Organic &
Biomolecular Chemistry

ROYAL SOCIETY
OF CHEMISTRY

PAPER

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Cite this: *Org. Biomol. Chem.*, 2023, **21**, 858

Received 16th September 2022,
Accepted 21st December 2022

DOI: 10.1039/d2ob01695h

rsc.li/obc

Persistent azulene α-carbocations: synthesis from aldehydes, spectroscopic and crystallographic properties†

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The non-benzenoid aromatic system azulene is sufficiently nucleophilic at C1 that it can react with a protonated aldehyde to form an α-azulenyl alcohol. This in turn may be protonated and undergo loss of water to give an azulene α-carbocation. We report the isolation of such azulenyl cations as salts with non-coordinating anions. The salts have been characterised by NMR, UV/Vis absorption and (in certain cases) X-ray crystallography. Reduction of representative salts to afford azulenyl(aryl) methylenes has been demonstrated.

Introduction

Azulene **1** is a bicyclic non-benzenoid aromatic hydrocarbon with a 10-electron π-system, which is isomeric with naphthalene **2**. Its properties differ from those of benzenoid **2** in several significant ways.[1] It is unusually polar for a molecule devoid of heteroatoms, possessing a dipole moment of 1.08 D,[2] which arises from the contribution to the resonance hybrid of structure **1′**, in which the two rings are both individual 6-electron aromatic systems. It also exhibits the anomalous fluorescence property of emitting as a result of the $S_0 \leftarrow S_2$ transition, in violation of Kasha's rule.[3] Strikingly, whereas **2** is colourless, **1** is a deep blue colour, as a result of its HOMO–LUMO gap being in the visible region. Ring substituents that perturb the azulene chromophore give rise to derivatives of many different colours. The relationship between the electronic nature of a substituent, its point of attachment and resultant shift in the absorption maximum has been studied.[4] Many new dyes based on azulene have been reported, and selected examples are shown in Fig. 1, such as azulenoisoindigo (**3**),[5] azulene-fused tetracene diimide **4**,[6] and biazulene diimides **5**.[7] Azulene dyes such as **6** have been exploited in dye-sensitized solar cells.[8] The changes in optical properties (both absorbance and fluorescence) that occur as a result of changes to the substituents make azulene derivatives ideal for use as chemosensors and chemodosimeters. For example, bis(pyrrolyl)azulene **7** is a fluorescent and colorimetric sensor for fluoride,[9] AzuFluor® 435-DPA-Zn (**8**) is a fluorescent sensor for ADP[10] and AzuFluor® 483-Bpin (**9**) is a fluorescent dosimeter for peroxynitrite.[11]

In any azulene **10** with a carbon substituent at the 1- or 3-position, a positive charge on that α-aryl carbon will be

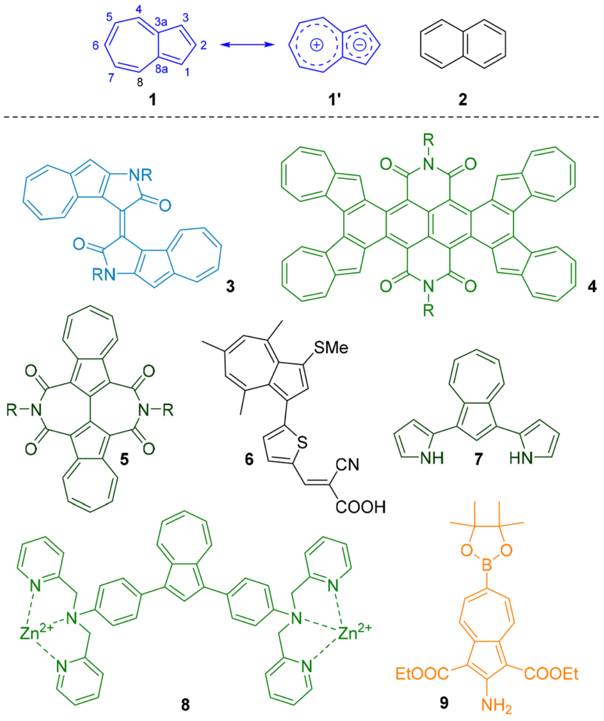

Fig. 1 Structures of azulene, naphthalene and azulene-based dyes.

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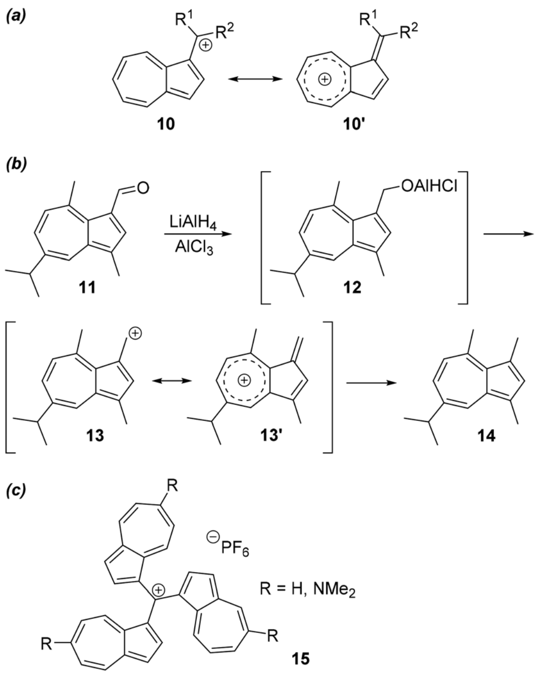
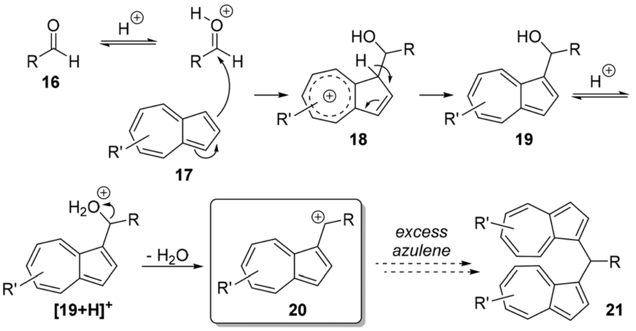
† Electronic supplementary information (ESI) available: NMR spectra, X-ray crystallographic data. CCDC 2129310–2129315. For ESI and crystallographic data in CIF or other electronic format see DOI: **https://doi.org/10.1039/d2ob01695h**

stabilised due to the existence of a resonance structure comprising a tropylium ring, **10′** (Scheme 1a). The stabilisation of such cations explains various aspects of azulene reactivity that are distinct from benzenoid aromatic systems.[12] For example, 3-formylguaiazulene (**11**) may be reduced twice (Scheme 1b), first to alkoxy intermediate **12**, and then to 3-methylguaiazulene (**14**).[13] This second reduction is enabled by the stability of cationic intermediate **13** (Scheme 1b). The intermediacy of cations such as **10** also enables reactions such as hydration of 1-azulenylalkynes,[14] formation of azuleno[2,1-*b*]thiophenes,[15] formation of calix[*n*]azulenes,[16] pyrrole-mediated azulene decarbonylation,[17] and protection of thiols with azulene-based protecting groups.[18] If cations of type **10** possess R^1 and R^2 substituents which are sufficiently cation-stabilising, then they may be isolable as stable salts with non-nucleophilic anions. A notable example are the tris(azulen-1-yl)cations **15**, which display exceedingly high pK_R^+ values as a result of the stability conferred by the three cation-stabilising azulene substituents (Scheme 1C). For example, **15** (R = H)[19] has $pK_R^+ = 11.3$, whereas the effect of additional electron donating groups is clearly shown for **15** (R = NMe_2),[20] with $pK_R^+ = 24.3$.

