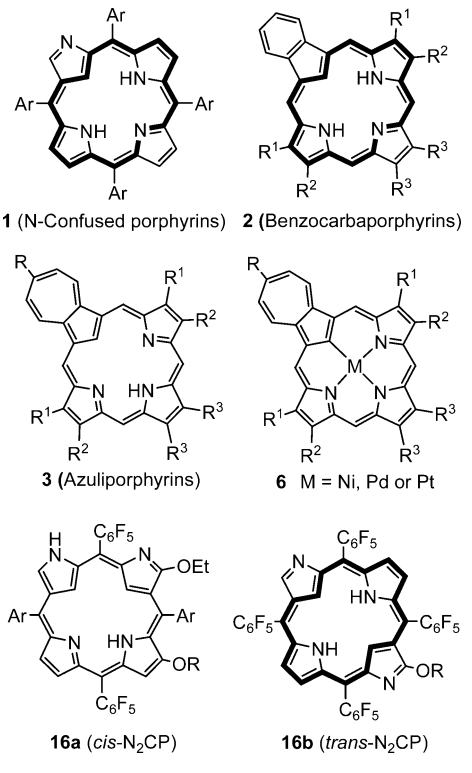
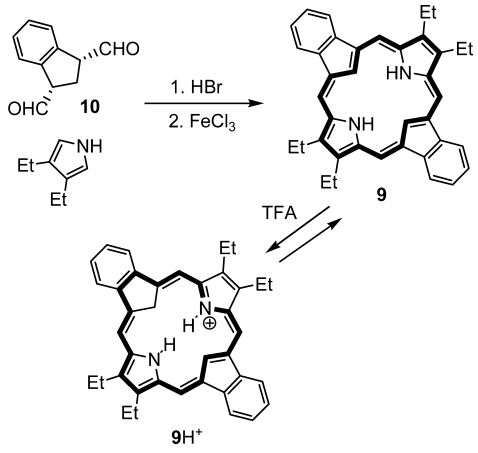
Scheme 1



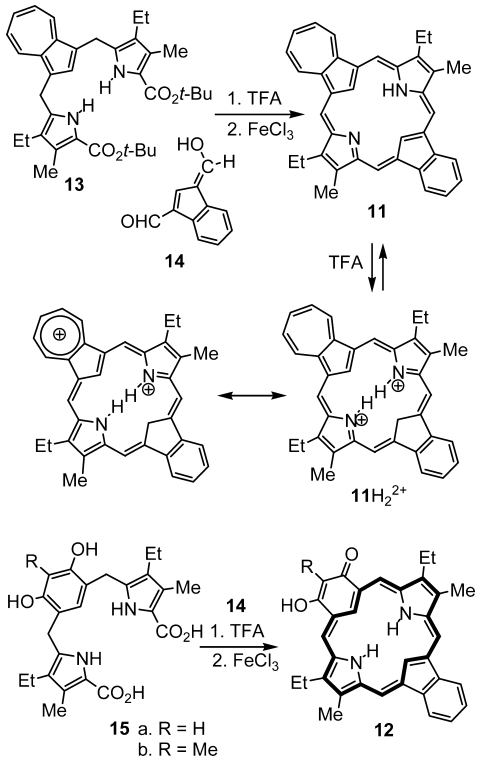


"3 + 1" condensation with indene dialdehyde **14** (Scheme 3).[25] The proton NMR spectrum of **11** showed a degree of diatropicity and the internal indene, azulene and NH protons

Scheme 2



Scheme 3



appeared as 1H singlets at 0.52, 1.25, and 1.99 ppm.[25] These results suggest that this system has comparable diatropic character to azuliporphyrins **3**. Addition of TFA to solutions of **11** afforded the related dication $\mathbf{11}H_2^{2+}$ where *C*-protonation had again occurred on the indene unit.[25] 24-Carbaoxybenziporphyrins **12**, which were also prepared by a "3 + 1" approach from tripyrrane analogues **15** and dialdehyde **14** (Scheme 3), were poorly soluble in most organic solvents, but in DMSO-d_6 this system exhibited a pronounced diamagnetic ring current and the proton NMR spectra showed the internal CH protons near −5 ppm.[26] Examples of *cis*-N-confused porphyrins **16a**[27] and *trans*-N-confused porphyrins **16b**[28] have also been reported, although only the latter shows a significant degree of diatropicity.[29]

Until recently, very little work had been carried out on the synthesis of dicarbaporphyrinoid systems where the subunits possessing the internal CHs are adjacent to one another (i.e.,

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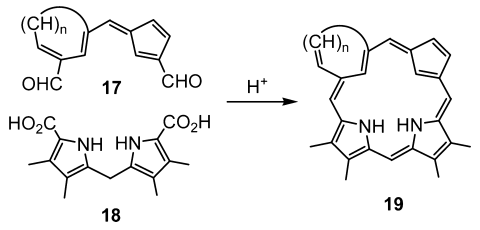
adj-dicarbaporphyrinoids) rather than opposite. We speculated that structures of this type might be accessible using fulvene dialdehydes **17** as the key intermediates (Scheme 4). Acid-

Scheme 4

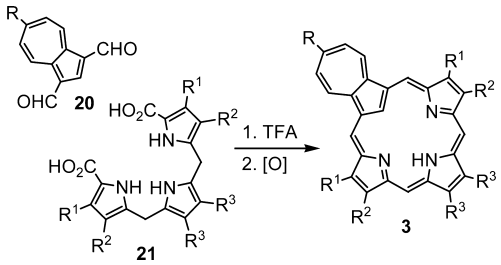


catalyzed MacDonald-type "2 + 2" condensation[30] of **17** with dipyrrylmethanes **18** would be expected to afford novel dicarbaporphyrinoids **19** (Scheme 4). However, fulvenes dialdehydes of this type had not been reported previously, and a synthetic strategy for the preparation of these crucial intermediates had to be developed. In this paper, the synthesis of azulene-derived fulvene mono- and dialdehydes are described, and syntheses of 22-carbaazuliporphyrins are reported.[31,32] Although this new class of *adj*-dicarbaporphyrinoids failed to generate organometallic derivatives, unusual oxidation reactions were observed.

RESULTS AND DISCUSSION

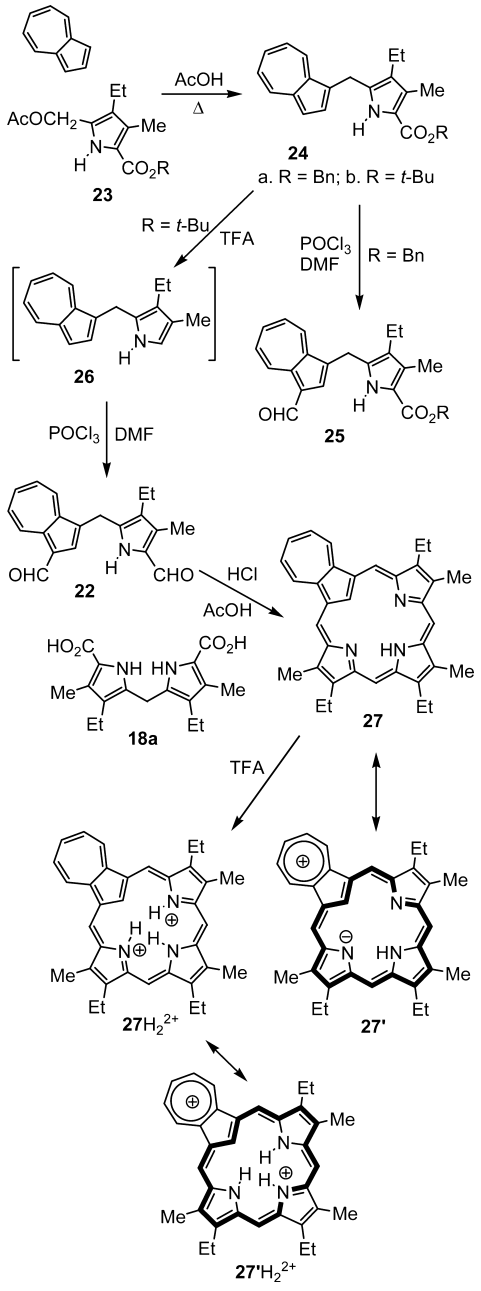
In most cases, carbaporphyrinoid systems have been prepared by a "3 + 1" variant on the MacDonald condensation,[33] and little use of the "2 + 2" methodology has been made.[34,35] For instance, azuliporphyrins **3** are readily prepared by reacting azulene dialdehydes **20** with tripyrranes **21** in the presence of TFA, followed by oxidation with DDQ or ferric chloride (Scheme 5).[6] As the use of the "2 + 2" strategy was crucial to

Scheme 5



the development of synthetic routes to *adj*-dicarbaporphyrinoid systems, we elected to carry out a model study to assess the viability of preparing azuliporphyrins by this approach. This required the preparation of an azulenylmethylpyrrole dialdehyde **22** that could be used in a MacDonald-type condensation (Scheme 6). The reaction of azulene with acetoxymethylpyrrole **23a** in the presence of acetic acid was somewhat solvent dependent. In refluxing acetic acid–ethyl acetate, the monosubstituted azulenes **24a** was isolated in 18% yield. In 2-pentanol, the yield was raised to 24%, but the best results were obtained in refluxing 2-propanol containing 10% acetic acid and **24a** could be isolated in 50% yield together with a related tripyrrane analogue (dibenzyl ester related to structure **13**). However, attempts to deprotect benzyl ester **24a** with hydrogen over 10% palladium–charcoal led instead to hydrogenation of the azulene unit. Reaction of **24a** with

Scheme 6



$POCl_3$–DMF, followed by hydrolysis with aqueous sodium acetate solution, afforded the monoaldehyde **25** in 66% yield, but the azulene moiety for this structure was also prone to reduction with hydrogen and 10% Pd/C. In order to overcome these problems, the related *tert*-butyl ester **24b** was prepared in 56% yield by reacting azulene with acetoxymethylpyrrole **23b** in refluxing acetic acid-2-propanol. Treatment of **24b** with TFA smoothly cleaved the *tert*-butyl ester to afford **25** and subsequent Vilsmeier formylation with $POCl_3$-DMF afforded the required dialdehyde **22** in 61% yield. The "2 + 2" condensation of **22** with dipyrrylmethane **18a**[36] was investigated using a variety of acid catalysts, including TFA, *p*-toluenesulfonic acid, HCl, and HI (Scheme 6). An oxidation step is also necessary to afford the fully conjugated azuliporphyrin system. The best results were obtained when **18a** was first treated with TFA and then diluted with acetic

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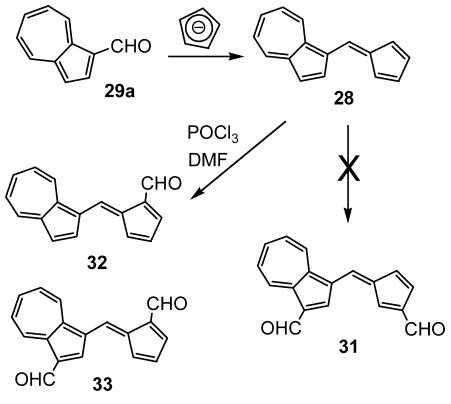
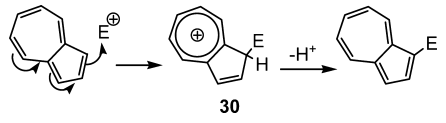
acid. The dialdehyde was then added, followed by a few drops of concd HCl, and the mixture was stirred under nitrogen for 16 h. The product was extracted with chloroform and oxidized by shaking the solution with a 0.1% aqueous solution of ferric chloride. Inferior results were obtained using DDQ as the oxidant. Under optimized conditions, following purification by column chromatography and recrystallization from chloroform-hexanes, azuliporphyrin **27** was isolated in 13% yield. This result demonstrates that the "2 + 2" route is a viable method for preparing carbaporphyrinoid systems but in the case of azuliporphyrins the "3 + 1" approach is a far superior methodology.[6] However, unlike structures prepared by the "3 + 1" approach, azuliporphyrin **27** is asymmetrically substituted, and this product had improved solubility in organic solvents. The UV−vis spectrum for **27** is typical of azuliporphyrins, showing four moderately intense bands at 355, 397, 445, and 472 nm and a broad absorption at higher wavelengths. The improved solubility of **27** allowed relatively high quality proton NMR spectra to be obtained, although the internal CH and NH resonances could not be identified. The *meso*-protons gave rise to four 1H singlets at 8.04, 8.05, 8.90, and 8.92 ppm, indicating that the macrocycle has significant diatropic character. This is commonly attributed to dipolar resonance contributors such as **27′** (Scheme 6) that possess 18π electron delocalization pathways. Addition of TFA leads to the formation of a related dication $\mathbf{27}H_2^{2+}$ that shows a greatly enhanced diatropic ring current. In the proton NMR spectrum, the *meso*-protons are now observed at 9.47, 9.48. 10.33, and 10.35 ppm while the internal CH and NH resonances can be observed at −2.85, −1.87, −0.16, and −0.15 ppm, respectively. These results are similar to those previously reported for more symmetrically substituted azuliporphyrins, albeit with an increased number of proton resonances. The improved diatropicity of $\mathbf{27}H_2^{2+}$ is attributed to the increased favorability of canonical forms such as $\mathbf{27'}H_2^{2+}$ that provide beneficial charge delocalization, whereas **27′** is less favorable due to the requirement for charge separation.

