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The synthesis and reaction network of 2-styryl-1-benzopyrylium salts: An unexploited class of potential colorants

Raquel Gomes, Ana M. Diniz, Alexandre Jesus, A. Jorge Parola, Fernando Pina*

REQUIMTE, Departamento de Química, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, 2829-516 Caparica, Portugal

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ABSTRACT

The syntheses, thermodynamic and kinetic properties of a series of 2-styryl-1-benzopyrylium compounds are reported. This family of compounds was found to follow the same pH- and light-dependent network of chemical reactions previously described for flavylium (2-phenyl-1-benzopyrylim) compounds. However, 2-styryl-1-benzopyrylium compounds exhibit absorption spectra substantially red shifted when compared with flavylium analogues (up to 90 nm). In particular, a photochromic system switching from yellow to light blue based on derivatives of natural anthocyanins is for the first time documented.

1. Introduction

Anthocyanins, the ubiquitous compounds responsible for most of the red and blue colors of flowers and fruits, have long been used as natural food colorants [1] after recognition of undesired physiological effects of easily synthesized azo dyes. Synthetic flavylium salts, possessing the same basic structure and identical network of chemical reactions as anthocyanins, are a versatile family of compounds. Their color and physical–chemical properties have been widely studied and are greatly dependent on the nature and position of the functional groups attached to the 2-phenyl-1-benzopyrylium skeleton [2].

After the work of Dubois, Brouillard and McClelland, the network of pH dependent chemical species arising from the benzopyrylium core was firmly established, see Scheme 1 [3–5].

Taking into account Scheme 1, in acidic media, the flavylium cation, AH^+, is the thermodynamically stable species, i.e., the dominant species. When the pH is increased, other species are formed: the quinoidal base A, which is generally a transient species formed immediately upon deprotonation of the phenol group (when present), the hemiketal B, through hydration in position 2 or 4 (usually B4 can be neglected) of the flavylium cation. On the other hand, the tautomerization of B2 leads to the formation of the *cis*-chalcone Cc, through a ring opening process, and finally, the *cis–trans* isomerisation results in the formation of the *trans*-chalcone Ct. The molar fraction distribution of all the species depends on the functional groups, as well as on the kinetics of the reactions. It is very common that at neutral or basic pH values the *trans*-chalcones are the most stable species. In some cases, as for example in 7-hydroxy-substituted flavylium salts, the *cis–trans* isomerisation barrier is small and photochromic systems are available upon irradiation of the Ct species leading to Cc that spontaneously evolves to AH^+, as shown in Scheme 1. The low kinetic barrier allows the system to revert back to the initial Ct species. In other cases, as for example in 4′-hydroxyflavylium, the *cis–trans* isomerisation barrier is very high and the AH^+ species or A (depending on the pH) are formed after irradiation and do not revert easily back to Ct. In this last case, the system can be viewed as a model for optical memories, capable of *read–write–erase* cycling [6–10].

In recent years, we have developed very efficient photochromic systems using 2-hydroxychalcones in the presence of micelles [11,12] or Pluronic gels [13], even when there is photochemical inertness in water. In particular, in the case of flavylium compounds, it is easy to obtain photochromic systems switching from colorless (or yellow) to yellow (or red), but the formation of blue or green colors by irradiation has shown to be a more difficult task.

Structurally related to flavylium compounds, and suggested as potential color additives for fruit drinks and juices [14] are 2-styryl-1-benzopyrylium salts that have the same basic skeleton with an extra double bond linking the benzopyrylium and the phenyl systems, see Scheme 2. The introduction of this double bond leads to an extended conjugation that might have profound effects in the

* Corresponding author. Tel.: +351 212 948 355; fax: +351 212 948 550.
E-mail address: fjp@dq.fct.unl.pt (F. Pina).