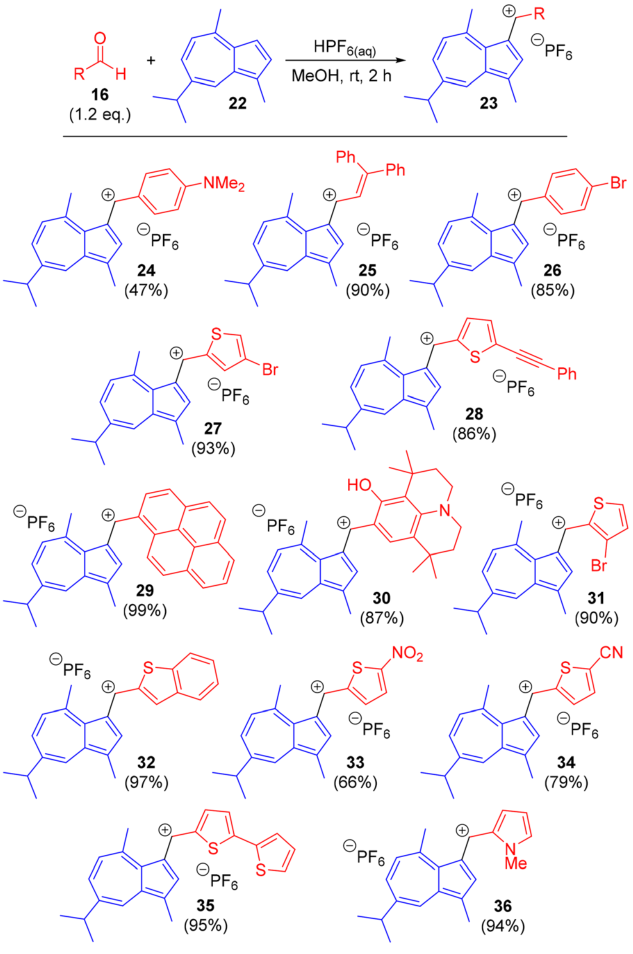
Cations of type **10** can be stable enough to be isolated even when R^1 = H, as long as $R^2 \neq$ H. Such cations can be conveniently prepared by reaction of an azulene with the requisite aldehyde in the presence of an appropriate Brønsted acid (*i.e.* one with a non-coordinating anion, such as HBF_4, HPF_6 or $HClO_4$) as shown in Scheme 2. Protonation of the aldehyde **16** activates it towards an S_EAr reaction with an azulene **17** to afford alcohol **19**. This in turns undergoes a second protonation, followed by loss of water to give persistent cations **20** (Scheme 2). The outcome of the reaction is dependent on stoichiometry, since if an excess of the azulene is used, a second S_EAr reaction can occur to give bis(azulen-1-yl)methines of type **21**. Products of type **20** have been studied by Reid[21] and by Stepanow,[22] who have demonstrated the applicability of this process to various aromatic and aliphatic aldehydes. Subsequently, Takekuma also disclosed extensive studies on this class of compounds.[23] Applications of salts of type **20** have been described in the patent literature, such as in optical data storage,[24] in thermal-transfer printing,[25] in photocros-



Scheme 1 Stability of α-aryl cations at the azulene 1- or 3-position.



Scheme 2 Synthesis of azulene α-aryl cations from aryl aldehydes.



Scheme 3 Synthesis of arylazulenyl cations **24–36**.

slinkable resins,[26] in cancer phototherapy[27] and in retinal tissue staining.[28] These salts have also been employed for the synthesis of various heterocycles[29] and in chemical sensing of various anions.[30] The wide substrate scope of the reaction shown in Scheme 2 led us to prepare and study novel cations of type **20** derived from aldehydes that have not previously been used in this process. The results of these investigations are reported here.

Results and discussion

We chose guaiazulene **22** as the substrate for cation formation, since not only is it appreciably cheaper than **1** (as a result of the availability of **22** from natural sources[31]), but the presence of the C1-methyl substituent precludes oligomerisation reactions.[32] Application of previously reported reaction conditions (HPF_6, MeOH, room temperature, 2 h) gave the expected products with a wide range of both aryl and heteroaryl aldehydes, including those bearing both electron-donating and electron-withdrawing substituents (Scheme 3). In the first instance we employed *p*-dimethylaminobenzaldehyde to prepare salt **24**. Other salt forms of **24** have been reported previously (with BF_4^-, ClO_4^-, or I^- counteranions).[21b,23f,r] Salt **24** was comprehensively characterised by NMR spectroscopy (see ESI†), which

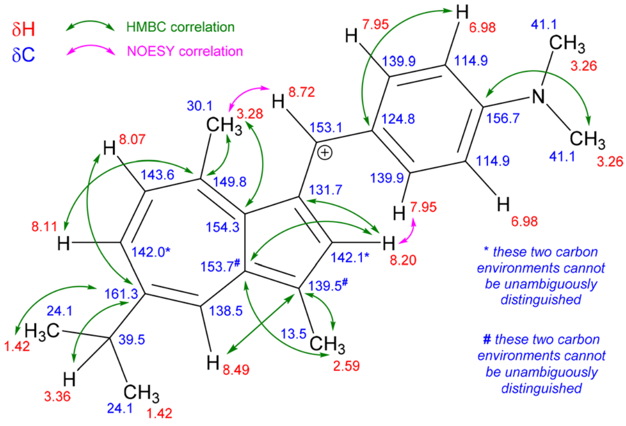


Fig. 2 Structure of **24**, with selected HMBC and NOESY interactions indicated.