In order to apply the "2 + 2" methodology to the synthesis of *adj*-dicarbaporphyrinoids, suitably substituted fulvene dialdehydes were required. The preparation of a fulvene derivative of azulene **28** was reported over 50 years ago by reacting 1-azulenecarbaldehyde (**29**) with cyclopentadiene under basic conditions (Scheme 7).[37] Azulene favors electrophilic substitution at the 1- and 3-positions due to the formation of an intermediary tropylium cation **30** (Scheme 8), and we speculated that the azulene unit in fulvene **28** might be able to direct substitution onto the cyclopentadiene moiety and thereby facilitate the formation of the desired fulvene dialdehyde **31**. Resonance contributors such as **28′** and **28″** suggest that electrophilic substitution at the required positions may be favorable (Scheme 9), and with this in mind, the Vilsmeier formylation of **28** was attempted. Unfortunately, fulvene **28** is not very stable, and poor yields of the substitution products were isolated. However, a fraction corresponding to the monoaldehyde **32** was isolated together with a small amount of a dialdehyde tentatively identified as **33** (Scheme 7). These results provide proof of principle that the azulene moiety can direct substitution onto the cyclopentadiene ring. However, substitution onto the cyclopentadiene ring does not take place at the required position, and the instability of these products prevented further investigations. There are four open positions on the cyclopentadiene unit, and this factor facilitates the undesired regioselectivity for the formylation reaction. Clearly, if some of these sites are blocked it may be possible to introduce the formyl group at the desired position. Indene was reacted with azulene aldehyde **29a** and potassium hydroxide in refluxing methanol to give fulvene **34a** in 78% yield (Scheme 10). In this system, only two sites are open on the

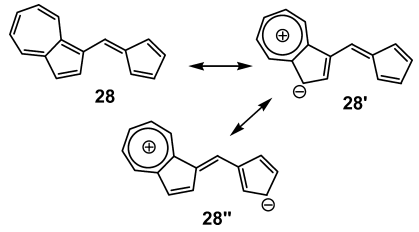
Scheme 7



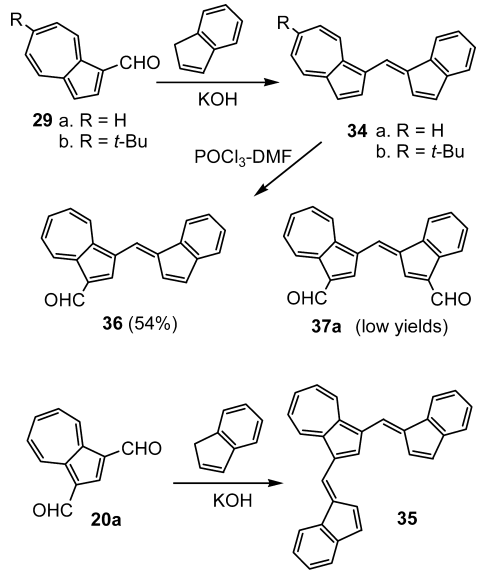
Scheme 8



Scheme 9



Scheme 10



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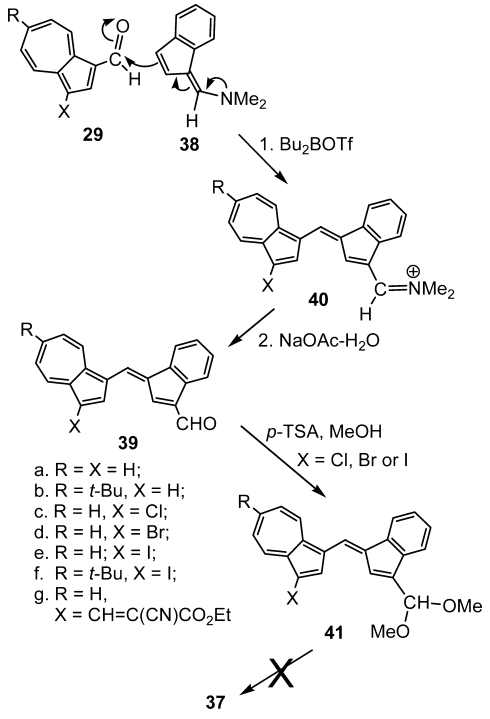
cyclopentadiene unit, and this limits the possible outcomes for electrophilic substitution reactions. In addition, unlike fulvene **28**, **34a** is a very stable compound and crystallizes as lustrous green crystals. A related fulvene **34b** was also easily prepared from 6-*tert*-butylazulene-1-carbaldehyde (**29b**) and indene, and this derivative was equally robust and easy to handle. In addition, azulene dialdehyde **20a** reacted with indene and KOH in refluxing ethanol to give difulvene **35** in 81% yield, and this also proved to be a stable compound. Therefore indene-derived fulvenes exhibit considerably improved characteristics for synthetic investigations. Fulvene **34a** was reacted with $POCl_3$–DMF and gave monoaldehyde **36** as the major product, although a low yield of the desired dialdehyde **37a** was observed (Scheme 10). In small-scale reactions, yields of **37a** as high as 27% were noted, but these results were poorly reproducible and this approach did not provide a practical route to this intermediate.

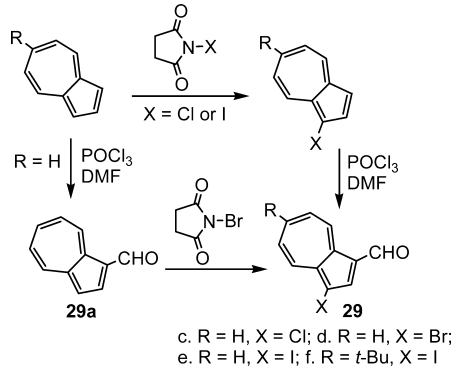
The formylation of fulvene **34** occurred preferentially on the azulene moiety and further substitution at the other terminus for this system was not favored. With this in mind, an alternative synthesis of fulvenes was developed that directly introduces the formyl group on the indene subunit. Enamine **38** is easily prepared by reacting indene with DMF dimethyl acetal in refluxing toluene (Scheme 11).[38] In principle, this

Scheme 11



enamine can be used to direct attack onto an aromatic aldehyde while simultaneously introducing a formyl moiety at the desired position on the indene. The reaction of **38** with **29a** was attempted with a number of Lewis acid catalysts including $AlCl_3$, $SnCl_4$, $TiCl_4$, $(C_5H_5)_2TiCl_2$, $(C_5H_5)_2ZrCl_2$, and Yb$(OTf)_3$, but only $TiCl_4$ gave even low yields of the expected fulvene **39a**. However, di-*n*-butylboron triflate was subsequently found to be a superior catalyst for this reaction. Reaction of azulene aldehyde **29a** with indene enamine **38** in the presence of 1 equiv of Bu_2BOTf, followed by hydrolysis of the intermediary imine salt **40** with an aqueous sodium acetate solution, gave fulvene monoaldehyde **39a** in 75% yield. The related *tert*-butyl-substituted fulvene was similarly obtained by reacting **38** with **29b** in the presence of Bu_2BOTf. It had been our expectation that the second aldehyde group could be installed onto the azulene subunit by carrying out a Vilsmeier formylation reaction, as this had been the preferential site for electrophilic substitution in fulvene **34**, but all attempts to carry out this transformation failed to give fulvene dialdehyde **37a**. Therefore, an alternative method for introducing the second aldehyde unit was needed. Halogenated azulene aldehydes **29c–f** were prepared in two steps from the corresponding azulenes (Scheme 12). Reaction of azulene with one equiv of

Scheme 12



N-chlorosuccinimide in dichloromethane gave 1-chloroazulene and the crude product was directly formylated with $POCl_3$–DMF to give 3-chloroazulene-1-carbaldehyde (**29c**) in 69% yield. Similarly, azulene reacted with *N*-iodosuccinimide to give 1-iodoazulene and this was directly formylated with $POCl_3$–DMF to afford aldehyde **29e** in 83% yield. The related *tert*-butyl iodoaldehyde **29f** was prepared similarly from 6-*tert*-butylazulene. The best results for bromoazulene aldehyde **29d** were obtained by reversing the order of the two steps. Reaction of azulene with $POCl_3$–DMF produces 1-azulenecarbaldehyde and subsequent treatment with *N*-bromosuccinimde in dichloromethane gave **29d** in 48% yield. The halogenated azulenes were reacted with **38** and Bu_2BOTf in dichloromethane, followed by hydrolysis with an aqueous sodium acetate solution. Chloro- and bromoazulene aldehydes **29c** and **29d** afforded the corresponding fulvenes **39c** and **39d** in 59% and 41% yields, respectively. However, reaction of iodoazulenes **29e** and **29f** under these conditions afforded a mixture of the desired iodofulvenes together with the dehalogenated species **39a** or **39b**. The results varied somewhat from one experiment to another but significant loss of iodine was noted in most of these experiments. Fortunately, it was possible to carry out a selective iodination reaction following fulvene formation. Hence, fulvenes **39a** and **39b** reacted with *N*-iodosuccinimide to give good yields of the iodo derivatives **39e** and **39f**. The availability of halogenated fulvenes allowed us to consider the introduction of the second formyl moiety by metal–halogen exchange, followed by reaction with DMF. Unfortunately, this approach also failed to give the desired dialdehydes. Aldehydes **39c–f** were protected as the corresponding dimethyl acetals **41** with methanol and a catalytic quantity of *p*-toluenesulfonic acid, and metal–halogen exchange was then attempted with *n*-butyllithium or *tert*-butyllithium in anhydrous ether or THF. No reaction was observed under any of the conditions that were investigated. Magnesium ate complexes have been used to

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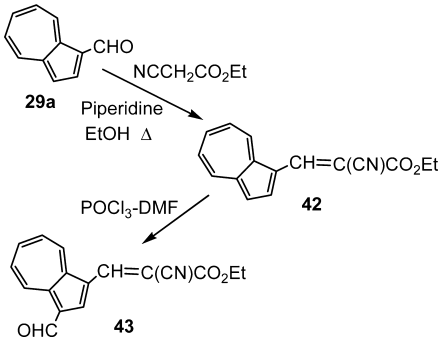
carry out metal−halogen exchange reactions,[39] and have been reported to give good results for metal−halogen exchange using iodoazulenes,[40] but treatment of **41c** or **41d** with *n*-Bu_3MgLi also gave poor results. Cyanovinyl substituents have been widely used as protective groups for pyrrole aldehydes[41] and the utility of this protective unit for fulvene derivatives was also briefly considered. Knoevenagel reaction of 1-azulenecarbaldehyde with ethyl cyanoacetate and piperidine in refluxing ethanol afforded the corresponding cyanovinylazulene **42** in 97% yield (Scheme 13). Subsequent Vilsmeier formylation with

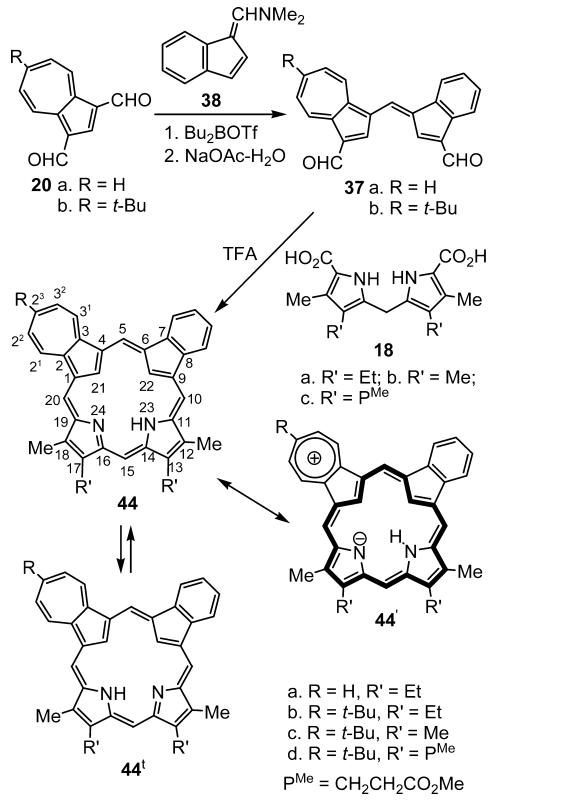
Scheme 13



$POCl_3$-DMF gave the related aldehyde **43** in 88% yield. Reaction of **43** with enamine **38** and Bu_2BOTf, followed by hydrolysis with aqueous sodium acetate solution, then gave fulvene aldehyde **39g** in 81% yield (Scheme 11). Unfortunately, deprotection of the cyanovinyl group requires strongly basic reaction conditions, typically refluxing sodium hydroxide solutions, and a procedure could not be found that could remove the protective unit without causing complete decomposition of the starting material.

Following from these investigations, attempts were made to prepare fulvene dialdehydes **37** directly from azulene dialdehydes **20** (Scheme 14). Hence, 1,3-azulenedicarbaldehyde (**20a**) was reacted with 1 equiv of indene enamine **38** and Bu_2BOTf to give the required dialdehyde **37a**. It was necessary to purify **37a** using column chromatography on silica gel, but this compound showed poor stability under these conditions, and the best results were obtained when the purification was carried out as rapidly as possible. Nevertheless, **37a** could be isolated in up to 53% yield. 6-*tert*-Butylazulene dialdehyde **20b** was also reacted with **38** and Bu_2BOTf to give the related fulvene dialdehyde **37b**. This product was more robust, did not appear to degrade during column chromatography, and was isolated in 34% yield. Dialdehyde **37a** was reacted with dipyrrylmethane dicarboxylic acid **18a** in TFA−dichloromethane, and following extraction, column chromatography on grade 3 alumina, and recrystallization from chloroform−hexanes, dicarbaporphyrinoid **44a** was isolated in 19% yield. Much better results were obtained with *tert*-butyl-substituted fulvene dialdehyde **37b**. This reacted with **18a** under the same conditions to give *tert*-butylcarbaazuliporphyrin **44b** in 80% yield. Dialdehyde **37b** similarly condensed with dipyrrylmethane **18b** to give **44c** in 46% yield, while reaction of dipyrrylmethane **18c** with **37b** afforded **44d** in 38% yield. No oxidation step is required in these reactions. The reaction of dialdehyde **22** with **18a** (Scheme 6) initially results in the formation of a dihydroporphyrinoid, and this necessitates an oxidation with ferric chloride. However, as fulvenes **37** are

Scheme 14



already fully conjugated, condensation with dipyrrylmethanes **18** generates dicarbaporphyrinoids **44** directly.

adj-Dicarbaporphyrinoids proved to be very stable in contrast to *opp*-dicarbaporphyrinoids such as the isomeric system **11**. In addition, the UV−vis spectra for **44a−d** closely resembled the spectra for azuliporphyrins **3** and **27**. For instance, the UV−vis spectrum for **44b** gave rise to four peaks at 368, 399, 470, and 494 nm, and broad absorptions were also noted between 500 and 800 nm (Figure 1). These