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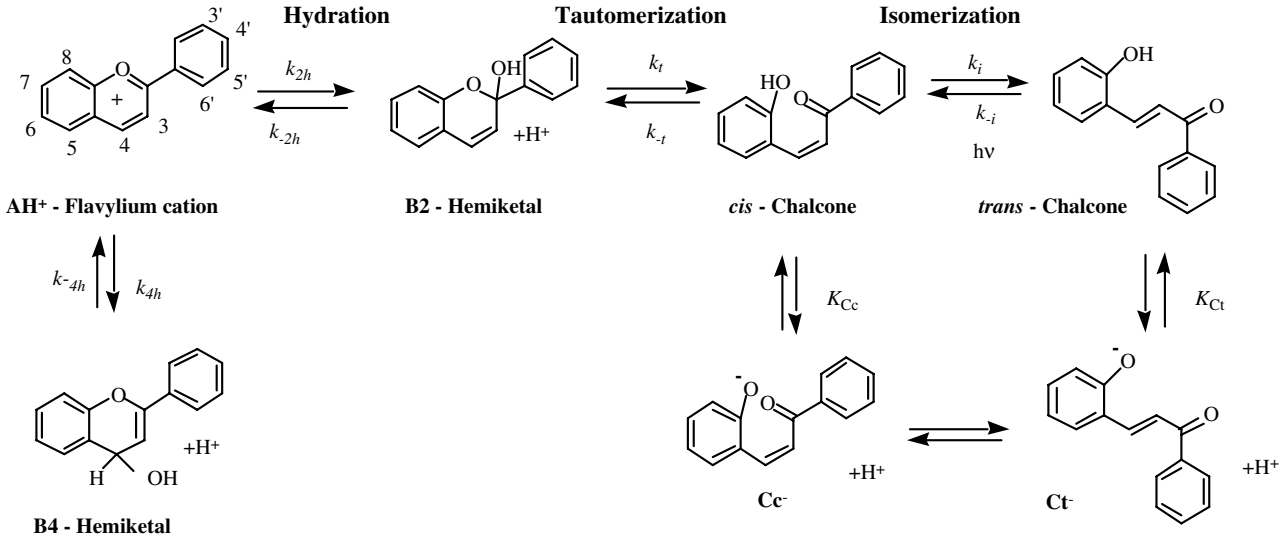


Scheme 1.

color and reaction network; particularly, it shifts the absorption maxima to the red, which allows obtaining darker and stronger tonalities [15].

On the other hand, it is documented in the literature that the pK_a of these pyrylium salts increases with the introduction of the double bond in the basic skeleton of anthocyanins (which retards the loss of color to higher pH values), attesting its usefulness as food colorants [15,16]. The introduction of this extra double bond also offers the possibility of having an extra isomerisation that would increase the number of available states in multistate/multifunctional systems based on 2-styryl-1-benzopyrylium salts. To our knowledge, no extensive study of this kind of compounds is reported in the literature, with the exception of the work by Amic et al. on 7-hydroxy-2-(4-methoxystyryl)-1-benzopyrylium [16].

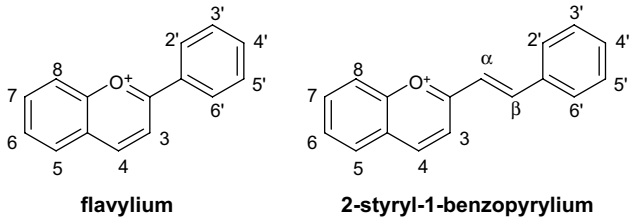
The synthesis of 2-styryl-1-benzopyrylium salts was reported in ancient literature [17], and mainly two methods were described: acidification of the corresponding distyryl ketones and condensation of a salicylaldehyde with a styrylmethylketone in acidic media (see Fig. 1). Styrylmethylketones can be synthesized with various functional groups [18].

In this work, we have performed the syntheses of a series of 2-styryl-1-benzopyrylium salts through acidic condensation, and carried out thermodynamic and kinetic studies on three of them, identifying the nature and pH range of the species involved. We have also briefly explored the use of this relatively unexploited family of compounds as photochromic systems.

2. Experimental

2.1. General procedure for synthesis

All reagents and solvents used were of analytical grade. ^{1}H NMR spectra were run on a Bruker AMX 400 instrument operating at 400.13 MHz. Mass spectra were run on Micromass GCT apparatus for EI and FD ionization and on an Applied Biosystems Voyager-DE™ PRO for MALDI. Elemental analyses were obtained on a Thermofinnigan Flash EA 1112 Series instrument.



Scheme 2.

2.2. Synthesis of styrylmethylketones

Styrylmethylketones were prepared according to the method described by Buck and Heilbron [19].