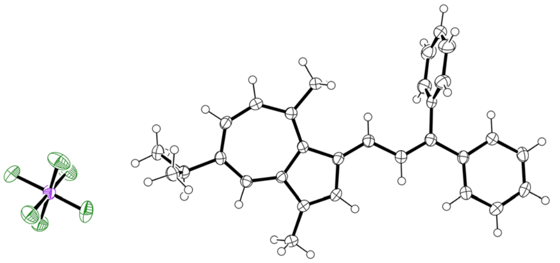


Fig. 3 ORTEP representation of the X-ray structure of **25**. Ellipsoids are shown at 50% probability. Hydrogens are shown as spheres of arbitrary radius. CCDC 2129313.†

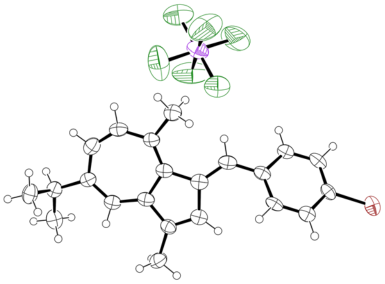


Fig. 4 ORTEP representation of the X-ray structure of **26**. Ellipsoids are shown at 50% probability. Hydrogens are shown as spheres of arbitrary radius. Only one of 3 independent molecules in the unit cell is shown for clarity. CCDC 2129312.†

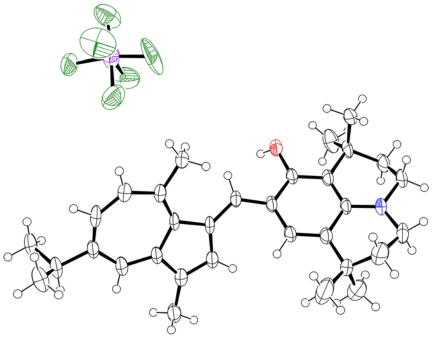


Fig. 5 ORTEP representation of the X-ray structure of **30**. Ellipsoids are shown at 50% probability. Hydrogens are shown as spheres of arbitrary radius. Only one of 2 independent molecules in the unit cell is shown. Disordered water molecules and disorder in PF_6^- anion are omitted for clarity. CCDC 2129314.†

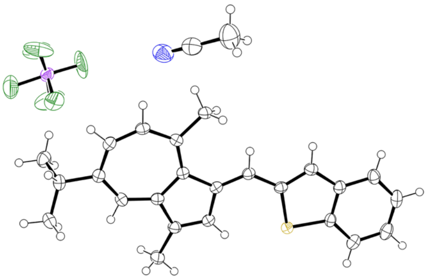


Fig. 6 ORTEP representation of the X-ray structure of **32**·MeCN. Ellipsoids are shown at 50% probability. Hydrogens are shown as spheres of arbitrary radius. Disorder in PF_6^- anion omitted for clarity. CCDC 2129315.†

Table 1 Selected parameters for X-ray structures of **25**, **26**, **30** and **32**; (X = C, S)

Salt	C^{Az}–C^+ bond length‡/Å	C^+–C^α bond length‡/Å	C^{Az}–C^+–$C^{Ar(\alpha)}$–$X^{Ar(\beta)}$ dihedral angle‡
25	1.372(3)	1.430(3)	n/a
26	1.36(1)–1.39(1)	1.45(2)	28(1)°–30(2)°
30	1.385(6)–1.391(6)	1.421(4)–1.426(5)	22.1(6)°–24.9(6)°
32	1.373(3)	1.428(3)	3.5(4)°

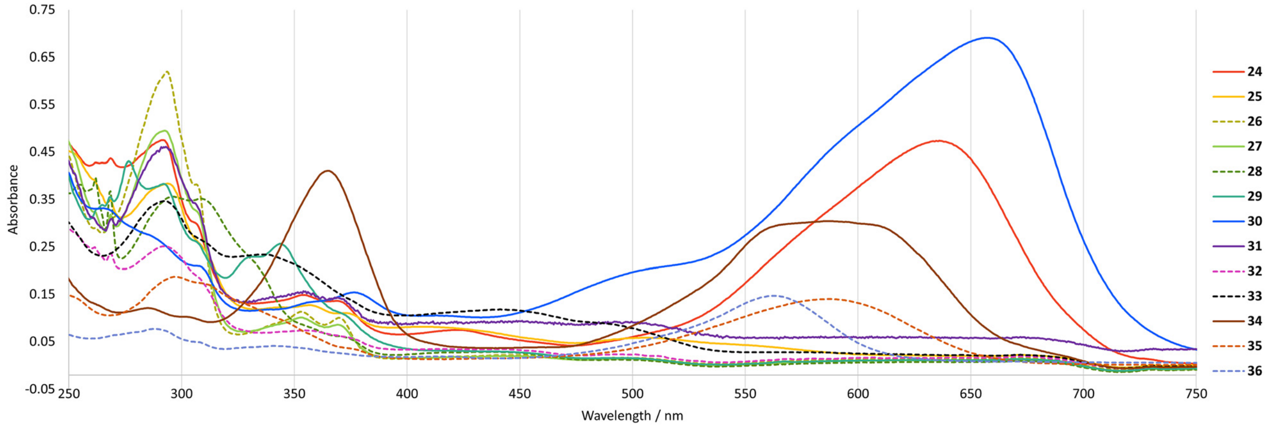


Fig. 7 UV/vis absorption spectra for salts **24–36** (15 μM) in MeCN.

allowed for assignment of each proton and carbon resonance in the structure (Fig. 2).

We next applied the reaction conditions to a selection of (hetero)aromatic aldehydes to synthesise novel salts **25–36**. These were isolated as air-stable crystalline solids in good yields (79–99%), with the exception of **33**, for which the yield was moderate (66%). This lower yield may be attributable to the presence of the highly electron-withdrawing nitro substituent. There are few reports of α-aryl cations in conjugation with nitro groups, but such salts can be isolable when other electron-donating groups are also present.[33] We next sought to characterise the novel salts crystallographically and were able to obtain X-ray structures for **25** (Fig. 3), **26** (Fig. 4), **30** (Fig. 5) and **32** (Fig. 6).

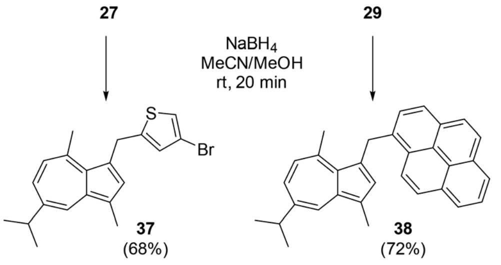
The structure of **25** reveals that in the solid state the π-system is not planar. Rather, the (*Z*)-phenyl substituent is oriented almost perpendicular to the propenyl chain; the $C{=}C{-}C^{ipso}{-}C^{ortho}$ dihedral angle is 85.1(3)°. This is in keeping with the trend observed for all 1,1-diphenylethenes for which X-ray crystallographic data have been reported, *i.e.* there are no examples in which this motif has the two phenyl rings oriented coplanar. Such an orientation would of course lead to the occlusion of the two *ortho*-hydrogen atoms, but it is nevertheless surprising that the deviation from planarity in **25** is as significant as it is.