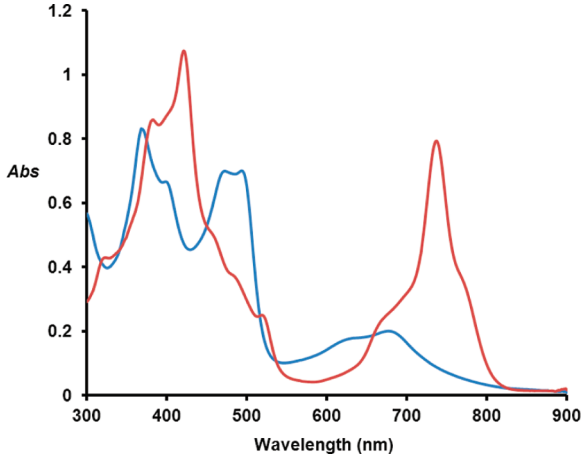


Figure 1. UV−vis spectra of 22-carbaazuliporphyrin **44b** in 1% Et_3N−chloroform (free base, blue line) and 5% TFA-chloroform (dication **44b**H_2^{2+}, red line).

carbaazuliporphyrins also exhibit diatropic character that is comparable to azuliporphyrins **3** and **27**. Porphyrinoid **44a** is poorly soluble in organic solvents but a proton NMR spectrum

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could be obtained in $CDCl_3$. This showed the internal azulene and indene protons as broad comparatively upfield resonances at 3.44 and 1.6 ppm, respectively, while the external *meso*-protons gave rise to downfield singlets at 7.52 (15-H), 7.99 (10-H), 8.56 (20-H), and 9.15 ppm (5-H). In some spectra, the NH resonance could be observed as a very broad peak at 4.3 ppm. The diatropic characteristics of this system are attributed to dipolar resonance contributors such as **44′** (Scheme 14) that possess 18π electron delocalization pathways. *tert*-Butyl-substituted carbaazuliporphyrin **44b** showed slightly enhanced diatropicity, showing the internal CH resonances at 3.03 and 1.15 ppm (Figure 2). The *meso*-protons are also shifted further

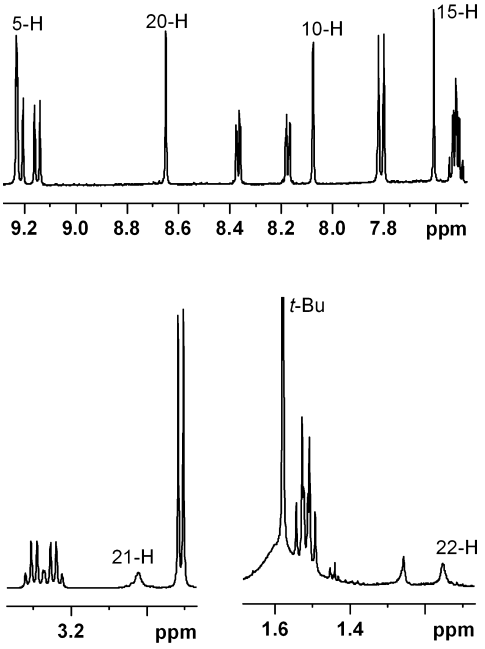
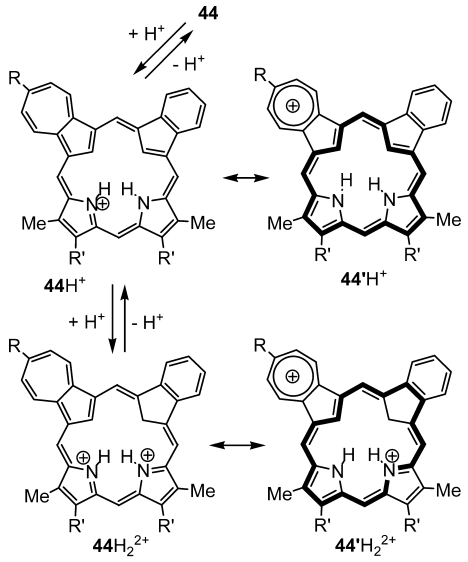


Figure 2. 500 MHz proton NMR spectrum of 22-carbaazuliporphyrin **44b**H_2 in $CDCl_3$.

downfield giving rise to four 1H singlets at 7.61, 8.08, 8.65, and 9.23 ppm. These data are consistent with the electron-donating *tert*-butyl group stabilizing dipolar canonical forms such as **44b′**, and similar trends have been observed for azuliporphyrins **3**. In pyridine-d_5, the *meso*-protons for **44a** shifted downfield to between 9.0 and 10.5 ppm, indicating that this relatively polar solvent further stabilizes resonance contributors like **44a′**. It is worth noting that two tautomeric forms are possible, **44** and **44^t** (Scheme 14), but the spectroscopic data could not distinguish between these two possibilities. It may be that both forms are actually present in solution and that they rapidly interconvert on the NMR time scale. The carbon-13 NMR spectra for **44** were also consistent with the proposed asymmetrical porphyrinoid structures. Although carbaazuliporphyrin **44a** was insufficiently soluble in $CDCl_3$ to produce a carbon-13 NMR spectrum, **44b−d** gave reasonable quality carbon-13 NMR spectra. Dicarbaporphyrinoid **44b** gave a resonance for the internal indene carbon (C-22) at 122.4 ppm, while the interior azulene carbon (C-21) showed up at 129.9 ppm. These assignments were made using the HSQC spectrum. The *meso*-carbons were observed at 90.1 (C-15), 97.3 (C-10), 106.7 (C-20) and 111.5 ppm (C-5). Dicarbaporphyrinoids **44c** and **44d** gave similar results to **44b** and will not be discussed further.

Addition of trace amounts of TFA to the NMR solutions of **44a−d** generated the corresponding cations **44**H^+, and these showed greatly increased diatropic character (Scheme 15). For

Scheme 15



instance, **44b**H^+ showed the resonances for the internal azulene and indene protons further upfield at −1.13 and −0.36 ppm, while the *meso*-protons shifted downfield to give four 1H singlets at 8.26, 8.66, 9.06, and 9.28 ppm. Further addition of TFA led to *C*-protonation and generated the corresponding dications **44**H_2^{2+}. For **44a**H_2^{2+}, the internal azulene proton was observed at −0.08 while the indene derived methylene unit appeared at −2.76 ppm, confirming that this species also retains substantial diatropicity. The *meso*-protons were also observed further downfield at 9.51 (15-H), 10.00 (10-H), 10.32 (20-H), and 10.37 ppm (5-H). The aromatic characteristics of the mono- and dicationic species **44**H^+ and **44**H_2^{2+} were attributed to tropylium-containing species such as **44′**H^+ and **44′**H_2^{2+} that facilitate charge delocalization as well as possessing 18π electron delocalization pathways.[42] The proton NMR spectrum for *tert*-butyl dicarbaporphyrinoid dication **44b**H_2^{2+} showed slightly enhanced diatropicity compared to **44a**H_2^{2+}, and the internal azulene and indene protons were shifted further upfield to −0.35 (1H) and −2.91 ppm (2H) (Figure 3). In addition, the *meso*-protons moved further downfield showing up as four 1H singlets at 9.60, 10.07, 10.32, and 10.41 ppm. Additional insights can be obtained from the chemical shifts for peripheral substituents. For instance, methyl substituents attached to porphyrins generally afford resonances at 3.5−3.6 ppm, while those attached to nonaromatic systems such as benziporphyrin appear near 2.4 ppm. In the free base forms, **44a** gave two 3H singlets for the methyl groups at 2.87 and 2.89 ppm, while **44b** gave these resonances at 2.92 and 3.03 ppm. The corresponding dications **44a**H_2^{2+} and **44b**H_2^{2+} gave these resonances at 3.26 and 3.29 ppm and 3.31 and 3.32 ppm, respectively. These data are not only consistent with greatly enhanced diatropicity in the diprotonated forms but also suggest that the *tert*-butyl grouping slightly increases diatropic character for both the free base forms **44** and the dications

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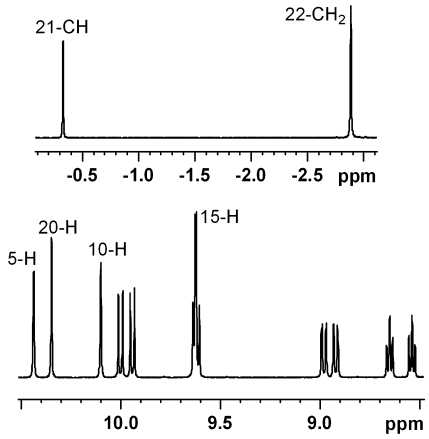
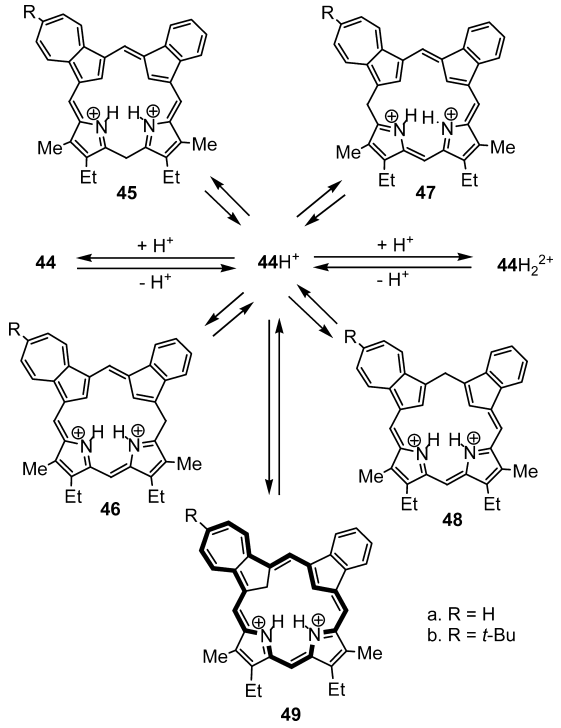


Figure 3. Partial 500 MHz proton NMR spectrum of 22-carbaazuliporphyrin dication **44b**H_2^{2+} in TFA–$CDCl_3$ showing details of the upfield and downfield regions.

44H_2^{2+}. The carbon-13 NMR spectra for dications **44**H_2^{2+} were also obtained in TFA–$CDCl_3$. Dication **44a**H_2^{2+} showed the internal CH_2 at 37.3 ppm, the internal azulene carbon gave a resonance at 129.4 ppm, and the *meso*-carbons afforded four peaks at 105.7 (C-10), 106.7 (C-15), 111.9 (C-5), and 118.7 ppm (C-20). Similarly, **44b**H_2^{2+} in TFA–$CDCl_3$ gave the 22-CH_2 resonance at 37.2 ppm, the C-21 peak at 128.5 ppm, and the *meso*-resonances at 105.6 (C-10), 106.8 (C-15), 111.8 (C-5) and 118.0 ppm (C-20). The UV–vis spectrum for dications **44a-d**H_2^{2+} show strong absorptions near 380, 420, and 740 nm. For instance, **44b**H_2^{2+} in 5% TFA–$CHCl_3$ gave strong absorptions at 383, 421, and 737 nm (Figure 1).

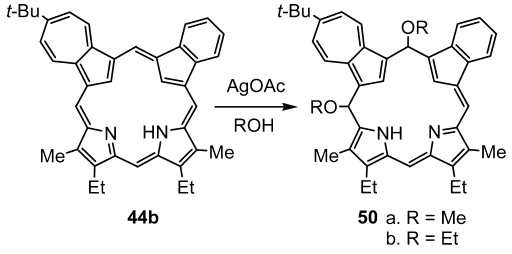
When TFA-*d* was added to a solution of **44a** in $CDCl_3$ at room temperature, proton NMR spectroscopy immediately showed that deuterium exchange with the 22-CH had occurred. Over a period of several hours at room temperature, the resonance at 9.51 ppm for the dicationic species **44a**H_2^{2+} showed a substantial decrease in intensity, demonstrating that deuterium exchange had occurred at the 15-position. This is presumably due to a low concentration of a *C*-protonated species like dication **45** being in equilibrium with **44a**H^+ and **44a**H_2^{2+} (Scheme 16), although a related monoprotonated structure may be involved. After 1 day, the intensities of all of the *meso*-resonances were reduced indicating that additional *C*-protonated species **46**–**48** were also present in solution. Deuterium exchange at position 5 between the azulene and indene rings was very slow, while exchange at positions 10 and 20 occurred at intermediary rates. Proton exchange was also observed at the interior azulene CH (21-H), although this was slower than the exchange at positions 10 and 20, and at room temperature the 21-CH resonance showed a significant decrease in intensity several hours after the addition of TFA-*d*. Deuterium exchange at position 21, although unexpected, can be attributed to the presence of a 22π electron delocalized dication **49** (Scheme 16). The data indicates that the stability of dications **44a**H_2^{2+} and **45**-**49** falls into the sequence **44a**H_2^{2+} ≫ **45a** > **47a** > **46a** > **49a** > **48a**. Even after several days, little sign of degradation was observed, but after 1 week additional peaks were noted suggesting that some decomposition had occurred. Similar results were obtained for the *tert*-butyl-substituted dicarbaporphyrinoid **44b**, although in this case exchange at the internal azulene CH occurred slightly faster than at positions 10 and 20 and the results indicate that the relative stability of the dications falls into the sequence **44b**H_2^{2+} ≫ **45b** > **49b** > **47b** > **46b** > **48b**. Presumably, the electron-donating *tert*-butyl substituent preferentially stabilizes dication **49**.

Scheme 16



The CHCHNHN core of 22-carbaazuliporphyrins **44** could conceivably act as an organometallic ligand. In fact, doubly N-confused porphyrins **16a** and **16b**, which have a similar core arrangement, have been shown to form silver(III) and copper(III) complexes,[27,28] and a diazuliporphyrin afforded a palladium(II) derivative.[43] Dicarbaporphyrinoid **44b** was reacted with silver(I) acetate in dichloromethane–methanol in an attempt to generate the corresponding silver(III) complex (Scheme 17). However, no evidence for a metalation reaction was obtained and instead a selective oxidation reaction occurred. Following column chromatography on grade 3 alumina, a dimethoxy derivative was isolated. This species appeared to be nonaromatic and showed six 1H singlets at 6.130, 6.133, 6.60, 6.87, 7.03, and 8.65 ppm. High-resolution electrospray ionization mass spectrometry gave a quasimolecular ion at *m*/*z* 623.3634 that corresponded to the [M + H] peak for $C_{43}H_{46}N_2O_2$. Selective oxidations have been observed in monocarbaporphyrinoid systems, and these reactions commonly occur on the internal carbon atoms. For this reason, we had anticipated that a similar oxidation process was occurring for **44b**. However, a careful analysis of the product

Scheme 17



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using NOE difference proton NMR spectroscopy demonstrated that the methoxy units were attached to the 5,20-positions, and the resulting derivative was assigned as structure **50a**. Only a single diastereomer was isolated, but the NMR data could not be used to determine whether the *cis* or *trans* isomers had been formed. This unusual product was not very stable and **50a** could not be isolated in pure form. The reaction of **44b** with silver(I) acetate was also carried out in ethanol and the related diethoxy compound **50b** was generated. In this case, a pure sample of the diethoxy derivative could be isolated in 41% yield.