2.2.1. Synthesis of p-hydroxystyrylmethylketone

p-Hydroxybenzaldehyde (4.00 g, 33 mmol) was dissolved in 15 ml of acetone and the solution treated with 5.3 ml of 50% NaOH (2 mol NaOH). Ten millilitres of water were then added and the mixture was gently warmed for a few moments and left overnight. By the following day, the whole had solidified to a mass, which was dissolved in water and acidified with HCl 6 M until a yellow oil was observed. In an ice bath, the oil crystallized into a golden-yellow solid (4.55 g, 28 mmol) that was filtered off and dried. Yield 84.0%. ^{1}H NMR ($CDCl_3$, 400.13 MHz) δ (ppm): 7.51–7.45 (3H, m), 6.88 (2H, d, ArH, $^3J = 8.6$ Hz), 6.61 (1H, d, $^3J = 16.2$ Hz), 6.05 (1H, br s, OH), 2.38 (3H, s).

2.2.2. Synthesis of o-hydroxystyrylmethylketone

Salicylaldehyde (7.5 ml, 71 mmol) was dissolved in 30 ml of acetone and the solution treated with 10.5 ml of 50% NaOH. Twenty millilitres of water were then added and the mixture was left in an ultrasound cleaner bath for approximately 20 min at 60 °C. After that, the whole had solidified to a mass that was re-dissolved in water and treated with HCl 6 M. In an ice bath, the oil that had appeared crystallized into a yellow solid that was filtered off and dried. This solid was recrystallized from a solvent mixture ethanol/water (5.47 g, 34 mmol). Yield 47.5%. ^{1}H NMR ($CDCl_3$, 400.13 MHz) δ (ppm): 7.87 (1H, d, $^3J = 16.4$ Hz), 7.66 (1H, br s), 7.47 (1H, dd, $^3J = 7.9$ Hz, $^4J = 1.3$ Hz), 7.26 (1H, ddd, $^3J = 7.7$ Hz, $^4J = 1.6$ Hz), 7.02 (1H, d, $^3J = 16.4$ Hz), 6.93–6.90 (2H, m), 2.43 (3H, s).

2.2.3. Synthesis of p-dimethylstyrylmethylketone

p-Dimethylaminobenzaldehyde (10.48 g, 70 mmol) was dissolved in 30 ml of acetone and the solution treated with 10 ml of 50% NaOH. Twenty millilitres of water were then added and the mixture was left heated overnight at approximately 50 °C. By the following day, the reaction mixture was neutralized with HCl, 6 M, and the orange solid that precipitated out was filtered off, washed

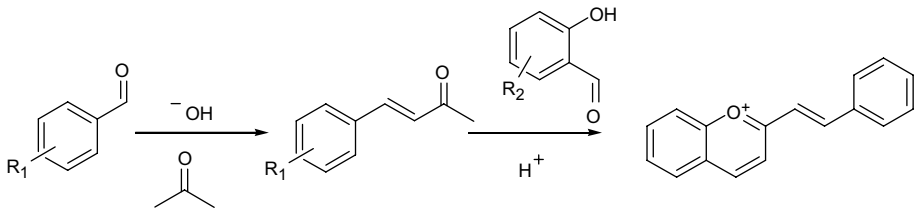


Fig. 1. Generic synthesis of 2-styryl-1-benzopyrylium salts based on the condensation of 2-hydroxychalcones and styrylmethylketones.

with diethyl ether and dried (11.62 g, 61 mmol). Yield 87.5%. ^{1}H NMR ($CDCl_3$, 400.13 MHz) δ (ppm): 7.50–7.43 (3H, m), 6.68 (2H, d, $^3J = 8.9$ Hz), 6.54 (1H, d, $^3J = 16.1$ Hz), 3.03 (6H, s), 2.34 (3H, s).

2.3. Synthesis of 2-styryl-1-benzopyrylium salts

These salts were prepared according to a procedure adapted either from Katritzky [20] or Robinson [21], both frequently used in the synthesis of 2-phenyl-1-benzopyrylium salts.