As per **25**, the structures of **26** and **30** also adopt conformations in the solid state where the π-system exhibits a degree of deviation from planarity (Table 1); the $C^{Az}{-}C^{+}{-}C^{Ar(\alpha)}{-}C^{Ar(\beta)}$ dihedral angle being between 28(1)° and 30(2)° for **26** and between 22.1(6)° and 24.9(6)° for **30**.‡ In both cases, this deviation from planarity can again be explained through occlusion of hydrogen atoms, in this case the phenyl *ortho*-hydrogen and the hydrogen at the azulene 2-position. In contrast, the π-system is close to fully planar for **32**, the $C^{Az}{-}C^{+}{-}C^{Ar(\alpha)}{-}S$ dihedral angle being 3.5(4)°. We suggest such a planar conformation is now more favourable as the sulfur atom lacks a substituent to occlude the azulene 2-position hydrogen.

We next characterised novel salts **24–36** by UV-vis absorption spectroscopy (Fig. 7 and Table 2). The diverse array of colours exhibited by **24–36** is reflected by the variation in absorption maxima that were observed. Notably, the two salts exhibiting the highest extinction coefficients in the visible region were **24** and **30**, which are the two salts bearing the most electron-donating substituents, *i.e.* amino groups. The difference in absorption maxima may be ascribable to the fact that **30** bears an additional conjugated electron-donating substituent, *i.e.* a hydroxyl group.

Table 2 Absorption maxima and extinction coefficients for salts **24–36** in MeCN

Compound	λ_{max}/nm (log ε)
24	640 (4.50), 421 (3.70), 354 (4.00)
25	506 (3.59), 409 (3.74), 357 (3.93)
26	669 (3.02), 447 (3.16), 370 (3.82)
27	676 (2.89), 445 (3.11), 370 (3.76)
28	670 (2.79), 439 (3.28)
29	669 (2.94), 490 (3.01)
30	657 (4.66), 377 (4.01)
31	656 (3.59), 499 (3.79), 355 (4.02)
32	674 (3.10), 492 (3.19), 353 (3.69)
33	672 (3.17), 441 (3.90)
34	586 (4.31), 365 (4.44)
35	587 (3.97), 298 (4.10)
36	563 (3.99), 289 (3.71)



Scheme 4 Reduction of salts **27** and **29**.

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‡ Ranges are given for these dihedral angles since for **26** and **30** the unit cells comprise multiple independent molecules.

We investigated the reduction of salts of type **23** with a hydridic reducing agent. Thus, two representative example salts (**27** and **29**) were treated with sodium borohydride to afford the corresponding methylene compounds **37** and **38** (Scheme 4). In both cases the desired reduction occurred rapidly at room temperature, with the product precipitating from solution in sufficient purity that after filtration, no further purification was necessary. Both **37** and **38** were blue in the solid state, as a consequence of the azulene motif no longer being conjugated to the other aromatic system. We were able to obtain an X-ray structure for **38** (Fig. 8).

The protons on the C4-methyl group of guaiazulene are acidic,[34] and in cations **24–36** they would be expected to be even more acidic due to the presence of the conjugated cation. However, deprotonation at the C4-methyl group of **24–36** would give an azulenoquinone dimethide system **39**, which would be expected to be unstable with respect to self-reaction[35] or other decomposition pathways (Scheme 5a). Of the salts **24–36**, julolidine derivative **30** is unique in possessing an alternative site of deprotonation, namely the hydroxyl group. In this case, deprotonation of **30** would lead to neutral *ortho*-quinone methide **40**, in which aromaticity of the azulene motif is retained (Scheme 5b). In the event treatment of a solution of **30** in CH_2Cl_2 with triethylamine led from a rapid colour change from blue to red, which we ascribe to formation of **40**. The red colour of the solution remained unchanged upon prolonged standing under air, and the halochromic behaviour was shown to be reversible, with addition of trifluoroacetic acid leading to regeneration of the blue colour of **30** (Fig. 9). This process could be repeated multiple times. Azulenes directly conjugated to *para*-quinone methides have been reported,[36] but to our knowledge **40** constitutes the first example of an azulene directly conjugated to an *ortho*-quinone methide.

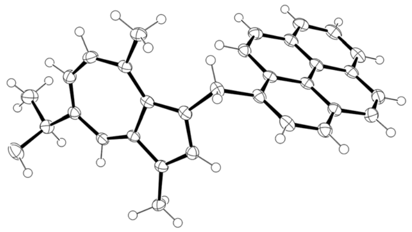
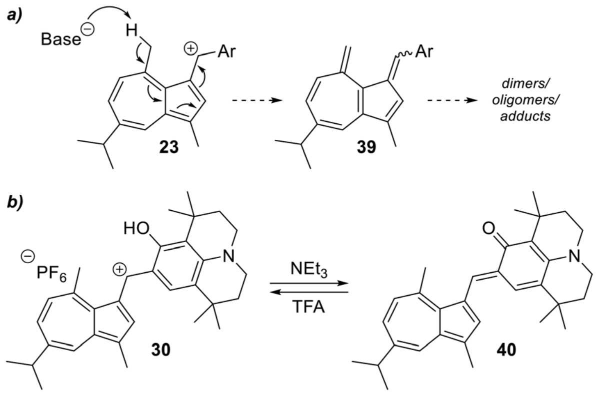


Fig. 8 ORTEP representation of the X-ray structure of **38**. Ellipsoids are shown at 50% probability. Hydrogens are shown as spheres of arbitrary radius. CCDC 2129310.†



Scheme 5 (a) Deprotonation at C4-methyl group leading to **39**, anticipated to be unstable. (b) Deprotonation of **30** at the hydroxyl group, leading to *o*-quinone methide **40**.

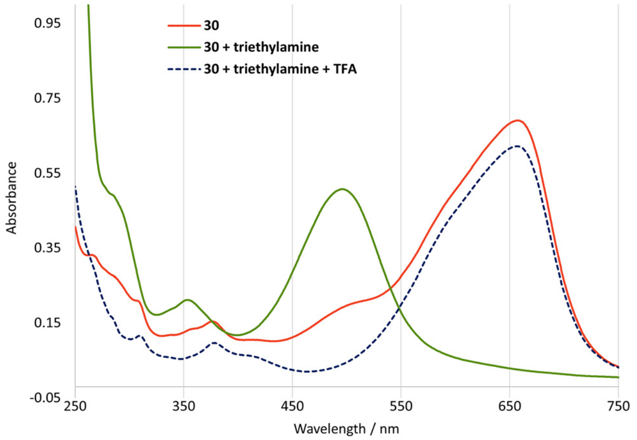


Fig. 9 UV/vis absorption spectra for salts **30** (15 μM) upon treatment with base and subsequent acid in MeCN.