CONCLUSIONS

Syntheses of azulene appended fulvenes have been investigated, and a series of fulvene aldehydes have been prepared by reacting azulene monoaldehydes with an indene-derived enamine **38** in the presence of di-*n*-butylboron triflate. Fulvene dialdehydes could also be conveniently generated by reacting 1,3-azulenedicarbaldehydes with enamine **38** and Bu_2BOTf.[44] These dialdehydes were condensed with dipyrrylmethane dicarboxylic acids in the presence of TFA to give a new class of dicarbaporphyrinoids with adjacent azulene and indene subunits. These carbaazuliporphyrins exhibited UV−vis spectra that closely resemble those previously reported for azuliporphyrins. The dicarbaporphyrinoids have significant diatropic character that is slightly enhanced by the presence of an electron-donating *tert*-butyl moiety on the azulene subunit. The diatropicity is further increased upon protonation, and in the presence of excess TFA a *C*-protonated dication is generated. In addition, oxidation of a 22-carbaazuliporphyrin with silver(I) acetate in alcohol solvents afforded unique nonaromatic dialkoxy-derivatives. These studies demonstrate that *adj*-dicarbaporphyrinoid systems are easily formed by the "2 + 2" MacDonald condensation, and this approach will make related porphyrinoid systems available for study.[45] In addition, the robust nature of these porphyrin analogues compared to previously synthesized *opp*-dicarbaporphyrinoids shows great promise for future investigations.

EXPERIMENTAL SECTION[46]

Benzyl 4-Ethyl-5-(3-formyl-1-azulenylmethyl)-3-methylpyrrole-2-carboxylate (25). Phosphorus oxychloride (0.25 g) was added dropwise to stirred DMF (0.12 mL) in a 10 mL round-bottom flask while the temperature was maintained between 10 and 20 °C. A solution of benzyl ester **24a**[6b] (100 mg, 0.26 mmol) in 2.4 mL of dichloromethane was then added over a period of 5 min, and the resulting mixture was allowed to stir for 10 min at room temperature. Sodium acetate trihydrate (1.1 g) in water (2 mL) was added, and the resulting biphasic mixture was stirred vigorously under reflux for 15 min. The mixture was cooled, diluted with dichloromethane, and washed with saturated sodium carbonate solution. The organic layer was separated and dried over sodium sulfate and the solvent removed under reduced pressure. The residue was purified by column chromatography on silica, eluting initially with 80% dichloromethane−chloroform and then with chloroform. The product fraction was evaporated and the residue recrystallized from ethanol to give the aldehyde (71 mg, 0.17 mmol, 66%) as dark blue crystals: mp 138−139 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.07 (3H, t, J = 7.5 Hz), 2.33 (3H, s), 2.49 (2H, q, J = 7.5 Hz), 4.32 (2H, s), 5.22 (2H, s), 7.26−7.35 (5H, m), 7.50 (1H, t, J = 9.8 Hz), 7.61 (1H, t, J = 9.8 Hz), 7.86 (1H, t, J = 9.9 Hz), 8.02 (1H, s), 8.39 (1H, d, J = 9.8 Hz), 8.45 (1H, br s), 9.55 (1H, d, J = 9.7 Hz), 10.30 (1H, s); ^{13}C NMR ($CDCl_3$) δ 10.8, 15.7, 17.6, 24.5, 65.7, 117.6, 124.4, 124.8, 127.2, 127.6, 128.1, 128.2, 128.7, 129.9, 131.4, 136.0, 136.7, 137.8, 140.3, 141.4, 142.2, 142.4, 161.6, 186.4; HRMS (EI) calcd for $C_{27}H_{25}NO_3$ 411.1834, found 411.1832. Anal. Calcd for $C_{27}H_{25}NO_3$: C, 78.81; H, 6.12; N, 3.40. Found: C, 78.46; H, 6.02; N, 3.57.

***tert*-Butyl 4-Ethyl-5-(1-azulenylmethyl)-3-methylpyrrole-2-carboxylate (24b).** Azulene (170 mg, 1.33 mmol) and *tert*-butyl 5-acetoxymethyl-4-ethyl-3-methylpyrrole-2-carboxylate[47] (**23b**, 370 mg, 1.32 mmol) were dissolved in 2-propanol (20 mL) and acetic acid (2 mL), and the solution was refluxed with stirring under nitrogen for 16 h. The solvent was evaporated under reduced pressure and the residue purified by column chromatography on silica eluting initially with 50% dichloromethane−hexanes and then with gradually increased proportions of CH_2Cl_2. Initially, a blue fraction corresponding to unreacted azulene was collected, followed by a major blue band for the title compound. A third blue band corresponding to an azulitripyrrane byproduct was also collected. The main product was recrystallized from 90% ethanol to give azulimethylpyrrole **24b** (260 mg, 0.745 mmol, 56%) as dark blue crystals: mp 112−113 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.11 (3H, t, J = 7.5 Hz), 1.48 (9H, s), 2.28 (3H, s), 2.53 (2H, q, J = 7.5 Hz), 4.37 (2H, s), 7.10−7.16 (2H, two overlapping triplets), 7.35 (1H, d, J = 3.8 Hz), 7.58 (1H, t, J = 9.9 Hz), 7.71 (1H, d, J = 3.8 Hz), 8.15 (1H, br s), 8.24 (1H, d, J = 9.7 Hz), 8.30 (1H, d, J = 9.6 Hz); ^{13}C NMR ($CDCl_3$) δ 10.7, 15.8, 17.6, 24.5, 28.7, 80.2, 117.3, 118.6, 122.4, 123.0, 123.4, 125.6, 126.0, 131.8, 133.5, 136.3, 137.1, 137.95, 137.97, 141.2, 161.6; HRMS (EI) calcd for $C_{23}H_{27}NO_2$ 349.2042, found 349.2041. Anal. Calcd for $C_{23}H_{27}NO_2 \cdot {}^1/_{10}H_2O$: C, 78.64; H, 7.80; N, 3.99. Found: C, 78.69; H, 7.83; N, 4.14.

4-Ethyl-5-(3-formyl-1-azulenylmethyl)-3-methylpyrrole-2-carbaldehyde (22). The foregoing azulenylmethylpyrrole (260 mg, 0.745 mmol) was stirred with TFA (5 mL) for 10 min, diluted with dichloromethane (20 mL), and washed sequentially with water and 10% aqueous sodium bicarbonate solution. The organic solution as dried over sodium sulfate, filtered, and evaporated under reduced pressure. Phosphorus oxychloride was added dropwise to DMF (0.3 mL) in a 50 mL round-bottom flask while the temperature was maintained between 10 and 20 °C with the aid of an ice bath. The mixture was allowed to stand for 15 min at room temperature. The deprotected azulenylmethylpyrrole **26** in dichloromethane (20 mL) was added dropwise over 10 min. The resulting mixture was stirred at room temperature for 10 min, and then a solution of sodium acetate trihydrate (11.0 g) in water (20 mL) was added. The resulting biphasic mixture was stirred under reflux for 15 min. The mixture was cooled, the organic layer separated, and the aqueous phase extracted with chloroform. The combined organic layers were washed with saturated sodium bicarbonate solution, dried over sodium sulfate, and evaporated under reduced pressure. The residue was recrystallized from ethanol to give the dialdehyde (138 mg, 0.452 mmol, 61%) as red crystals: mp 176−178 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.09 (3H, t, J = 7.6 Hz), 2.29 (3H, s), 2.50 (2H, q, J = 7.6 Hz), 4.36 (2H, s), 7.50 (1H, t, J = 9.8 Hz), 7.63 (1H, t, J = 9.8 Hz), 7.87 (1H, t, J = 9.8 Hz), 8.04 (1H, s), 8.38 (1H, d, J = 9.8 Hz), 8.89 (1H, br s), 9.41 (1H, s), 9.56 (1H, d, J = 9.8 Hz), 10.30 (1H, s); ^{13}C NMR ($CDCl_3$) δ 8.9, 15.4, 17.3, 24.6, 124.9, 126.1, 128.2, 128.5, 130.0, 135.9, 136.4, 137.9, 140.4, 141.4, 142.2, 142.5, 176.3, 186.3; HRMS (EI) calcd for $C_{20}H_{19}NO_2$ 305.1416, found 305.1413.

3-Chloroazulene-1-carbaldehyde (29c). A solution of *N*-chlorosuccinimide (1.052 g, 7.88 mmol) in dichloromethane (50 mL) was added dropwise to a stirred solution of azulene (1.008 g, 7.88 mmol) in dichloromethane (30 mL), and the mixture was stirred at room temperature overnight. The solution was washed with water (2 × 100 mL), dried over sodium sulfate, and evaporated under reduced pressure to give crude 1-chloroazulene. Phosphorus oxychloride (6.5 mL) was added dropwise to DMF (10 mL), maintaining the temperature between 10 and 20 °C with the aid of an ice bath. The resulting solution of the Vilsmeier reagent was allowed to stand at room temperature for 10 min and then added dropwise over 3 min to a stirred solution of the crude 1-chloroazulene in DMF (60 mL). The mixture was stirred for 15 min at room temperature and poured into 100 mL of ice−water. The mixture was basified with 20% aqueous sodium hydroxide solution and then extracted with dichloromethane. The organic phase was washed with water, dried over sodium sulfate,

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and then evaporated under reduced pressure, initially using a water aspirator and then switching over to an oil pump to remove residual DMF. The residue was purified on a silica column, eluting with 30% hexanes−dichloromethane. A blue band corresponding to dichloroazulene was collected initially, followed by a dark purple band corresponding to the product. Recrystallization from hexanes gave the aldehyde (1.033 g, 5.42 mmol, 69%) as dark red-purple crystals: mp 115−116 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.60 (1H, t, J = 9.8 Hz), 7.64 (1H, t, J = 9.9 Hz), 7.91 (1H, t, J = 9.9 Hz), 8.14 (1H, s), 8.57 (1H, d, J = 9.9 Hz), 9.55 (1H, d, J = 9.9 Hz), 10.29 (1H, s); ^{13}C NMR ($CDCl_3$) δ 118.8, 123.7, 128.6, 130.2, 137.0, 138.6, 139.1, 139.3, 139.8, 141.4, 185.8. Anal. Calcd for $C_{11}H_7ClO$: C, 69.31; H, 3.70. Found: C, 69.34; H, 3.57.

3-Bromoazulene-1-carbaldehyde (29d). A solution of the Vilsmeier reagent, prepared as described above from phosphorus oxychloride (1.5 mL) and DMF (10 mL), was added dropwise to a solution of azulene (0.250 g, 1.95 mmol) in DMF (15 mL), and the mixture was stirred for 2 h. The solution was poured into 40 mL of ice−water and basified with 20% sodium hydroxide solution. The mixture was extracted with chloroform, washed with water, dried over sodium sulfate, and evaporated under reduced pressure to give 1-azulenecarbaldehyde. A solution of *N*-bromosuccinimide (0.357 g) in dichloromethane (25 mL) was added dropwise to a stirred solution of the crude aldehyde in dichloromethane (25 mL), and the mixture was stirred for 20 min. The solution was washed with water and dried over sodium sulfate and the solvent removed under reduced pressure. Recrystallization from hexanes gave the aldehyde (0.220 g, 0.94 mmol, 48%) as purple needles: mp 103−104 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.62 (1H, t, J = 9.8 Hz), 7.64 (1H, t, J = 9.9 Hz), 7.90 (1H, t, J = 9.9 Hz), 8.21 (1H, s), 8.54 (1H, d, J = 9.9 Hz), 9.54 (1H, d, J = 9.7 Hz), 10.26 (1H, s); ^{13}C NMR ($CDCl_3$) δ 106.3, 125.0, 128.9, 130.4, 138.3, 138.7, 139.8, 141.3, 141.6, 142.7, 185.8. Anal. Calcd for $C_{11}H_7BrO$: C, 55.97; H, 2.99. Found: C, 56.05; H, 2.85.

3-Iodoazulene-1-carbaldehyde (29e). The iodoazulene aldehyde was prepared by the procedure used to prepared **29c** from azulene (1.00 g, 7.8 mmol) and *N*-iodosuccinimide (1.85 g, 95%, 7.8 mmol). Recrystallization from hexanes gave the iodo aldehyde (1.837 g, 6.51 mmol, 83%) as red-brown crystals: mp 104−105 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.67−7.73 (2H, two overlapping triplets), 7.95 (1H, t, J = 9.9 Hz), 8.39 (1H, s), 8.50 (1H, d, J = 9.9 Hz), 9.58 (1H, d, J = 9.8 Hz), 10.30 (1H, s); ^{13}C NMR ($CDCl_3$) δ 76.9, 127.3, 129.2, 130.7, 137.6, 140.4, 141.0, 141.4, 145.2, 149.0, 185.8. Anal. Calcd for $C_{11}H_7IO$: C, 46.84; H, 2.50. Found: C, 46.97; H, 2.21.

6-*tert*-Butyl-3-iodoazulene-1-carbaldehyde (29f). The title compound was prepared by the previous procedure from 6-*tert*-butylazulene[6c] (280 mg, 1.52 mmol) and *N*-iodosuccinimide (360 mg, 95%, 1.52 mmol). Recrystallization from hexanes gave the aldehyde (231 mg, 0.683 mmol, 45%) as red-purple needles: mp 76−77 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.50 (9H, s), 7.87 (2H, d, J = 10.7 Hz), 8.28 (1H, s), 8.41 (1H, d, J = 10.8 Hz), 9.48 (1H, d, J = 10.7 Hz), 10.25 (1H, s); ^{13}C NMR ($CDCl_3$) δ 32.0, 39.4, 76.0, 127.2, 127.8, 128.6, 136.8, 139.3, 140.2, 144.1, 144.1, 147.9, 166.1, 185.7; HRMS (EI) calcd for $C_{15}H_{15}IO$ 338.0168, found 338.0170.