2.3.1. Synthesis of 2-styryl-1-benzopyrylium tetrafluoroborate

Salicylaldehyde (1.0 ml, 9.4 mmol) and benzalacetone (1.36 g, 9.3 mmol) were dissolved in 10 ml of acetic acid and 2 ml of HBF_4 [20]. Ten millilitres of acetic anhydride were then added dropwise and the temperature of the reaction mixture reached 75 °C. The reaction mixture was stirred overnight. By the following day, 5 ml of ethyl acetate were added and the brown precipitated solid was filtered off, washed with diethyl ether and dried (0.69 g, 2.2 mmol). Yield: 23.7%. ^{1}H NMR (D_2O/DCl, pD ≈ 1.0, AH^+ species, 400.13 MHz) δ (ppm): 8.79 (1H, d, $^3J = 8.6$ Hz), 8.18 (1H, d, $^3J = 15.9$ Hz), 7.86 (1H, t, $^3J = 7.5$ Hz), 7.75–7.81 (3H, m), 7.51 (1H, t, $^3J = 7.5$ Hz), 7.47 (2H, br d, $^3J = 7.2$ Hz), 7.27 (1H, d, $^3J = 15.9$ Hz), 7.06–7.12 (3H, m). FD MS: m/z (%): 233.096 $[M]^+$ (100), 250.099 $[M + OH]^+$ (45). EA calcd for $C_{17}H_{13}BF_4O$: C 63.79, H 4.09; found: C 63.51, H 4.45.

2.3.2. Synthesis of 2-(2-hydroxystyryl)-1-benzopyrylium tetrafluoroborate

Salicylaldehyde (0.42 ml, 3.9 mmol) and *o*-hydroxystyrylmethylketone (0.65 g, 4.0 mmol) were dissolved in 4 ml of acetic acid and 0.8 ml of HBF_4 [20]. Four millilitres of acetic anhydride were then added dropwise and the temperature of the reaction mixture rose until 68 °C. The reaction mixture was stirred overnight. By the following day, the precipitated solid was filtered off, washed with water and then carefully with diethyl ether and dried (0.41 g, 1.2 mmol). Yield: 30.8%. ^{1}H NMR (D_2O/DCl, pD ≈ 1.0, AH^+ species, 400.13 MHz) δ (ppm): 8.87 (1H, d, $^3J = 8.8$ Hz), 8.27 (1H, d, $^3J = 15.9$ Hz), 7.78-7.88 (4H, m), 7.61 (1H, d, $^3J = 7.7$ Hz), 7.51 (1H, t, $^3J = 7.5$ Hz), 7.26 (1H, d, $^3J = 15.9$ Hz), 7.16 (1H, t, $^3J = 7.7$ Hz), 7.00 (1H, t, $^3J = 7.5$ Hz), 6.83 (1H, d, $^3J = 8.1$ Hz). FD MS: m/z (%): 248.080 $[M - H]^+$ (100). EA calcd for $C_{17}H_{13}BF_4O_2$: C 60.75, H 3.90; found: C 60.32, H 3.89.

2.3.3. Synthesis of 2-(4-hydroxystyryl)-1-benzopyrylium tetrafluoroborate

Salicylaldehyde (1.0 ml, 9.4 mmol) and *p*-hydroxystyrylmethylketone (1.50 g, 9.3 mmol) were dissolved in 10 ml of acetic acid and 2 ml of HBF_4 [20]. Nine millilitres of acetic anhydride were then added dropwise and the temperature of the reaction mixture rose until 75 °C. The reaction mixture was stirred overnight. By the following day, the precipitated solid was filtered off, washed with water and then carefully with diethyl ether and dried (0.93 g, 2.8 mmol). Yield: 30.1%. ^{1}H NMR (D_2O/DCl, pD ≈ 1.0, AH^+ species, 400.13 MHz) δ (ppm): 8.61 (1H, d, $^3J = 8.6$ Hz), 8.16 (1H, d, $^3J = 15.7$ Hz), 7.86 (1H, t, $^3J = 7.8$ Hz), 7.78 (1H, d, $^3J = 7.9$ Hz), 7.71 (1H, d, $^3J = 8.6$ Hz), 7.64 (1H, d, $^3J = 8.9$ Hz), 7.53 (1H, t, $^3J = 7.6$ Hz), 7.44 (2H, d, $^3J = 8.2$ Hz), 7.04 (1H, d, $^3J = 15.7$ Hz), 6.49 (2H, d, $^3J = 8.2$ Hz). FD MS: m/z (%): 248.088 $[M - H]^+$ (100). EA calcd for $C_{17}H_{13}BF_4O_2 \cdot H_2O$: C 57.66, H 4.27; found: C 57.12, H 4.69.