Conclusions

We have reported the synthesis and characterisation of highly conjugated azulene-substituted cations, which are readily isolated as hexafluorophosphate salts. They are stable in the solid state, with no decomposition observed after being stored on the bench >1 year (with no protection from air/light). The cations persist in both protic (MeOH) and aprotic (MeCN, CH_2Cl_2) solvents. The synthesis of these salts requires only one step and employs a cheap, naturally-occurring azulene starting material. Furthermore, salts with high extinction coefficients and different absorption maxima in the visible region (and hence different colours) are accessible by varying the aldehyde starting material. As such salts of the type described here may find applications as low-cost dyestuffs. Salts such as **30**, with an appropriate acidic proton, can display halochromic behaviour as a result of deprotonation to form neutral quinoidal systems, such as **40**. Further studies on salts of this type are ongoing in our laboratory and the results will be reported in due course.

Experimental

Materials and methods

See the ESI† for general details of the materials and methods used.

Synthetic procedures

General procedure A for synthesis of compounds 24–36. To a solution of guaiazulene **22** (100 mg, 0.50 mmol, 1 eq.) in MeOH (2 mL) was added a solution of aldehyde (0.61 mmol, 1.2 eq.) in MeOH (4 mL) containing HPF_6 (55% aqueous solution, 0.12 mL, 2.7 eq.). The reaction mixture was stirred at room temperature under air until the starting material was consumed, as shown by TLC (EtOAc/petrol 1 : 4). The reaction mixture was diluted with diethyl ether (10 mL), then cooled to 0 °C for the specified time. Precipitated material was isolated by filtration, dried under vacuum and then purified as specified.

[4-(Dimethylamino)phenyl]-3-guaiazulenylmethylium hexafluorophosphate 24. *General procedure A* was used with *p*-diaminobenzaldehyde (90 mg); reaction time 1.5 h; cooling time 10 min. Recrystallisation from MeCN/diethyl ether gave **24** as green crystals (113 mg, 47% yield). M.pt 181 °C; ^{1}H-NMR (500 MHz, CD_3CN) δ = 8.72 (s, 1H), 8.49 (d, J = 2.1 Hz, 1H), 8.20 (s, 1H), 8.11 (dd, J = 11.1, 2.1 Hz, 1H), 8.07 (d, J = 11.1 Hz, 1H), 7.95 (d, J = 9.3 Hz, 2H), 6.98 (d, J = 9.3 Hz, 2H), 3.36 (hept, J = 6.9, 1H), 3.28 (s, 3H, 14), 3.26 (s, 6H), 2.59 (d, J = 1.0 Hz, 3H), 1.42 (d, J = 6.8 Hz, 6H) ppm; ^{13}C-NMR (126 MHz, CD_3CN) δ = 161.3, 156.7, 154.3, 153.7, 153.1, 149.8, 143.6, 142.0, 142.1, 139.8, 139.4, 138.5, 124.8, 114.9, 41.0, 39.4, 30.0, 24.0, 13.4 ppm. NMR data in agreement with those previously reported for the tetrafluoroborate salt.[23f]

(2,2-Diphenylethenyl)-3-guaiazulenylmethylium hexafluorophosphate 25. *General procedure A* was used with β-phenylcinnamaldehyde (126 mg); reaction time 3 h; cooling time 10 min. Recrystallisation from MeCN/diethyl ether gave **25** as red crystals (244 mg, 90% yield). M.pt 199 °C; ^{1}H-NMR (500 MHz, CD_3CN) δ = 8.56 (s, 1H), 8.34–8.26 (m, 4H), 7.92 (d, J = 12.0 Hz, 1H), 7.65–7.47 (m, 8H), 7.43–7.39 (m, 2H), 3.45 (hept, J = 6.9 Hz, 1H), 2.86 (s, 3H), 2.56 (s, 3H), 1.43 (d, J = 6.8 Hz, 6H) ppm; ^{13}C-NMR (126 MHz, CD_3CN) δ = 169.4, 163.5, 160.3, 156.6, 152.4, 149.4, 148.1, 144.4, 143.9, 141.3, 140.1, 139.8, 139.5, 139.0, 132.3, 131.9, 131.0, 130.6, 129.9, 129.7, 126.6, 40.1, 28.8, 23.8, 13.9 ppm. IR $\nu_{\max}$ 2967, 1553, 1397, 1339, 1295, 1255, 1210, 1109, 1046, 985, 825, 780, 705, 596, 555 cm^{-1}. HRMS (ESI$^+$): calc. for $C_{30}H_{29}$ $[M]^+$ 389.2264, found 389.2264.

(4-Bromophenyl)-3-guaiazulenylmethylium hexafluorophosphate 26. *General procedure A* was used with 4-bromobenzaldehyde (112 mg); reaction time 4 h; cooling time 10 min. **26** was obtained as orange crystals (219 mg, 85% yield); no further purification was necessary. M.pt 173 °C; ^{1}H-NMR (500 MHz, CD_3CN) δ = 8.69 (s, 1H), 8.59 (d, J = 2.2 Hz, 1H), 8.56 (d, J = 11.3 Hz, 1H), 8.45 (dd, J = 11.3, 2.2 Hz, 1H), 7.93 (s, 1H, 7), 7.80–7.77 (m, 2H), 7.72–7.69 (m, 2H), 3.51 (hept, J = 6.9 Hz, 1H), 3.36 (s, 3H), 2.51 (s, 3H), 1.46 (d, J = 6.9 Hz, 6H) ppm; ^{13}C-NMR (126 MHz, CD_3CN) δ = 172.6, 162.0, 158.4, 153.8, 151.3, 148.8, 146.8, 145.4, 141.0, 140.1, 135.6, 135.1, 133.5, 127.3, 40.4, 29.7, 23.8, 13.9 ppm. One aromatic carbon was not observed. IR $\nu_{\max}$ 2974, 1573, 1552, 1454, 1403, 1344, 1313, 1195, 1071, 1047, 1005, 983, 826, 743, 662, 635, 555, 502 cm^{-1}. HRMS (ESI$^+$): calc. for $C_{22}H_{22}{}^{79}Br$ $[M]^+$ 365.0900, found 365.0901.

(4-Bromothiophen-2-yl)-3-guaiazulenylmethylium hexafluorophosphate 27. *General procedure A* was used with 4-bromo-2-thiophenecarboxaldehyde (116 mg); reaction time 4 h; cooling time 10 min. **27** was obtained as orange crystals (246 mg, 93% yield); no further purification was necessary. M. pt 178 °C; ^{1}H-NMR (500 MHz, CD_3CN) δ = 8.63 (s, 1H), 8.57 (d, J = 2.2 Hz, 1H), 8.49 (d, J = 11.2 Hz), 8.40 (dd, J = 11.2, 2.2 Hz, 1H), 8.16 (br s, 1H), 8.01–8.00 (m, 1H), 7.85 (br s, 1H), 3.49 (hept, J = 6.8 Hz, 1H), 3.32 (s, 3H), 2.56 (s, 3H), 1.45 (d, J = 6.8 Hz, 6H) ppm; ^{13}C-NMR (126 MHz, CD_3CN) δ = 171.4, 160.8, 157.7, 154.0, 150.7, 146.7, 145.2, 142.2, 141.3, 140.2, 139.1, 137.7, 136.1, 113.6, 40.2, 29.7, 23.8, 14.0 ppm. One aromatic carbon was not observed. IR $\nu_{\max}$ 3115, 2963, 1568, 1398, 1344, 1294, 1168, 1118, 1045, 825, 742, 585, 555 cm^{-1}. HRMS (ESI$^+$): calc. for $C_{20}H_{20}{}^{81}BrS$ $[M]^+$ 373.0444, found 373.0445.