Ethyl 3-(1-Azulenyl)-2-cyano-2-propenoate (42). 1-Azulenecarbaldehyde (1.21 g, 7.75 mmol) was heated under reflux with ethyl cyanoacetate (1.0 mL) and six drops of piperidine in ethanol (14 mL) for 16 h. The mixture was cooled in an ice bath and filtered to give the Knoevenagel condensation product. Recrystallization from ethanol gave the cyanovinylazulene (1.895 g, 7.55 mmol, 97%) as red-brown crystals: mp 116−117 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.41 (3H, t, J = 7.1 Hz), 4.39 (2H, q, J = 7.1 Hz), 7.53−7.57 (3H, m), 7.59 (1H, t, J = 9.9 Hz), 8.47 (1H, d, J = 9.6 Hz), 8.73 (1H, d, J = 9.8 Hz), 8.82 (1H, s), 9.07 (1H, d, J = 4.5 Hz); ^{13}C NMR ($CDCl_3$) δ 14.6, 62.2, 94.8, 118.3, 121.9, 122.5, 128.2, 129.1, 134.2, 137.9, 138.8, 140.2, 143.6, 144.1, 146.1, 164.9. Anal. Calcd for $C_{16}H_{13}NO_2$: C, 76.48; H, 5.21; N, 5.57. Found: C, 76.24; H, 5.06; N, 5.67.

Ethyl 2-Cyano-3-(3-formyl-1-azulenyl)-2-propenoate (43). Phosphorus oxychloride (1.36 g) was added dropwise to DMF (4 mL) while the temperature was maintained between 10 and 20 °C with the aid of an ice bath. The resulting solution of the Vilsmeier reagent was allowed to stand at room temperature for 10 min and then added dropwise over 3 min to a stirred solution of the foregoing cyanovinylazulene **42** (1.80 g, 7.17 mmol) in DMF (8 mL). The mixture was stirred for 15 min at room temperature and poured into 50 mL of ice−water. The mixture was basified with 20% aqueous sodium hydroxide solution and then extracted with dichloromethane. The organic phase was washed with water, dried over sodium sulfate, and then evaporated under reduced pressure, initially using a water aspirator and then switching over to an oil pump to remove residual DMF. Recrystallization from ethanol gave the aldehyde (1.77 g, 6.34 mmol, 88%) as a red-brown solid: mp 218−219 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.43 (3H, t, J = 7.1 Hz), 4.41 (2H, q, J = 7.1 Hz), 7.89 (1H, t, J = 9.9 Hz), 7.92 (1H, t, J = 9.8 Hz), 8.12 (1H, t, J = 9.8 Hz), 8.81 (1H, s), 8.88 (1H, d, J = 9.9 Hz), 9.40 (1H, s), 9.90 (1H, d, J = 9.8 Hz), 10.39 (1H, s); ^{13}C NMR ($CDCl_3$) δ 14.5, 62.6, 98.0, 117.5, 121.1, 127.9, 131.9, 134.2, 136.3, 140.8, 142.5, 143.2, 143.9, 144.2, 147.1, 164.0, 188.2. Anal. Calcd for $C_{17}H_{13}NO_3$: C, 73.11; H, 4.69; N, 5.01. Found: C, 73.00; H, 4.50; N, 5.06.

6-(6-*tert*-Butyl-1-azulenyl)benzo[*a*]fulvene (34b). A solution of potassium hydroxide in methanol (1% w/v, 8 mL) was added to a stirred solution of 6-*tert*-butylazulene-1-carbaldehyde (250 mg, 1.18 mmol) and indene (385 mg, 3.32 mmol) in methanol (15 mL), and the resulting mixture was stirred under nitrogen for 2 days. The mixture was diluted with dichloromethane, washed with water, and dried over sodium sulfate. Following evaporation of the solvent under reduced pressure (water aspirator) and removal of excess indene with an oil pump, the residue was purified by column chromatography on silica, eluting with toluene. An initial orange fraction was discarded, and the product was collected as a green band. Recrystallization from hexanes gave the fulvene (330 mg, 1.06 mmol, 90%) as lustrous dark green needles: mp 158−159 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.48 (9H, s), 7.04 (1H, d, J = 5.5 Hz), 7.22−7.25 (2H, m), 7.33 (1H, d, J = 5.5 Hz), 7.36−7.38 (1H, m), 7.40−7.43 (2H, m), 7.50 (1H, dd, J = 1.6, 10.5 Hz), 7.82−7.84 (1H, m), 8.07 (1H, s), 8.25 (1H, d, J = 10.2 Hz), 8.34 (1H, d, J = 4.2 Hz), 8.61 (1H, d, J = 10.6 Hz); ^{13}C NMR ($CDCl_3$) δ 32.0, 38.9, 118.8, 120.2, 121.07, 121.12, 123.2, 123.6, 124.7, 126.1, 126.4, 126.8, 132.2, 133.4, 135.8, 136.7, 137.3, 138.3, 138.5, 141.6, 142.4, 163.3. Anal. Calcd for $C_{24}H_{22}$: C, 92.86; H, 7.14. Found: C, 92.87; H, 7.08.

Difulvene 35. The difulvene was prepared by the foregoing procedure by reacting 1,3-azulenedicarbaldehyde[37] (400 mg, 2.17 mmol) with indene (1.28 g, 11.0 mmol) in methanol (48 mL) with 24 mL of 1% potassium hydroxide in methanol. Recrystallization from dichloromethane−hexanes gave the title compound (671 mg, 1.76 mmol, 81%) as dark purple crystals: mp 220−222 °C, dec; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.10 (2H, dd, J = 1.2, 5.5 Hz), 7.25−7.28 (6H, m), 7.33 (2H, t, J = 9.9 Hz), 7.36−7.40 (2H, m), 7.71 (1H, t, J = 9.8 Hz), 7.81−7.85 (2H, m), 8.00 (2H, s), 8.59 (2H, d, J = 9.9 Hz), 8.77 (1H, s); ^{13}C NMR ($CDCl_3$) δ 119.1, 119.9, 121.3, 125.1, 126.5, 126.6, 127.2, 127.5, 133.9, 135.1, 138.0, 138.4, 139.4, 140.3, 141.7, 142.0; HRMS (EI) calcd for $C_{30}H_{20}$ 380.1565, found 380.1567. Anal. Calcd for $C_{30}H_{20}$: C, 94.70; H, 5.30. Found: C, 94.26; H, 5.17.

6-(6-*tert*-Butyl-1-azulenyl)benzo[*a*]fulvene-3-carbaldehyde (39b). Dibutylboron triflate (1.0 M in dichloromethane, 1.2 mL) was added to a stirred mixture of 6-*tert*-butylazulene-1-carbaldehyde (200 mg, 0.943 mmol) and sodium sulfate in 1,2-dichloroethane (300 mL). A solution of indene enamine **38** (143 mg, 0.836 mmol) in 1, 2-dichloroethane (50 mL) was then added dropwise over 10 min, and the resultant solution was stirred under reflux for 4 h. Saturated sodium acetate solution (120 mL) was added, and the mixture was allowed to stir for 10 min. The solution changed color from greenish red to dark red. The mixture was extracted with dichloromethane, washed with saturated sodium bicarbonate solution, and then dried over sodium sulfate. The solvent was removed under reduced pressure, and the residue was purified by column chromatography on silica eluting with 30% hexanes−dichloromethane. Recrystallization from chloroform−-hexanes gave the fulvene aldehyde (161 mg, 0.476 mmol, 57%) as dark purple crystals: mp 198−200 °C dec; ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.50 (9H, s), 7.31−7.36 (2H, m), 7.48 (1H, d, J = 4.4 Hz), 7.57 (1H, dd, J = 1.8, 10.2 Hz), 7.66 (1H, dd, J = 1.8, 10.7 Hz),

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7.85−7.88 (1H, m), 8.03 (1H, s), 8.15−8.18 (1H, m), 8.33 (1H, d, J = 10.3 Hz), 8.37 (1H, s), 8.42 (1H, d, J = 4.3 Hz), 8.69 (1H, d, J = 10.7 Hz), 10.22 (1H, s); ^{13}C NMR ($CDCl_3$) δ 32.0, 39.1, 118.7, 121.9, 122.8, 125.3, 125.7, 125.8, 125.9, 126.8, 128.3, 133.1, 133.7, 136.5, 137.50, 137.54, 138.9, 140.26, 140.29, 140.4, 144.0, 164.6, 189.0; HRMS (EI) calcd for $C_{25}H_{22}O$ 338.1671, found 338.1678.

6-(3-Chloro-1-azulenyl)benzo[*a*]fulvene-3-carbaldehyde (39c). Dibutylboron triflate (1.0 M in dichloromethane, 0.90 mL) was added to a stirred solution of 3-chloroazulene-1-carbaldehyde (150 mg, 0.787 mmol) in dichloromethane (100 mL). A solution of indene enamine **38** (150 mg, 0.877 mmol) in dichloromethane (50 mL) was then added dropwise over 10−20 min, and the resultant solution was stirred at room temperature for 16 h. Saturated sodium acetate solution (100 mL) was added, and the solution turned from dark blue to red. The mixture was allowed to stir for 10 min and then extracted with dichloromethane and washed with saturated sodium bicarbonate solution. The organic phase was dried over sodium sulfate, the solvent was removed under reduced pressure, and the residue was purified by column chromatography on silica eluting with 30% hexanes−dichloromethane. Recrystallization with chloroform−hexanes gave the fulvene aldehyde (147 mg, 0.464 mmol, 59%) as a dark red-purple solid: mp >260 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.32−7.36 (2H, m), 7.41 (2H, t, J = 9.8 Hz), 7.79 (1H, t, J = 9.8 Hz), 7.82−7.85 (1H, m), 7.91 (1H, s), 8.12−8.16 (1H, m), 8.23 (1H, s), 8.33 (1H, s), 8.44 (1H, d, J = 9.7 Hz), 8.64 (1H, d, J = 9.9 Hz), 10.22 (1H, s); ^{13}C NMR ($CDCl_3$) δ 119.0, 121.7, 123.0, 123.6, 126.3, 126.8, 127.3, 127.4, 134.8, 135.3, 135.6, 136.3, 136.7, 138.3, 138.5, 139.5, 139.8, 141.3, 141.4, 189.1; HRMS (EI) calcd for $C_{21}H_{13}ClO$ 316.0655, found 316.0667.

6-(3-Bromo-1-azulenyl)benzo[*a*]fulvene-3-carbaldehyde (39d). The bromofulvene was prepared by the foregoing procedure from 3-bromoazulene-1-carbaldehyde (102 mg, 0.434 mmol), indene enamine **38** (78 mg, 0.456 mmol) and dibutylboron triflate (1.0 M in dichloromethane, 0.40 mL). Recrystallization from chloroform-hexanes gave the fulvene aldehyde (64 mg, 0.177 mmol, 41%) as a dark purple-red solid, mp >260 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.32−7.36 (2H, m), 7.45 (2H, t, J = 9.8 Hz), 7.81 (1H, t, J = 9.9 Hz), 7.83−7.86 (1H, m), 7.91 (1H, s), 8.12−8.16 (1H, m), 8.24 (1H, s), 8.42−8.44 (1H, overlapping singlet and doublet), 8.65 (1H, d, J = 9.8 Hz), 10.23 (1H, s); ^{13}C NMR ($CDCl_3$) δ 109.6, 119.0, 123.0, 124.9, 126.2, 126.3, 126.9, 127.4, 127.6, 134.9, 135.0, 136.8, 138.0, 138.5, 138.8, 139.6, 140.1, 140.4, 141.2, 141.5, 189.1; HRMS (EI) calcd for $C_{21}H_{13}BrO$ 360.0150, found 360.0132.

6-(3-(2-Ethoxycarbonyl-2-cyanoethenyl)-1-azulenyl)benzo-[*a*]fulvene-3-carbaldehyde (39g). The cyanovinylfulvene was prepared by the foregoing procedure from **43** (279 mg, 1.00 mmol), indene enamine **38** (188 mg, 1.10 mmol), and dibutylboron triflate (1.0 M in dichloromethane, 1.10 mL). Recrystallization from chloroform−hexanes gave the fulvene aldehyde (330 mg, 0.815 mmol, 81%) as a dark red-brown powder, mp >260 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.45 (3H, t, J = 7.6 Hz), 4.43 (2H, q, J = 7.6 Hz), 7.33−7.38 (2H, m), 7.68−7.74 (2H, two overlapping triplets), 7.82−7.85 (1H, m), 7.94 (1H, s), 8.00 (1H, t, J = 9.9 Hz), 8.12−8.15 (1H, m), 8.19 (1H, s), 8.73 (1H, d, J = 9.9 Hz), 8.79 (1H, s), 8.80 (1H, d, J = 9.8 Hz), 9.54 (1H, s), 10.16 (1H, s); ^{13}C NMR ($CDCl_3$) δ 14.5, 61.8, 97.2, 118.1, 119.4, 122.9, 123.4, 125.3, 126.6, 128.07, 128.10, 130.4, 130.5, 135.3, 136.4, 137.4, 138.08, 138.12, 138.8, 140.0, 141.8, 143.0, 143.3, 144.2, 145.3, 164.1, 189.6. Anal. Calcd for $C_{17}H_{19}NO_3$: C, 79.98; H, 4.72; N, 3.45. Found: C, 79.64; H, 4.48; N, 3.58.

6-(3-Iodo-1-azulenyl)benzo[*a*]fulvene-3-carbaldehyde (39e). *N*-Iodosuccinimide (192 mg, 95%, 0.851 mmol) was added to a stirred solution of fulvene **39a** (200 mg, 0.709 mmol) in dichloromethane (100 mL). Two drops of TFA were added, and the mixture was stirred for 5 min. The solution was washed with saturated sodium bicarbonate solution, and the organic phase was dried over sodium sulfate. The solvent was removed under reduced pressure and the residue purified by flash chromatography on silica eluting with 30% hexanes−dichloromethane. Recrystallization from chloroform−hexanes gave the fulvene (220 mg, 0.539 mmol, 76%) as dark red-brown crystals: mp 211−212 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.33−7.37 (2H, m), 7.49−7.54 (2H, two overlapping triplets), 7.85 (1H, t, J = 9.9 Hz), 7.86−7.89 (1H, m), 7.95 (1H, s), 8.16−8.19 (1H, m), 8.25 (1H, s), 8.38 (1H, d, J = 9.7 Hz), 8.58 (1H, s), 8.66 (1H, d, J = 9.8 Hz), 10.28 (1H, s); ^{13}C NMR ($CDCl_3$) δ 80.7, 119.1, 123.0, 126.1, 126.3, 127.18, 127.22, 127.4, 127.9, 134.3, 135.1, 136.9, 138.5, 139.6, 140.8, 141.0, 141.6, 143.8, 145.2, 189.1; HRMS (EI) calcd for $C_{21}H_{13}IO$ 408.0012, found 408.0018.