2.3.4. Synthesis of 7-hydroxy-2-styryl-1-benzopyrylium tetrafluoroborate (HS)

2,4-Dihydroxybenzaldehyde (1.24 g, 9.0 mmol) and benzalacetone (1.37 g, 9.4 mmol) were dissolved in 10 ml of acetic acid and 2 ml of HBF_4 [20]. Acetic anhydride (8.5 ml) was then added dropwise and the temperature of the reaction mixture rose until 85 °C. The reaction mixture was stirred overnight. By the following day, the precipitated solid was filtered off, washed with water and then carefully with diethyl ether and dried (0.95 g, 2.8 mmol). Yield: 31.1%. ^{1}H NMR (D_2O/DCl, pD ≈ 1.0, AH^+ species, 400.13 MHz) δ (ppm): 8.94 (1H, d, $^3J = 8.3$ Hz), 8.25 (1H, d, $^3J = 16.1$ Hz), 8.03 (1H, d, $^3J = 8.7$ Hz), 7.72–7.78 (3H, m), 7.35–7.49 (6H, m). MS FD: m/z (%): 248.091 $[M - H]^+$ (100). EA calcd for $C_{17}H_{13}BF_4O_2$: C 60.75, H 3.90; found: C 60.61, H 3.88.

2.3.5. Synthesis of 7-hydroxy-2-(4-hydroxystyryl)-1-benzopyrylium chloride (DHS)

2,4-Dihydroxybenzaldehyde (1.40 g, 10 mmol) and *p*-hydroxystyrylmethylketone (1.61 g, 10 mmol) were dissolved in 25 ml of acetic acid. The solution was saturated with dry hydrogen chloride (3 h 30 min) [21]. The solution became dark purple and a solid precipitated out. The precipitated solid was filtered off, carefully washed with diethyl ether and dried. The solid was recrystallized by dissolving it in acetonitrile with a few drops of HCl and letting diethyl ether gently diffuse (2.34 g, 7.7 mmol). Yield: 78.0%. ^{1}H NMR (D_2O/DCl, pD ≈ 1.0, AH^+ species, 400.13 MHz) δ (ppm): 8.59 (1H, d, $^3J = 8.7$ Hz), 8.10 (1H, d, $^3J = 16.1$ Hz), 7.77 (1H, d, $^3J = 8.3$ Hz), 7.51 (2H, d, $^3J = 8.6$ Hz), 7.46 (1H, d, $^3J = 8.3$ Hz), 7.08-7.14 (2H, m), 7.05 (1H, d, $^3J = 16.1$ Hz), 6.70 (2H, d, $^3J = 8.6$ Hz). ^{1}H NMR (D_2O/CD_3OD, pD ≈ 6.1, Ct species, 400.13 MHz) δ (ppm): 7.87 (1H, d, $^3J = 15.9$ Hz), 7.57 (1H, d, $^3J = 15.8$ Hz), 7.51 (2H, d, $^3J = 8.4$ Hz), 7.47 (1H, d, $^3J = 8.6$ Hz), 7.03 (1H, d, $^3J = 15.4$ Hz), 6.99 (1H, d, $^3J = 15.2$ Hz), 6.81 (2H, d, $^3J = 8.6$ Hz), 6.38 (1H, d, $^3J = 8.2$ Hz), 6.30 (1H, d). ^{1}H NMR (NaOD/CD_3OD, pD ≈ 12.0, Ct^{2-} species, 400.13 MHz) δ (ppm): 8.52 (1H, d, $^3J = 15.4$ Hz), 7.48 (1H, d, $^3J = 15.4$ Hz), 7.37 (2H, d, $^3J = 8.6$ Hz), 7.27 (1H, d, $^3J = 8.8$ Hz), 7.15 (1H, d, $^3J = 15.5$ Hz), 6.59 (2H, d, $^3J = 8.4$ Hz), 6.55 (1H, d, $^3J = 15.6$ Hz), 5.98 (1H, s), 5.96 (1H, d, $^3J = 9.1$ Hz). EI MS: m/z (%): 57.069 (100), 69.069 (55), 83.082 (50), 160.052 (50), 264.080 (30), 265.084 $[M]^+$ (20), 266.092 (25). EA calcd for $C_{17}H_{13}O_3Cl \cdot (1/2)H_2O$: C 65.92, H 4.56; found: C 65.71, H 4.88.