3-Guaiazulenyl-(5-(phenylethynyl)thiophen-2-yl)methylium hexafluorophosphate 28. *General procedure A* was used with 5-(2-phenyleth-1-ynyl)thiophene-2-carbaldehyde (116 mg); reaction time 4 h; cooling time 10 min. Recrystallisation from MeCN/diethyl ether gave **28** as dark green lustrous crystals in two batches (148 mg and 87 mg; 86% total yield). M.pt 198 °C; ^{1}H-NMR (500 MHz, CD_3CN) δ = 8.74 (s, 1H), 8.57 (d, J = 2.2 Hz, 1H), 8.43 (d, J = 11.2 Hz, 1H), 8.36 (dd, J = 11.2, 2.2 Hz, 1H), 8.21 (br s, 1H), 7.91 (d, J = 4.2 Hz, 1H), 7.61–7.59 (m, 2H), 7.50 (d, J = 4.2 Hz, 1H), 7.50–7.45 (m, 3H), 3.47 (hept, J = 6.9 Hz, 1H), 3.34 (s, 3H), 2.58 (s, 3H), 1.45 (d, J = 6.9 Hz, 6H) ppm; ^{13}C-NMR (126 MHz, CD_3CN) δ = 170.1, 160.0, 157.3, 153.7, 149.8, 146.1, 144.8, 143.4, 141.6, 140.2, 140.1, 139.2, 136.7, 136.4, 135.2, 132.6, 131.1, 130.0, 122.4, 101.8, 83.1, 40.1, 29.8, 23.8, 14.0 ppm. IR $\nu_{\max}$ 2965, 2198, 1980, 1601, 1565, 1400, 1377, 1343, 1175, 1101, 1042, 837, 822, 806, 747, 688, 665, 551, 517 cm^{-1}. HRMS (ESI$^+$): calc. for $C_{28}H_{25}S$ $[M]^+$ 393.1672, found 393.1672.

3-Guaiazulenyl-(1-pyrenyl)methylium hexafluorophosphate 29. *General procedure A* was used with pyrene-1-carbaldehyde (139 mg); reaction time 4 h; cooling time 10 min. Recrystallisation from MeCN/diethyl ether gave **29** as burgundy crystals (279 mg, 99% yield). M.pt 187 °C; ^{1}H-NMR (500 MHz, CD_3CN) δ = 9.65 (s, 1H), 8.55–8.49 (m, 3H), 8.44–8.37 (m, 5H), 8.33–8.30 (m, 2H), 8.24 (d, J = 8.9 Hz, 1H), 8.16 (app t, J = 7.7 Hz, 1H), 7.89 (s, 1H), 3.51 (hept, J = 6.9 Hz, 1H), 3.48 (s, 3H), 2.48 (s, 3H), 1.49 (d, J = 6.9 Hz, 6H) ppm; ^{13}C-NMR (126 MHz, CD_3CN) δ = 171.7, 161.2, 157.9, 150.5, 148.3, 146.2, 145.0, 142.6, 141.5, 139.8, 135.2, 132.7, 132.2, 131.7, 131.5, 131.0, 130.7, 128.40, 128.36, 128.20, 128.17, 126.5, 125.4, 124.6, 40.3, 29.9, 23.8, 13.9 ppm. IR $\nu_{\max}$ 2972, 1560, 1532, 1431, 1387, 1340, 1318, 1258, 1235, 1208, 1113, 1043, 829, 718, 681, 658, 629, 598, 556 cm^{-1}. HRMS (ESI$^+$): calc. for $C_{32}H_{27}$ $[M]^+$ 411.2108, found 411.2112.

3-Guaiazulenyl-(8-hydroxy-1,1,7,7-tetramethyl-2,3,6,7-tetrahydro-1*H*,5*H*-pyrido[3,2,1-*ij*]quinolin-9-yl)methylium hexafluorophosphate 30. *General procedure A* was used with 8-hydroxy-1,1,7,7-tetramethyljulolidine-9-carboxaldehyde (165 mg); reaction time 4 h; cooling time 10 min. **30** was obtained as lustrous green-gold crystals (262 mg, 87% yield); no further purification was necessary. M.pt 170 °C; ^{1}H-NMR (500 MHz, CD_3CN) δ = 8.82 (s, 1H), 8.40 (d, J = 2.2 Hz, 1H), 7.91 (s, 1H), 7.88 (dd, J = 10.9, 2.2 Hz, 1H), 7.72 (d, J = 10.9 Hz, 1H), 7.64 (br s, 1H), 7.61 (s, 1H), 3.65–3.62 (m, 2H), 3.55–3.53 (m, 2H), 3.27 (hept, J = 6.9 Hz, 1H), 3.17 (s, 3H), 2.61 (s, 3H), 1.84–1.79 (m, 4H), 1.46 (s, 6H), 1.40 (d, J = 6.9 Hz, 6H), 1.29 (s, 6H) ppm; ^{13}C-NMR (126 MHz, CD_3CN) δ = 160.9, 155.3, 154.3, 151.8, 148.6, 145.3, 145.0, 142.3, 140.3, 138.1, 137.5, 134.5, 132.8, 131.5, 127.7, 119.8, 118.0, 50.0, 49.1, 39.1, 38.6, 35.0, 32.9, 32.7, 29.7, 28.8, 27.9, 24.3, 13.3 ppm. IR ν_{max} 3574, 2957, 1611, 1528, 1500, 1462, 1312, 1257, 1089, 1046, 904, 824, 777, 648, 592, 554 cm^{-1}. HRMS (ESI$^+$): calc. for $C_{32}H_{40}NO$ $[M]^+$ 454.3105, found 454.3107.