6-(6-*tert*-Butyl-3-iodo-1-azulenyl)benzo[*a*]fulvene-3-carbaldehyde (39f). *N*-Iodosuccinimide (370 mg, 95%, 1.56 mmol) was added to fulvene **39b** (358 mg, 1.06 mmol) dissolved in 100 mL of dichloromethane, and the mixture was stirred for 15 min. The solution was washed with water and dried over sodium sulfate. The solvent was removed under reduced pressure and the residue purified by column chromatography on silica eluting with 30% hexanes−dichloromethane. Recrystallization from chloroform−hexanes gave the fulvene (444 mg, 0.957 mmol, 90%) as a dark powder: mp 215−216 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.50 (9H, s), 7.31−7.36 (2H, m), 7.66−7.70 (2H, m), 7.82−7.86 (1H, m), 7.96 (1H, s), 8.14−8.17 (1H, m), 8.22 (1H, s), 8.28 (1H, d, J = 10.7 Hz), 8.48 (1H, s), 8.60 (1H, d, J = 10.7 Hz), 10.24 (1H, s); ^{13}C NMR ($CDCl_3$) δ 31.9, 39.3, 80.2, 118.9, 123.0, 125.8, 126.17, 126.22, 126.4, 126.9, 127.2, 133.5, 134.2. 136.7, 138.6, 139.73, 139.75, 140.0, 141.1, 142.8, 144.1, 165.8, 189.1; HRMS (EI) calcd for $C_{25}H_{21}IO$ 464.0638, found 464.0641.

6-(6-*tert*-Butyl-3-formyl-1-azulenyl)benzo[*a*]fulvene-3-carbaldehyde (37b). Dibutylboron triflate (1.0 M in dichloromethane, 1.50 mL) was added to a stirred solution of 6-*tert*-butyl-1,3-azulenedicarbaldehyde[6c] (248 mg, 1.03 mmol) in dichloromethane (300 mL) at 5 °C. A solution of indene enamine **38** (174 mg, 1.02 mmol) in dichloromethane (50 mL) was added dropwise over 10−20 min, and the resulting dark solution was stirred at room temperature for 16 h. Saturated sodium acetate solution (100 mL) was added, and the solution turned from dark blue to purple. The mixture was allowed to stir for 1 h and then extracted with dichloromethane and washed with saturated sodium bicarbonate solution. The organic phase was dried over sodium sulfate, the solvent was removed under reduced pressure, and the residue was purified by column chromatography on silica eluting with 5% methanol−chloroform and then on a second silica column eluting with chloroform. A dark orange fraction was collected and evaporated under reduced pressure. Recrystallization from acetone-hexanes gave the fulvene dialdehyde (128 mg, 0.350 mmol, 34%) as a dark red-brown solid: mp 233−234 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.54 (9H, s), 7.34−7.38 (2H, m), 7.83−7.87 (1H, m), 7.94 (1H, s), 7.95−7.98 (2H, m), 8.12−8.18 (1H, m), 8.27 (1H, s), 8.68 (1H, s), 8.80 (1H, d, J = 11.0 Hz), 9.62 (1H, d, J = 10.7 Hz), 10.25 (1H, s), 10.46 (1H, s); ^{13}C NMR ($CDCl_3$) δ 32.0, 39.6, 119.1, 123.1, 125.4, 126.5, 127.1, 127.6, 127.7, 129.2, 130.5, 135.8, 136.0, 137.1, 138.3, 138.5, 139.6, 141.7, 141.9, 143.0, 144.0, 167.4, 187.1, 189.2; HRMS (EI) calcd for $C_{26}H_{22}O_2$ 366.1620, found 366.1618.

7,13,17-Triethyl-8,12,18-trimethylazuliporphyrin (27). Concentrated hydrochloric acid (10 drops) was added to a stirred solution of dipyrrylmethanedicarboxylic acid **18a**[36] (40 mg, 0.12 mmol) and dialdehyde **22** (36 mg, 0.12 mmol), and the mixture was stirred under nitrogen at room temperature overnight. The mixture was diluted with dichloromethane, washed with water, and then shaken vigorously with 0.1% aqueous ferric chloride solution. The organic phase was separated, washed with water and saturated sodium bicarbonate solution, and evaporated under reduced pressure. The residue was loaded onto a grade 3 alumina column and eluted with 5% methanol−chloroform. A deep green fraction was collected, evaporated under reduced pressure, and recrystallized from chloroform−hexanes to give the azuliporphyrin (7.5 mg, 0.015 mmol, 13%) as a dark green solid: mp >300 °C; UV−vis (1% Et_3N−$CHCl_3$) λ_{max} (log ε) 355 (4.78), 397 (4.71), 445 (4.70), 472 (4.80), 621 nm (4.21); UV−vis (1% TFA−$CHCl_3$) λ_{max} (log ε) 365 (4.94), 437 (4.70), 462 (5.03), 642 nm (4.43); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.54 (6H, obscured by water peak), 1.59 (3H, t, J = 7.8 Hz), 2.89 (3H, s), 2.98 (3H, s), 2.99 (3H, s), 3.33 (2H, q, J = 7.7 Hz), 3.40−3.47 (4H, two overlapping quartets), 7.58−7.63 (2H, m), 7.69 (1H, t, J = 9.5 Hz), 8.04 (1H, br s), 8.05 (1H, br s), 8.90 (1H, s), 8.92 (1H, s), 9.24 (1H, d, J = 9.6 Hz),

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9.25 (1H, d, J = 9.6 Hz); ^{1}H NMR (500 MHz, TFA−$CDCl_3$) δ −2.85 (1H, s), −1.87 (1H, v br), −0.16 (1H, s), −0.15 (1H, s), 1.62 (3H, t, J = 7.7 Hz), 1.65−1.69 (6H, two overlapping triplets), 3.32 (3H, s), 3.37 (3H, s), 3.43 (3H, s), 3.78−3.85 (4H, two overlapping quartets), 3.90 (2H, q, J = 7.7 Hz), 8.45 (1H, t, J = 9.6 Hz), 8.58 (2H, t, J = 9.6 Hz), 9.47 (1H, s), 9.48 (1H, s), 9.94−9.98 (2H, two overlapping doublets), 10.33 (1H, s), 10.35 (1H, s); ^{13}C NMR ($CDCl_3$) δ 10.6, 10.8, 10.9, 16.3, 16.5, 17.1, 18.9, 19.1, 19.2, 92.94, 92.98, 107.6, 126.1, 131.6, 134.7, 139.4, 139.8, 141.6, 146.4, 148.5; ^{13}C NMR (TFA−$CDCl_3$) δ 11.2, 11.5, 11.6, 16.07, 16.15, 16.4, 19.6, 19.9, 20.1, 94.9, 95.4, 109.7, 110.0, 123.9, 128.00, 128.04, 135.8, 139.1, 140.38, 140.42, 140.9, 141.8, 142.38, 142.45, 142.51, 144.2, 145.0, 145.6, 146.4, 147.4, 148.1, 148.9, 153.83, 153.89; HRMS (FAB) calcd for $C_{35}H_{35}N_3$ + H 498.2909, found 498.2911.

13,17-Diethyl-12,18-dimethyl-22-carbabenzo[*g*]-azuliporphyrin (44a). Dipyrrole dicarboxylic acid **18a** (30 mg, 0.094 mmol) was dissolved in TFA (5 mL) and then diluted with dichloromethane (150 mL). Fulvene dialdehyde **37a** (30 mg, 0.097 mmol) was added to the stirred solution, and the mixture was stirred in the dark under nitrogen for 16 h. The solution was washed with saturated sodium bicarbonate solution, dried over sodium sulfate, and evaporated under reduced pressure. The residue was loaded onto a grade 3 alumina column and eluted with 50% dichloromethane−chloroform. A bright green fraction was collected and the solvent evaporated. Recrystallization from chloroform−hexanes gave the dicarbaporphyrinoid (9.0 mg, 0.018 mmol, 19%) as dark green crystals: mp >300 °C; UV−vis (free base in 1% Et_3N−$CHCl_3$) λ_{max} (log ε) 368 (4.76), 401 (4.67), 470 (4.68), 496 (4.65), 659 nm (4.09); UV−vis (monocation **44a**H$^+$ in 0.5% TFA−$CHCl_3$) λ_{max} (log ε) 314 (4.51), 373 (4.80), 471 (4.60), 522 (sh, 4.40), 690 nm (4.50); UV−vis (dication **44a**H_2^{2+} in 5% TFA−$CHCl_3$) λ_{max} (log ε) 388 (4.79), 421 (4.83), 516 (sh, 4.26), 670 (infl, 4.14), 743 (4.64), 779 nm (infl, 4.36); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.48−1.53 (6H, two overlapping triplets), 2.87 (3H, s), 2.89 (3H, s), 3.22 (2H, q, J = 7.7 Hz), 3.27 (2H, q, J = 7.7 Hz), 3.44 (1H, br s), 7.49−7.56 (5H, m), 7.70 (1H, t, J = 9.7 Hz), 7.99 (1H, s), 8.14 (1H, d, J = 6.8 Hz), 8.35 (1H, d, J = 6.8 Hz), 8.56 (1H, s), 9.10 (1H, s), 9.15 (1H, s), 9.18 (1H, d, J = 9.8 Hz); ^{1}H NMR (500 MHz, TFA−$CDCl_3$): δ −2.76 (2H, s), −0.08 (1H, s), 1.55 (3H, t, J = 7.7 Hz), 1.62 (3H, t, J = 7.7 Hz), 3.26 (3H, s), 3.29 (3H, s), 3.67−3.75 (4H, two overlapping quartets), 8.47 (1H, t, J = 7.5 Hz), 8.56−8.72 (4H, m), 9.51 (1H, s), 9.54 (1H, d, J = 8.1 Hz), 9.57 (1H, d, J = 8.1 Hz), 9.95 (1H, d, J = 9.4 Hz), 9.99−10.01 (2H, overlapping singlet and doublet), 10.32 (1H, s), 10.37 (1H, s); ^{13}C NMR (TFA−$CDCl_3$) δ 11.1, 11.3, 16.0, 16.1, 19.6, 19.9, 105.7, 106.7, 111.9, 118.7, 123.6, 124.8, 129.4, 131.6, 131.9, 135.1, 135.3, 137.0, 140.0, 140.63, 140.67, 141.9, 142.1, 142.6, 142.8, 142.9, 143.5, 144.0, 144.8, 146.8, 147.9, 150.6, 154.1, 154.2, 156.6, 158.0; HRMS (EI) calcd for $C_{37}H_{32}N_2$ 504.2565, found 504.2563.

2^3-*tert*-Butyl-13,17-diethyl-12,18-dimethyl-22-carbabenzo-[*g*]azuliporphyrin (44b). Using the foregoing procedure, dipyrrylmethane **18a** (30 mg, 0.094 mmol) was reacted with fulvene dialdehyde **37b** (30 mg, 0.082 mmol). Recrystallization from chloroform−hexanes gave the dicarbaporphyrinoid (37 mg, 0.066 mmol, 80%) as a dark green powder: mp >300 °C; UV−vis (free base, 1% Et_3N−$CHCl_3$) λ_{max} (log ε) 368 (4.78), 399 (4.68), 470 (4.70), 494 (4.70), 624 (sh, 4.10), 677 nm (4.16); UV−vis (monocation **44b**H$^+$, 0.1% TFA−$CHCl_3$) λ_{max} (log ε) 314 (4.49), 376 (4.70), 418 (4.46), 473 (4.55), 522 (infl, 4.38), 692 nm (4.41); UV−vis (dication **44b**H_2^{2+}, 5% TFA−$CHCl_3$) λ_{max} (log ε) 383 (4.79), 421 (4.89), 458 (sh, 4.55), 485 (sh, 4.42), 520 (sh, 4.25), 672 (sh, 4.25), 737 (4.76), 772 nm (sh, 4.40); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.15 (1H, br s), 1.49−1.54 (6H, two overlapping triplets), 1.58 (9H, s), 2.90 (3H, s), 2.92 (3H, s), 3.03 (1H, br s), 3.25 (2H, q, J = 7.7 Hz), 3.30 (2H, q, J = 7.7 Hz), 3.74 (1H, v br), 7.49−7.55 (2H, m), 7.61 (1H, s), 7.80−7.82 (2H, m), 8.08 (1H, s), 8.17−8.19 (1H, m), 8.36−8.38 (1H, m), 8.65 (1H, s), 9.15 (1H, d, J = 10.7 Hz), 9.21 (1H, d, J = 10.7 Hz), 9.23 (1H, s); ^{1}H NMR (500 MHz, trace TFA−$CDCl_3$) δ −1.13 (1H, br s), −0.36 (1H, br s), 1.51−1.57 (6H, two overlapping triplets), 1.59 (9H, s), 2.99 (3H, s), 3.00 (3H, s), 3.42−3.50 (4H, m), 3.74 (1H, v br), 7.38 (1H, t, J = 7.2 Hz), 7.44 (1H, t, J = 7.2 Hz), 7.96−8.00 (2H, m), 8.06−8.09 (1H, m), 8.26 (1H, s), 8.66 (1H, s), 9.06 (1H, s), 9.15 (1H, d, J = 10.7 Hz), 9.20 (1H, d, J = 10.5 Hz), 9.28 (1H, s); ^{1}H NMR (500 MHz, TFA−$CDCl_3$) δ −2.91 (2H, s), −0.35 (1H, s), 0.89 (1H, br), 1.27 (1H, br), 1.59 (3H, t, J = 7.7 Hz), 1.66 (3H, t, J = 7.8 Hz), 1.73 (9H, s), 3.31 (3H, s), 3.32 (3H, s), 3.71−3.80 (4H, two overlapping quartets), 8.51 (1H, t, J = 7.4 Hz), 8.62 (1H, t, J = 7.5 Hz), 8.89 (1H, dd, J = 1.9, 10.3 Hz), 8.95 (1H, dd, J = 1.9, 10.6 Hz), 9.58−9.61 (3H, m), 9.91 (1H, d, J = 10.5 Hz), 9.97 (1H, d, J = 10.8 Hz), 10.07 (1H, s), 10.32 (1H, s) 10.41 (1H, s); ^{13}C NMR ($CDCl_3$) δ 10.8, 11.1, 16.2, 16.5, 18.9, 19.1, 31.9, 39.1, 90.1, 97.3, 106.7, 111.5, 119.5, 119.8, 122.4, 125.6, 126.7, 126.8, 128.76, 128.83, 129.9, 134.4, 134.6, 135.2, 136.6, 137.9, 138.8, 139.2, 139.9, 141.1, 142.4, 143.0, 143.8, 164.9; ^{13}C NMR (TFA−$CDCl_3$) δ 11.1, 11.2, 16.0, 16.1, 19.7, 19.9, 31.5, 37.2, 41.9, 105.6, 106.8, 111.8, 118.0, 123.6, 124.7, 128.5, 131.9, 132.3, 135.0, 135.7, 136.7, 139.3, 139.5, 139.7, 141.2, 141.5, 141.6, 142.1, 142.7, 142.8, 144.0, 145.1, 147.7, 150.6, 153.0, 153.5, 155.8, 156.9, 174.9; HRMS (EI) calcd for $C_{41}H_{40}N_2$ 560.3191, found 560.3197. Anal. Calcd for $C_{41}H_{40}N_2 \cdot {}^1/_{10}CHCl_3$: C, 86.20; H, 7.06; N, 4.89. Found: C, 86.19; H, 6.89; N, 5.07.