2.3.6. Synthesis of 7-hydroxy-2-(4-dimethylaminophenyl)-1-benzopyrylium chloride (DAS)

2,4-Dihydroxybenzaldehyde (0.69 g; 5 mmol) and *p*-dimethylaminostyrylmethylketone (0.94 g; 5 mmol) were dissolved in 10 ml of acetic acid. The solution was saturated with dry hydrogen chloride [21]. The solution became dark green and was left under stirring overnight. A solid was precipitated by the addition of ethyl acetate that was filtered off, carefully washed with diethyl ether and dried. Yield: 54.9%. ^{1}H NMR (D_2O/DCl, pD ≈ 1.0, AH^+ species, 400.13 MHz) δ (ppm): 8.23 (1H, d, $^3J = 8.6$ Hz), 7.38 (1H, d, $^3J = 15.9$ Hz), 7.26 (1H, d, $^3J = 8.6$ Hz), 7.07 (3H, m), 6.86 (2H, d,

$^3J = 8.3$ Hz), 6.60 (1H, d, $^3J = 5.3$ Hz), 6.55 (1H, d, $^3J = 5.3$ Hz), 6.52 (1H, s), 2.66 (6H, s). MALDI TOF MS (+): 292.6156 $[M]^+$ (100), 293.6040 (65), 291.6009 (20). EA calcd for $C_{19}H_{19}Cl_2NO_2 \cdot (3/2)\,H_2O$: C 58.32, H 5.67, N 3.58; found: C 57.98, H 5.53, N 3.65.

2.4. Solution studies.

Measurements. Solutions were prepared using Millipore water and acetonitrile (when needed). The pH of solutions was adjusted by addition of HCl, NaOH or universal buffer of Theorell and Stenhagen [22] and pH was measured in a Radiometer Copenhagen PHM240 pH/ion meter. UV–vis absorption spectra were recorded in a Varian-Cary 100 Bio spectrophotometer or in a Shimadzu VC2501-PC. Quantum yields were determined by irradiation at 436 nm, using a medium pressure mercury arc lamp and the excitation bands were isolated with interference filters (Oriel). Actinometry was made using the ferrioxalate system [23]. Some irradiations were performed in a 300 W solar lamp from OSRAM.

3. Results and discussion

3.1. Synthesis and characterization

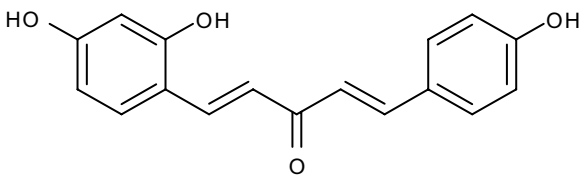
The synthetic approach was tested with adequate starting materials and six 2-styryl-1-benzopyrylium salts were obtained with poor to reasonable isolated yields. The yields seem to be better when gaseous HCl is used instead of aqueous HBF_4. In all NMR experiments, performed at pH 1, where the flavylium cation is the thermodynamic stable species, clear evidence was found for the existence of the double bond in *trans* configuration – in all cases, protons β and α show coupling constants between 15 and 16 Hz [24]. All compounds were also identified by Mass Spectrometry (MALDI TOF, FD, EI) and Elemental Analysis.

For compound DHS, a NMR spectrum was obtained in an equilibrated solution at pH 6. At these pH values, the species equivalent to Ct in Scheme 1 should be the thermodynamically stable species. Two double bonds could be identified, with a geometry that is clearly *trans* in both cases as evidenced by the presence of two pairs of doublets with scalar coupling constants between 15 and 16 Hz. The same NMR spectrum was obtained upon a pH jump from 1 to 6 and from 12 to 6. On this basis, from now on and for the sake of simplicity, Ct will also be the designation of this species in 2-styryl-1-bemzopyrylium salts, knowing that it corresponds to the *trans–trans*-isomer, see Scheme 3.

The NMR spectrum was also performed at pH 12, where Ct^{2-} should be the thermodynamically stable species and, again, the *trans–trans* configuration was found.

3.2. 2-styryl-1-benzopyrylium salts without OH in position 7

Differently from 2-styryl-1-benzopyrylium tetrafluoroborate[1], 2-(2-hydroxystyryl)-1-benzopyrylium tetrafluoroborate and 2-(4-hydroxystyryl)-1-benzopyrylium tetrafluoroborate, solutions of 7-hydroxy-2-styryl-1-benzopyrylium tetrafluoroborate (HS), 7-hydroxy-2-(4-hydroxystyryl)-1-benzopyrylium chloride (DHS) and



Ct of DHS

Scheme 3.