(3-Bromothiophen-2-yl)-3-guaiazulenylmethylium hexafluorophosphate 31. *General procedure A* was used with 3-bromothiophene-2-carboxaldehyde (116 mg); reaction time 4 h; cooling time 10 min. **31** was obtained as burgundy crystals (235 mg, 90% yield); no further purification was necessary. M.pt 169 °C; ^{1}H-NMR (500 MHz, CD_3CN) δ = 8.83 (s, 1H), 8.59 (d, J = 2.2 Hz, 1H), 8.51 (d, J = 11.2 Hz, 1H,), 8.41 (dd, J = 11.2, 2.2 Hz, 1H), 8.23 (s, 1H), 8.16 (d, J = 5.4 Hz, 1H), 7.41 (d, J = 5.4 Hz, 1H), 3.49 (hept, J = 6.9 Hz, 1H), 3.39 (s, 3H), 2.57 (s, 3H), 1.46 (d, J = 6.9 Hz, 6H) ppm. ^{13}C-NMR (126 MHz, CD_3CN) δ = 171.1, 160.5, 157.3, 154.2, 150.6, 146.9, 145.1, 140.3, 139.7, 138.6, 138.3, 137.1, 135.1, 133.6, 127.3, 40.2, 29.8, 23.8, 14.1 ppm. IR ν_{max} 3121, 2967, 1599, 1563, 1447, 1398, 1377, 1296, 1211, 1158, 1103, 1042, 979, 819, 738, 659, 608, 554 cm^{-1}. HRMS (ESI$^+$): calc. for $C_{20}H_{20}{}^{81}BrS$ $[M]^+$ 373.0444, found 373.0443.

(Benzothiophen-2-yl)-3-guaiazulenylmethylium hexafluorophosphate 32. *General procedure A* was used with benzothiophene-2-carboxaldehyde (98 mg); reaction time 4 h; cooling time 10 min. **32** was obtained as red crystals (238 mg, 97% yield); no further purification was necessary. M.pt 192 °C; ^{1}H-NMR (500 MHz, CD_3CN) δ = 8.80 (s, 1H), 8.52 (d, J = 2.2 Hz, 1H), 8.43 (d, J = 11.2 Hz, 1H), 8.36 (dd, J = 11.2, 2.2 Hz, 1H), 8.23 (s, 1H), 8.19 (s, 1H), 7.92 (d, J = 7.4 Hz, 1H), 7.91 (d, J = 8.2 Hz, 1H), 7.47–7.44 (m, 1H), 7.37 (app t, J = 7.6 Hz, 1H), 3.48 (hept, J = 6.9 Hz, 1H), 3.33 (s, 3H), 2.57 (s, 3H), 1.47 (d, J = 6.9 Hz, 6H) ppm. ^{13}C-NMR (126 MHz, CD_3CN) δ = 170.8, 160.4, 157.6, 153.6, 150.3, 146.2, 145.6, 145.0, 141.5, 141.2, 140.2, 140.0, 139.6, 139.3, 137.8, 130.1, 127.3, 127.1, 123.7, 40.2, 29.8, 23.8, 14.1 ppm. IR ν_{max} 2972, 1605, 1568, 1494, 1308, 1342, 1299, 1173, 1160, 1120, 1042, 825, 765, 658, 556 cm^{-1}. HRMS (ESI$^+$): calc. for $C_{24}H_{23}S$ $[M]^+$ 343.1515, found 343.1517.

3-Guaiazulenyl-(5-nitrothiophen-2-yl)methylium hexafluorophosphate 33. *General procedure A* was used with 5-nitrothiophene-2-carboxaldehyde (95 mg); reaction time 4 h; cooling time 10 min. **33** was obtained as burgundy crystals (162 mg, 66% yield); no further purification was necessary. M.pt 189 °C; ^{1}H-NMR (500 MHz, CD_3CN) δ = 8.59 (s, 1H), 8.57 (d, J = 11.2 Hz, 1H), 8.46 (dd, J = 11.2, 2.2 Hz, 1H), 8.15–8.11 (m, 1H), 8.07 (d, J = 4.4 Hz, 1H), 7.80 (dd, J = 4.4, 0.9 Hz, 1H), 3.51 (hept, J = 6.9 Hz, 1H), 3.34 (s, 3H), 2.57 (s, 3H), 1.46 (d, J = 6.8 Hz, 6H) ppm. ^{13}C-NMR (126 MHz, CD_3CN) δ = 173.7, 162.1, 158.6, 154.3, 152.1, 149.0, 145.9, 144.8, 140.9, 140.5, 138.7, 138.4, 137.9, 130.6, 40.5, 29.6, 23.7, 14.1 ppm. One aromatic carbon was not observed. IR ν_{max} 3105, 2980, 1605, 1574, 1522, 1494, 1455, 1419, 1404, 1334, 1319, 1250, 1200, 1109, 1048, 985, 814, 730, 653, 523, 555 cm^{-1}. HRMS (ESI$^+$): calc. for $C_{20}H_{20}NO_2S$ $[M]^+$ 338.1210, found 338.1210.

3-Guaiazulenyl-(5-cyanothiophen-2-yl)methylium hexafluorophosphate 34. *General procedure A* was used with 5-cyanothiophene-2-carboxaldehyde (83 mg); reaction time 4 h; cooling time 10 min. **34** was obtained as orange-red crystals (185 mg, 79% yield); no further purification was necessary. M.pt 194 °C; ^{1}H-NMR (500 MHz, CD_3CN) δ = 8.66 (s, 1H), 8.59 (d, J = 2.2 Hz, 1H), 8.55 (d, J = 11.2 Hz, 1H), 8.44 (dd, J = 11.2, 2.2 Hz, 1H), 8.11 (s, 1H), 7.89 (d, J = 4.1 Hz, 1H), 7.86 (d, J = 4.1 Hz, 1H), 3.50 (hept, J = 6.6 Hz, 1H), 3.33 (s, 3H), 2.56 (s, 3H), 1.46 (d, J = 6.9 Hz, 6H) ppm. ^{13}C-NMR (126 MHz, CD_3CN) δ = 173.1, 161.8, 158.4, 154.3, 151.7, 148.4, 145.7, 145.6, 140.4, 140.1, 140.0, 139.4, 138.6, 137.7, 114.2, 40.4, 29.7, 23.7, 14.1 ppm. One aromatic carbon was not observed. IR ν_{max} 3640, 3570, 3084, 2962, 2286, 2165, 1626, 1548, 1517, 1417, 1362, 1330, 1197, 1022, 811, 750, 669, 558 cm^{-1}. HRMS (ESI$^+$): calc. for $C_{21}H_{20}NS$ $[M]^+$ 318.1311, found 318.1312.

3-Guaiazulenyl-((2,2′-bithiophen)-5-yl)methylium hexafluorophosphate 35. *General procedure A* was used with 5-cyanothiophene-2-carboxaldehyde (116 mg); reaction time 3 h; cooling time 10 min. **35** was obtained as dark green powder (247 mg, 95% yield); no further purification was necessary. M.pt 194–196 °C; ^{1}H-NMR (500 MHz, CD_3CN) δ = 8.80 (1H, s), 8.56 (1H, d, J = 2.2 Hz), 8.37 (1H, d, J = 11.2 Hz), 8.32 (1H, dd, J = 11.2, 2.2 Hz), 8.31 (1H, br s), 7.93 (1H, d, J = 4.2 Hz), 7.65–7.62 (2H, m), 7.52 (1H, d, J = 4.1 Hz), 7.21 (1H, dd, J = 5.0, 3.7 Hz), 3.45 (1H, hept, J = 6.9 Hz), 3.34 (3H, s), 2.60 (3H, s), 1.45 (6H, d, J = 6.9 Hz) ppm. ^{13}C-NMR (126 MHz, CD_3CN) δ = 168.1, 158.5, 156.4, 152.7, 152.6, 148.6, 146.0, 144.5, 144.2, 141.1, 139.6, 139.3, 139.0, 136.3, 134.7, 130.7, 130.2, 128.7, 126.8, 39.9, 29.8, 23.9, 14.0 ppm. IR ν_{max} 3129, 2967, 1376, 1497, 1223, 1040, 734, 611 cm^{-1}. HRMS (ESI$^+$): calc. for $C_{24}H_{23}S_2$ $[M]^+$ 375.1236, found 375.1241.