2^3-*tert*-Butyl-12,13,17,18-tetramethyl-22-carbabenzo[*g*]-azuliporphyrin (44c). Using the previous procedure, dipyrrylmethane **18b** (27 mg, 0.094 mmol) was reacted with fulvene dialdehyde **37b** (30 mg, 0.082 mmol). Recrystallization from chloroform−hexanes gave the dicarbaporphyrinoid (20 mg, 0.037 mmol, 46%) as a dark green powder: mp >300 °C; UV−vis (1% Et_3N−$CHCl_3$) λ_{max} (log ε) 368 (4.77), 398 (4.67), 470 (4.70), 492 (4.70), 626 (sh, 4.10), 677 nm (4.15); UV−vis (0.1% TFA−$CHCl_3$) λ_{max} (log ε) 375 (4.83), 474 (4.64), 522 (infl, 4.44), 692 nm (4.55); UV−vis (5% TFA−$CHCl_3$) λ_{max} (log ε) 382 (4.79), 421 (4.89), 460 (sh, 4.55), 485 (sh, 4.42), 520 (4.24), 670 (sh, 4.24), 737 (4.76), 770 nm (4.41); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.15 (1H, br s), 1.58 (9H, s), 2.76 (3H, s), 2.80 (3H, s), 2.87 (6H, s), 3.00 (1H, v br), 7.49−7.54 (3H, m), 7.80 (2H, d, J = 10.5 Hz), 8.02 (1H, s), 8.14−8.17 (1H, m), 8.34−8.37 (1H, m), 8.58 (1H, s), 9.12 (1H, d, J = 10.5 Hz), 9.18−9.21 (2H, m); ^{1}H NMR (500 MHz, TFA−$CDCl_3$) δ −2.72 (2H, s), −0.18 (1H, s), 1.72 (9H, s), 3.20 (3H, s), 3.25 (3H, s), 3.27 (6H, s), 8.47 (1H, t, J = 7.4 Hz), 8.59 (1H, t, J = 7.4 Hz), 8.82 (1H, d, J = 10.1 Hz), 8.88 (1H, d, J = 10.6 Hz), 9.53 (1H, s), 9.54−9.57 (2H, m), 9.86 (1H, d, J = 10.3 Hz), 9.91 (1H, d, J = 10.6 Hz), 9.97 (1H, s), 10.26 (1H, s), 10.33 (1H, s); ^{13}C NMR ($CDCl_3$) δ 10.6, 11.0, 11.3, 32.0, 39.1, 89.8, 97.4, 106.1, 111.4, 119.4, 119.8, 122.3, 125.4, 126.5, 126.5, 126.6, 128.9, 129.6, 132.3, 134.3, 134.5, 135.7, 136.2, 137.6, 139.4, 139.9, 142.3, 143.1, 143.4, 143.9, 164.8; ^{13}C NMR (TFA−$CDCl_3$) δ 11.3, 11.4, 11.5, 11.7, 31.7, 37.2, 105.6, 107.4, 111.7, 118.3, 123.5, 124.6, 129.1, 131.5, 132.1, 134.6, 135.4, 137.0, 138.5, 139.2, 139.4, 140.4, 140.9, 141.5, 142.0, 142.1, 142.5, 142.7, 143.9, 144.3, 147.6, 152,7, 153.6, 155.4, 157.3; HRMS (EI) calcd for $C_{39}H_{36}N_2$ 532.2879, found 532.2882. Anal. Calcd for $C_{39}H_{36}N_2 \cdot {}^1/_3CHCl_3$: C, 82.58; H, 6.40; N, 4.90. Found: C, 82.57; H, 6.29; N, 5.06.

2^3-*tert*-Butyl-13,17-bis(2-methoxycarbonylethyl)-12,18-dimethyl-22-carbabenzo[*g*]azuliporphyrin (44d). Using the previous procedure, dipyrrylmethane **18c** (41 mg, 0.10 mmol) was reacted with fulvene dialdehyde **37b** (30 mg, 0.082 mmol). Recrystallization from chloroform−hexanes gave the dicarbaporphyrinoid (21 mg, 0.031 mmol, 38%) as a dark green powder: mp >300 °C; UV−vis (free base, 1% Et_3N−$CHCl_3$) λ_{max} (log ε) 371 (4.80), 398 (sh, 4.70), 474 (4.72), 495 (4.72), 628 (sh, 4.13), 678 nm (4.20); UV−vis (monocation, 0.1% TFA−$CHCl_3$) λ_{max} (log ε) 314 (4.51), 377 (4.81), 418 (4.51), 472 (4.63), 525 (infl, 4.43), 692 nm (4.55); UV−vis (dication, 5% TFA−$CHCl_3$) λ_{max} (log ε) 385 (sh, 4.81), 423 (4.91), 461 (sh, 4.58), 486 (sh, 4.47), 520 (4.31), 670 (sh, 4.28), 735 nm (4.75); ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.91 (1H, br s), 1.58 (9H, s), 2.73 (1H, br), 2.91 (2H, t, J = 7.8 Hz), 2.93 (6H, s), 2.94 (2H, t, J = 7.8 Hz), 3.57 (2H, t, J = 7.8 Hz), 3.63 (2H, t, J = 7.8 Hz), 3.70 (3H, s), 3.71 (3H, s), 7.50−7.55 (2H, m), 7.59 (1H, br s), 7.83 (2H, d, J = 10.5 Hz), 8.11 (1H, s), 8.17 (1H, d, J = 6.8 Hz), 8.36 (1H, d, J = 6.5 Hz), 8.64 (1H, br), 9.10−9.15 (1H, m), 9.18−9.23 (2H, m); ^{1}H NMR (500 MHz, TFA−$CDCl_3$) δ −2.94 (2H, s), −0.39 (1H, s), 1.74 (9H, s), 3.07 (2H, t, J = 7.7 Hz), 3.12 (2H, t, J = 7.7 Hz), 3.33 (3H, s), 3.34 (3H, s), 3.750 (3H, s), 3.755 (3H, s), 4.11 (2H, t, J = 7.7 Hz),

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4.14 (2H, t, J = 7.7 Hz), 8.54 (1H, t, J = 7.5 Hz), 8.65 (1H, t, J = 7.5 Hz), 8.94 (1H, dd, J = 1.9, 10.4 Hz), 9.00 (1H, dd, J = 1.9, 10.7 Hz), 9.59−9.63 (2H, two overlapping doublets), 9.89 (1H, s), 9.93 (1H, d, J = 10.6 Hz), 9.99 (1H, d, J = 10.8 Hz), 10.09 (1H, s), 10.34 (1H, s), 10.43 (1H, s); ^{13}C NMR ($CDCl_3$): δ 11.0, 11.3, 20.9, 21.3, 31.9, 35.7, 36.0, 39.1, 51.9, 52.0, 89.7, 98.0, 107.1, 111.6, 119.5, 119.9, 122.7, 125.4, 125.7, 126.7, 126.9, 129.15, 129.20, 129.8, 134.4, 134.7, 134.9, 136.4, 136.7, 137.2, 137.9, 139.8, 140.8, 142.3, 143.3, 144.1, 165.1, 173.6, 173.9; ^{13}C NMR (TFA−$CDCl_3$) δ 11.25, 11.30, 21.1, 21.3, 31.5, 35.32, 35.37, 37.2, 41.0, 53.4, 105.7, 107.6, 111.9, 123.6, 124.8, 128.5, 132.1, 132.7, 135.2, 136.2, 138.0, 139.2, 139.7, 139.8, 140.3, 141.3, 141.6, 141.9, 142.1, 143.0, 143.3, 144.4, 145.8, 147.8, 153.1, 153.3, 156.1, 157.3, 175.4, 176.2, 176.5; HRMS (EI) calcd for $C_{45}H_{44}N_2O_4$ 676.3301, found 676.3315.

2^3-*tert*-Butyl-13,17-diethyl-5,20-dihydro-5,20-dimethoxy-12,18-dimethyl-22-carbabenzo[*g*]azuliporphyrin (50a). A suspension of silver(I) acetate (75 mg, 0.45 mmol) in methanol (25 mL) was added to a stirred solution of dicarbaporphyrin **44b** (25 mg, 0.044 mmol) in dichloromethane (25 mL), and the resulting mixture was stirred in the dark for 10 h at room temperature. The solution was washed with water and brine, back-extracting each time with dichloromethane, and the organic solutions were evaporated under reduced pressure. The residue was purified on a grade 3 basic alumina column, eluting with 50:50 dichloromethane−hexanes. A green and a purple fraction eluted initially, and the product then eluted as a second purple fraction. This was further purified by chromatography on a grade 3 alumina column, eluting with dichloromethane−hexanes. Following evaporation of the solvent on a rotary evaporator and drying in vacuo overnight, the dimethoxy derivative (9.0 mg, 0.014 mmol, 32%) was obtained as a dark solid: mp 155−157 °C, dec; UV−vis (1% Et_3N−$CHCl_3$) λ_{max} (relative intensities) 287 (1.00), 343 (0.60), 488 (0.33), 582 nm (0.35); ^{1}H NMR (500 MHz, $CDCl_3$): δ 1.06 (3H, t, J = 7.6 Hz), 1.16 (3H, t, J = 7.6 Hz), 1.42 (9H, s), 2.07 (3H, s), 2.31 (3H, s), 2.50 (2H, q, J = 7.6 Hz), 2.59 (2H, q, J = 7.6 Hz), 3.47 (3H, s), 3.48 (3H, s), 6.130 (1H, s), 6.133 (1H, s), 6.60 (1H, s), 6.87 (1H, s), 7.03 (1H, s), 7.22 (1H, dt, J = 0.9, 7.5 Hz), 7.29−7.34 (3H, m), 7.63 (1H, d, J = 7.5 Hz), 7.74 (1H, d, J = 7.5 Hz), 8.12 (1H, d, J = 10.6 Hz), 8.42 (1H, d, J = 10.9 Hz), 8.65 (1H, s), 10.40 (1H, v br); ^{13}C NMR ($CDCl_3$) δ 9.6, 9.8, 16.34, 16.38, 17.9, 18.3, 32.1, 38.7, 56.6, 57.5, 72.6, 115.4, 116.6, 119.4, 121.02, 121.04, 121.3, 125.2, 125.3, 126.8, 127.5, 128.2, 131.4, 131.9, 136.76, 136.84, 137.2, 139.1, 141.8, 148.0, 161.8; HRMS (ESI) calcd for $C_{43}H_{46}N_2O_2$ + H 623.3638, found 623.3634.

2^3-*tert*-Butyl-5,20-diethoxy-13,17-diethyl-5,20-dihydro-12,18-dimethyl-22-carbabenzo[*g*]azuliporphyrin (50b). Dicarbaporphyrin **44b** (25 mg, 0.044 mmol) was reacted with silver(I) acetate (75 mg, 0.45 mmol) in dichloromethane (25 mL) and ethanol (25 mL) using the conditions described above. The diethoxy derivative (12 mg, 0.018 mmol, 41%) was isolated as a dark solid: mp 160−163 °C, dec; UV−vis ($CHCl_3$) λ_{max} (relative intensities) 288 (1.00), 341 (0.52), 403 (0.26), 501 (sh, 0.30), 556 nm (0.37); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.05 (3H, t, J = 7.6 Hz), 1.15 (3H, t, J = 7.6 Hz), 1.26 (3H, t, J = 7.0 Hz), 1.30 (3H, t, J = 7.0 Hz), 1.41 (9H, s), 2.07 (3H, s), 2.30 (3H, s), 2.49 (2H, q, J = 7.0 Hz), 2.58 (2H, q, J = 7.6 Hz), 3.57−3.76 (4H, m), 6.231 (1H, s), 6.236 (1H, br s), 6.59 (1H, s), 6.82 (1H, br s), 7.01 (1H, s), 7.21 (1H, dt, J = 0.9, 7.5 Hz), 7.27−7.34 (3H, m), 7.62 (1H, d, J = 7.6 Hz), 7.75 (1H, d, J = 7.4 Hz), 8.11 (1H, d, J = 10.5 Hz), 8.40 (1H, d, J = 10.8 Hz), 8.67 (1H, s), 10.76 (1H, v br); ^{13}C NMR ($CDCl_3$) δ 9.6, 9.8, 15.8, 15.9, 16.36, 16.37, 17.9, 18.2, 32.1, 38.7, 64.3, 65.2, 71.0, 115.2, 116.5, 119.3, 120.9, 121.0, 121.1, 125.2, 126.0, 127.30, 127.34, 128.1, 131.3, 131.8, 136.6, 136.9, 137.1, 139.3, 141.7, 148.0, 161.7; HRMS (ESI) calcd for $C_{45}H_{50}N_2O_2$ + H 651.3951, found 651.3956.

■ ASSOCIATED CONTENT

Supporting Information

Selected ^{1}H NMR, ^{1}H−^{1}H COSY, HSQC, DEPT-135, ^{13}C NMR, MS, and UV−vis spectra are provided. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: tdlash@ilstu.edu.

Notes

The authors declare no competing financial interest.

†Conjugated Macrocycles Related to the Porphyrins. 61. For part 60, see ref 15.