3-Guaiazulenyl-(*N*-methylpyrrol-2-yl)methylium hexafluorophosphate 36. *General procedure A* was used with *N*-methylpyrrole-2-carboxaldehyde (65 mg); reaction time 3 h; cooling time 10 min. **36** was obtained as dark purple crystals (218 mg, 94% yield); no further purification was necessary. M.pt 168–171 °C; ^{1}H-NMR (500 MHz, CD_3CN) δ = 8.60 (1H, s), 8.53 (1H, s), 8.27 (1H, br s), 8.19 (2H, br s), 7.61 (1H, d, J = 4.5 Hz), 7.55 (1H, br s), 6.65 (1H, ddd, J = 4.5, 2.2, 0.9 Hz), 3.92 (3H, s), 3.40 (1H, hept, J = 6.9 Hz), 3.33 (3H, s), 2.59 (3H, s), 1.43 (6H, d, J = 6.9 Hz) ppm. ^{13}C-NMR (126 MHz, CD_3CN) δ = 163.6, 154.5, 151.2, 145.4, 142.8, 141.4, 140.8, 139.9, 139.1, 136.5, 136.4, 133.9, 130.8, 127.1, 117.1, 39.6, 35.6, 29.8, 24.0, 13.6 ppm. IR ν_{max} 3129, 2967, 1583, 1377, 1225, 1041, 828, 651 cm^{-1}. HRMS (ESI$^+$): calc. for $C_{21}H_{24}N$ $[M]^+$ 290.1903, found 290.1896.

General procedure B for synthesis of compounds 37–38. To a solution of the relevant guaiazulenyl carbocation (0.008 mmol, 1 eq.) in MeCN (2.0 mL) was added a solution of $NaBH_4$ (7 mg, 0.17 mmol, 2.1 eq.) in EtOH (2 mL). The mixture was stirred at room temperature under air until the starting material was consumed, as shown by TLC (EtOAc/petrol 1 : 4), approximately 20 min. Precipitation of solid was observed, which was isolated by filtration, then dried under vacuum to afford the desired product; no further purification was necessary.

4-Bromo-2-((5-isopropyl-3,8-dimethylazulen-1-yl)methyl)thiophene 37. *General procedure B* was used with cation **27**. Product **37** was obtained as a navy blue solid (21 mg, 68% yield). M.pt 104 °C; ^{1}H-NMR (500 MHz, $CDCl_3$) δ = 8.12 (d, J = 2.1 Hz, 1H), 7.47 (s, 1H), 7.30 (dd, J = 10.8, 2.1 Hz, 1H, 6), 7.01 (d, J = 1.4 Hz, 1H), 6.86 (d, J = 10.7 Hz, 1H), 6.51 (d, J = 1.3 Hz, 1H), 4.67 (s, 2H), 3.04 (hept, J = 6.9 Hz, 1H), 2.87 (s, 3H), 2.62 (s, 3H), 1.35 (d, J = 6.9 Hz, 6H) ppm. ^{13}C-NMR (126 MHz, $CDCl_3$) δ = 149.2, 145.3, 140.7, 139.7, 138.1, 135.1, 133.9, 132.9, 126.95, 126.93, 124.5, 123.8, 121.0, 109.3, 37.9, 31.9, 26.7, 24.7, 13.0 ppm. IR ν_{max} 3084, 2962, 1626, 1548, 1517, 1417, 1362, 1330, 1197, 1022, 811, 750, 667, 558 cm^{-1}. HRMS (ESI$^+$): calc. for $C_{20}H_{21}{}^{81}BrS$ [M + H]$^+$ 375.0600, found 375.0593.

1-((5-Iso-propyl-3,8-dimethylazulen-1-yl)methyl)pyrene 38. *General procedure B* was used with cation **29**. Product **38** was obtained as a light blue solid (27 mg, 72% yield). M.pt 149 °C; ^{1}H-NMR (500 MHz, $CDCl_3$) δ = 8.36 (d, J = 9.2 Hz, 1H), 8.18 (d, J = 7.6 Hz, 2H), 8.12 (d, J = 2.2 Hz, 1H), 8.11 (d, J = 9.2 Hz, 1H), 8.04 (d, J = 7.7 Hz, 1H), 8.03 (s, 2H), 8.00 (app t, J = 7.6 Hz, 1H), 7.55 (d, J = 8.0 Hz, 1H), 7.30 (dd, J = 10.8, 2.2 Hz, 1H), 7.19 (s, 1H), 6.85 (d, J = 10.7 Hz, 1H), 5.36 (s, 2H), 3.05 (hept, J = 7.0 Hz, 1H), 2.92 (s, 3H), 2.54 (s, 3H), 1.54 (s, 2H), 1.37 (d, J = 6.8 Hz, 6H); ppm. ^{13}C-NMR (126 MHz, $CDCl_3$) δ = 145.8, 141.0, 139.1, 137.9, 136.9, 135.1, 133.7, 133.5, 131.6, 131.1, 129.9, 128.7, 127.75, 127.74, 127.6, 126.8, 126.5, 126.0, 125.8, 125.14, 125.13, 125.10, 125.08, 124.96, 124.5, 123.7, 37.9, 35.4, 26.9, 24.8, 13.0 ppm. IR ν_{max} 3035, 2952, 2859, 1588, 1547, 1517, 1444, 1312, 1244, 1181, 1098, 1055, 1003, 774, 843, 753, 706, 690, 644 cm^{-1}. HRMS (ESI$^+$): calc. for $C_{32}H_{28}$ [M + H]$^+$ 413.2264, found 413.2250.

Author contributions

SEL conceived the project and acquired funding; CH, JLH and LCM carried out synthesis and spectroscopic characterisation. GKK acquired and interpreted X-ray crystallographic data. SEL wrote the manuscript with input from all authors.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

We thank EPSRC for IAA funding (EP/R51164X/1) and for DTG PhD studentships to L. C. M. and J. L. H. The authors acknowledge the Material and Chemical Characterisation Facility (MC^2) at University of Bath (https://doi.org/10.15125/mx6j-3r54).

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