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■ REFERENCES

(1) (a) Lash, T. D. *Synlett* **2000**, 279−295. (b) Lash., T. D. *Eur. J. Org. Chem.* **2007**, 5461−5481.

(2) (a) Lash, T. D. In *The Porphyrin Handbook*; Kadish, K. M., Smith, K. M., Guilard, R., Eds.; Academic Press: San Diego, 2000; Vol. 2, pp 125−199. (b) Lash, T. D. In *Handbook of Porphyrin Science - With Applications to Chemistry, Physics, Material Science, Engineering, Biology and Medicine*; Kadish, K. M., Smith, K. M., Guilard, R., Eds.; World Scientific: Singapore, 2012; Vol. *16*, pp 1−329.

(3) (a) Stepien, M.; Latos-Grazynski, L. *Acc. Chem. Res.* **2005**, *38*, 88−98. (b) Pawlicki, M.; Latos-Grazynski, L. In *Handbook of Porphyrin Science - With Applications to Chemistry, Physics, Material Science, Engineering, Biology and Medicine*; Kadish, K. M., Smith, K. M., Guilard, R., Eds.; World Scientific: Singapore, 2010; Vol. 2, pp 104−192.

(4) (a) Srinivasan, A.; Furuta, H. *Acc. Chem. Res.* **2005**, *38*, 10−20. (b) Harvey, J. D.; Ziegler, C. J. *Coord. Chem. Rev.* **2003**, *247*, 1−19. (c) Toganoh, M.; Furuta, H. In *Handbook of Porphyrin Science - With Applications to Chemistry, Physics, Material Science, Engineering, Biology and Medicine*; Kadish, K. M., Smith, K. M., Guilard, R., Eds.; World Scientific: Singapore, 2010; Vol. 2, pp 295−367. (d) Toganoh, M.; Furuta, H. *Chem. Commun.* **2012**, *48*, 937−954.

(5) (a) Lash, T. D.; Hayes, M. J. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 840−842. (b) Lash, T. D.; Hayes, M. J.; Spence, J. D.; Muckey, M. A.; Ferrence, G. M.; Szczepura, L. F. *J. Org. Chem.* **2002**, *67*, 4860−4874. (c) Liu, D.; Lash, T. D. *J. Org. Chem.* **2003**, *68*, 1755−1761.

(6) (a) Lash, T. D.; Chaney, S. T. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 839−840. (b) Lash, T. D.; Colby, D. A.; Graham, S. R.; Chaney, S. T. *J. Org. Chem.* **2004**, *69*, 8851−8864. (c) Lash, T. D.; El-Beck, J. A.; Ferrence, G. M. *J. Org. Chem.* **2007**, *72*, 8402−8415.

(7) (a) Colby, D. A.; Lash, T. D. *Chem.—Eur. J.* **2002**, *8*, 5397−5402. (b) Lash, T. D.; Colby, D. A.; Ferrence, G. M. *Eur. J. Org. Chem.* **2003**, 4533−4548. (c) El-Beck, J. A.; Lash, T. D. *Eur. J. Org. Chem.* **2007**, 3981−3190.

(8) (a) Lash, T. D.; Chaney, S. T. *Tetrahedron Lett.* **1996**, *37*, 8825−8828. (b) Bergman, K. M.; Ferrence, G. M.; Lash, T. D. *J. Org. Chem.* **2004**, *69*, 7888−7897.

(9) Hayes., M. J.; Lash, T. D. *Chem.—Eur. J.* **1998**, *4*, 508−511.

(10) (a) Berlin, K.; Breitmaier, E. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 1246−1247. (b) Stepien, M.; Latos-Grazynski, L. *Chem.—Eur. J.* **2001**, *7*, 5113−5117. (c) Szymanski, J. T.; Lash, T. D. *Tetrahedron Lett.* **2003**, *44*, 8613−8616. (d) Stepien, M.; Latos-Grazynski, L.; Szterenberg, L.; Panek, J.; Latajka, Z. *J. Am. Chem. Soc.* **2004**, *126*, 4566−4580. (e) Lash, T. D.; Szymanski, J. T.; Ferrence, G. M. *J. Org. Chem.* **2007**, *72*, 6481−6492. (f) Lash, T. D.; Yant, V. R. *Tetrahedron* **2009**, *65*, 9527−9535.

(11) (a) Lash, T. D. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 2533−2535. (b) Lash, T .D.; Chaney, S. T.; Richter, D. T. *J. Org. Chem.* **1998**, *63*, 9076−9088.

(12) (a) Richter, D. T.; Lash, T. D. *Tetrahedron* **2001**, *57*, 3659−3673. (b) Miyake, K.; Lash, T. D. *Chem. Commun.* **2004**, 178−179. (c) El-Beck, J. A.; Lash, T. D. *Org. Lett.* **2006**, *8*, 5263−5266. (d) Lash,

T. D.; Miyake, K.; Xu, L.; Ferrence, G. M. *J. Org. Chem.* **2011**, *76*, 6295−6308.
(13) Lash, T. D.; Young, A. M.; Rasmussen, J. M.; Ferrence, G. M. *J. Org. Chem.* **2011**, *76*, 5636−5651.
(14) Latos-Grazynski, L.; Pawlicki, M. *Chem. Rec.* **2006**, *6*, 64−78.
(15) Lash, T. D.; Lammer, A. D.; Ferrence, G. M. *Angew. Chem., Int. Ed.* **2011**, *50*, 9718−9721.
(16) (a) Lash, T. D.; Young, A. M.; Von Ruden, A. L.; Ferrence, G. M. *Chem. Commun.* **2008**, 6309−6311. (b) Young, A. M.; Von Ruden, A. L.; Lash, T. D. *Org. Biomolec. Chem.* **2011**, *9*, 6293−6305.
(17) (a) Mysliborski, R.; Latos-Grazynski, L. *Eur. J. Org. Chem.* **2005**, 5039−5048. (b) Lash, T. D.; Pokharel, K.; Serling, J. M.; Yant, V. R.; Ferrence, G. M. *Org. Lett.* **2007**, *9*, 2863−2866.
(18) (a) Muckey, M. A.; Szczepura, L. F.; Ferrence, G. M.; Lash, T. D. *Inorg. Chem.* **2002**, *41*, 4840−4842. (b) Lash, T. D.; Colby, D. A.; Szczepura, L. F. *Inorg. Chem.* **2004**, *43*, 5258−5267.
(19) (a) Graham, S. R.; Ferrence, G. M.; Lash, T. D. *Chem. Commun.* **2002**, 894−895. (b) Lash, T. D.; Colby, D. A.; Graham, S. R.; Ferrence, G. M.; Szczepura, L. F. *Inorg. Chem.* **2003**, *42*, 7326−7338. (c) Lash, T. D.; Rasmussen, J. M.; Bergman, K. M.; Colby, D. A. *Org. Lett.* **2004**, *6*, 549−552. (d) Lash, T. D. *Macroheterocycles* **2008**, *1*, 9−20.
(20) (a) Hayes, M. J.; Spence, J. D.; Lash, T. D. *Chem. Commun.* **1998**, 2409−2410. (b) Lash, T. D.; Muckey, M. A.; Hayes, M. J.; Liu, D.; Spence, J. D.; Ferrence, G. M. *J. Org. Chem.* **2003**, *68*, 8558−8570.
(21) Colby, D. A.; Ferrence, G. M.; Lash, T. D. *Angew. Chem., Int. Ed.* **2004**, *43*, 1346−1349.
(22) (a) Morgenthaler, J. B.; Peters, S. J.; Cedeño, D. L.; Constantino, M. H.; Edwards, K. A.; Kamowski, E. M.; Passini, J. C.; Butkus, B. E.; Young, A. M.; Lash, T. D.; Jones, M. A. *Bioorg. Med. Chem.* **2008**, *16*, 7033−7038. (b) Taylor, V. M.; Cedeño, D. L.; Muñoz, D. L.; Jones, M. A.; Lash, T. D.; Young, A. M.; Constantino, M. H.; Esposito, N.; Vélez, I. D.; Robledo, S. M. *Antimicrob. Agents Chemother.* **2011**, *55*, 4755−4764.
(23) Lash, T. D. *Chem. Commun.* **1998**, 1683−1684.
(24) Lash, T. D.; Romanic, J. L.; Hayes, M. J.; Spence, J. D. *Chem. Commun.* **1999**, 819−820.
(25) Graham, S. R.; Colby, D. A.; Lash, T. D. *Angew. Chem., Int. Ed.* **2002**, *41*, 1371−1374.
(26) Xu, L.; Lash, T. D. *Tetrahedron Lett.* **2006**, *47*, 8863−8866.
(27) Furuta, H.; Maeda, H.; Osuka, A. *J. Am. Chem. Soc.* **2000**, *122*, 803−807.
(28) Maeda, H.; Osuka, A.; Furuta, H. *J. Am. Chem.. Soc.* **2003**, *125*, 15690−15691.
(29) Heterodicarbaporphyrinoids with alternating azulene and furan or thiophene rings have also been reported: (a) Sprutta, N.; Swiderska, M.; Latos-Grazynski, L. *J. Am. Chem. Soc.* **2005**, *127*, 13108−13109. (b) Sprutta, N.; Siczek, M.; Latos-Grazynski, L.; Pawlicki, M.; Szterenberg, L.; Lis, T. *J. Org. Chem.* **2007**, *72*, 9501−9509.
(30) Arsenault, G. P.; Bullock, E.; MacDonald, S. F. *J. Am. Chem. Soc.* **1960**, *82*, 4384−4389.
(31) Preliminary communication: Lash, T. D.; Colby, D. A.; Idate, A. S.; Davis, R. N. *J. Am. Chem. Soc.* **2007**, *129*, 13800−13801.
(32) These results were presented, in part, at the following meetings: (a) 224th National Meeting of the American Chemical Society, Boston, MA, August 2002 (Colby, D. A.; Lash, T. D. *Book of Abstracts*, ORGN 746). (b) 225th National Meeting of the American Chemical Society, New Orleans, LA, March 2003 (Abstract: Colby, D. A.; Lash, T. D. *Book of Abstracts*, ORGN 502). (c) 231st National Meeting of the American Chemical Society, Atlanta, GA, March 26−30, 2006 (Abstract: Idate, A. S.; Lash, T. D. *Book of Abstracts*, ORGN 538). (d) Fourth International Conference on Porphyrins and Phthalocyanines, Rome, Italy, July 2006 (Abstract: Idate, A. S.; Davis, R. N.; Colby, D. A.; Lash, T. D. *J. Porphyrins Phthalocyanines* 2006, *10*, 737).
(33) (a) Lash, T. D. *Chem.—Eur. J.* **1996**, *2*, 1197−1200. (b) Lash, T. D. *J. Porphyrins Phthalocyanines* **1997**, *1*, 29−44.
(34) A synthesis of a *meso*-unsubstituted N-confused porphyrin by the "2 + 2" MacDonald approach has been reported: Liu, B. Y.; Brückner, C.; Dolphin, D. *Chem. Commun.* **1996**, 2141−2142.
(35) Alternative "3 + 1" MacDonald-type routes to *meso*-unsubstituted N-confused porphyrins have also been published: (a) Lash, T. D.; Richter, D. T.; Shiner, C. M. *J. Org. Chem.* **1999**, *64*, 7973−7982. (b) Lash, T. D.; Von Ruden, A. L. *J. Org. Chem.* **2008**, *73*, 9417−9425.
(36) Lash, T. D.; Armiger, Y. L. S.-T. *J. Heterocycl. Chem.* **1991**, *28*, 965−970.
(37) Hafner, K.; Bernhard, C. *Liebigs Ann. Chem.* **1959**, *625*, 108−123.
(38) Arnold, Z. *Collect. Czech. Chem. Commun.* **1965**, 2783−2792.
(39) (a) Iida, T.; Wada, T.; Tomimoto, K.; Mase, T. *Tetrahedron Lett.* **2001**, *42*, 4841−4844. (b) Böhm, V. P. W; Schulze, V.; Brönstrup, M.; Müller, M.; Hoffmann, R. W. *Organometallics* **2003**, *22*, 2925−2930. (c) Seitz, L. M.; Brown, T. L. *J. Am. Chem. Soc.* **1996**, *88*, 4140−4147. (d) Dumouchel, S.; Mongin, F.; Trécourt, F.; Quéguiner, G. *Tetrahedron* **2003**, *59*, 8629−8640. (e) Hatano, M.; Matsumura, T.; Ishihara, K. *Org. Lett.* **2005**, *7*, 573−576. (f) Inoue, A.; Kitagawa, K.; Shinokubo, H.; Oshima, K. *J. Org. Chem.* **2001**, *66*, 4333−4339.
(40) Ito, S.; Kubo, T.; Morita, N.; Matsui, Y.; Watanabe, T.; Ohta, A.; Fujimori, K.; Murafuji, T.; Sugihara, Y.; Tajiri, A. *Tetrahedron Lett.* **2004**, *45*, 2891−2894.
(41) Paine, J. B. III; Woodward, R. B.; Dolphin, D. *J. Org. Chem.* **1976**, *41*, 2826−2835.
(42) The [18]annulene model for porphyrinoid aromaticity continues to provide an excellent explanation for the diatropic characteristics of these systems. See: (a) Vogel, E. *J. Heterocycl. Chem* **1996**, *33*, 1461−1487. (b) Lash, T. D.; Jones, S. A.; Ferrence, G. M. *J. Am. Chem. Soc.* **2010**, *132*, 12786−12787. (c) Lash, T. D. *J. Porphyrins Phthalocyanines* **2011**, *15*, 1093−1115.
(43) Zhang, Z.; Ferrence, G. M.; Lash, T. D. *Org. Lett.* **2009**, *11*, 101−104.
(44) Numerous examples of fulvene aldehydes have also been prepared by reacting benzaldehydes with enamine **38**. See: Davis, R. N.; Lash, T. D. *Tetrahedron* **2009**, *65*, 9935−9943.
(45) This methodology was recently applied to the synthesis of a 22-oxacarbaporphyrin. See: Jain, P.; Ferrence, G. M.; Lash, T. D. *J. Org. Chem.* **2010**, *75*, 6563−6573.
(46) Synthetic procedures for **34a**, **36**, **29a**, and **37a** are provided in ref 31.
(47) Clezy, P. S.; Crowley, R. J.; Hai, T. T. *Aust. J. Chem.* **1982**, *35*, 411−421.