7-hydroxy-2-(4-dimethylaminophenyl)-1-benzopyrylium (DAS) are stable and thermodynamic and kinetic studies could be carried out. It could be speculated that the predictable presence of a thermal barrier between *trans*- and *cis*-chalcones is related with the observed instability of the solutions [25].

3.3. 2-Styryl-1-benzopyrylium salts with OH in position 7

3.3.1. 7-Hydroxy-2-styryl-1-benzopyrylium tetrafluoroborate (HS)

Flavylium salts in solution evolve to form diverse species, as reported in Scheme 1. In principle, if the insertion of the double bond has no effect, 2-styryl-1-benzopyrylium salts should behave similar to flavylium ions.

After verifying the stability of the aqueous mother solution at pH 1, pH jumps were performed to various final pH values by mixing 1 ml of buffer at the desired pH value, 1 ml of 0.1 M base and, finally, 1 ml of the 2.5×10^{-5} M mother solution of the compound under study at pH = 1.0. In Fig. 2, the AH^+ species of HS ($\lambda_{max} = 471$ nm, $\varepsilon_{max} = 32{,}000\ cm^{-1}\,M^{-1}$) is transformed immediately after the pH jump into a species with absorption maximum at 512 nm, that by analogy with flavylium salts [2] must correspond to the quinoidal base A ($\varepsilon_{max} = 16{,}800\ cm^{-1}\,M^{-1}$), Eq. (1). Fitting of the experimental data allows the determination of $pK_a = 3.7 \pm 0.1$.

$$AH^+ + H_2O \leftrightharpoons A + H_3O^+ \quad K_a \tag{1}$$

The formation of the quinoidal base A upon deprotonation of AH^+ is the fastest process but this species is not the most thermodynamically stable. Slower competitive processes leading to the usually most stable species B, Cc and Ct, are also formed, Eqs. (2)–(4). In other words, A is a kinetic product that disappears with time to give mostly Ct.

$$AH^+ + 2H_2O \leftrightharpoons B + H_3O^+ \quad K_h \tag{2}$$

$$B \leftrightharpoons Cc \quad K_t \tag{3}$$

$$Cc \leftrightharpoons Ct \quad K_i \tag{4}$$

Eqs. (1)–(4) can be substituted by a single acid–base equilibrium [2] as shown by Eq. (5):

$$AH^+ + 2H_2O \leftrightharpoons CB + H_3O^+ \quad K'_a \tag{5}$$

where $[CB] = [A]+[B]+[Cc]+[Ct]$ and $K'_a = K_a + K_h + K_hK_t + K_hK_tK_i$.

At the final thermodynamic equilibrium, Fig. 3, the major species Ct ($\lambda_{max} = 380$ nm) is formed in equilibrium with other minor forms, $pK'_a = 3.1 \pm 0.1$. At pH values when AH^+ is no longer available, we can define:

$$C_0 = [A] + [B] + [Cc] + [Ct] = [A]\left(1 + \frac{K_h}{K_a} + \frac{K_tK_h}{K_a} + \frac{K_iK_tK_h}{K_a}\right) \tag{6}$$

Eq. (6) can be rearranged to Eq. (7) that allows calculation of the percentage of base A present at the final equilibrium. In this case, A is present in $24 \pm 5\%$, the major component being Ct and the other species are present in non-detectable concentrations [26].

[1] We did not succeed to stabilize solutions of 2-styryl-1-benzopyrylium compounds lacking a hydroxyl substituent in position 7. Usually, a precipitate is observed in old aqueous solutions of 2-styryl-1-benzopyrylium tetrafluoroborate and if this precipitate is filtered off, after some days it is reformed. The spectral evolutions do not reach a final state of equilibrium, at least after one month, even in very diluted solutions (10^{-7} M) where no precipitate is observed. On the other hand, these compounds are sensitive to light, showing some photodegradation. We have tried preparing solutions also in water–organic solvent mixtures (alcohols, acetonitrile), in the absence of oxygen, in the dark, in the presence of SDS micelles and with various acid concentrations; in all cases, there is a spectral evolution that could neither be suppressed nor fully understood until now.

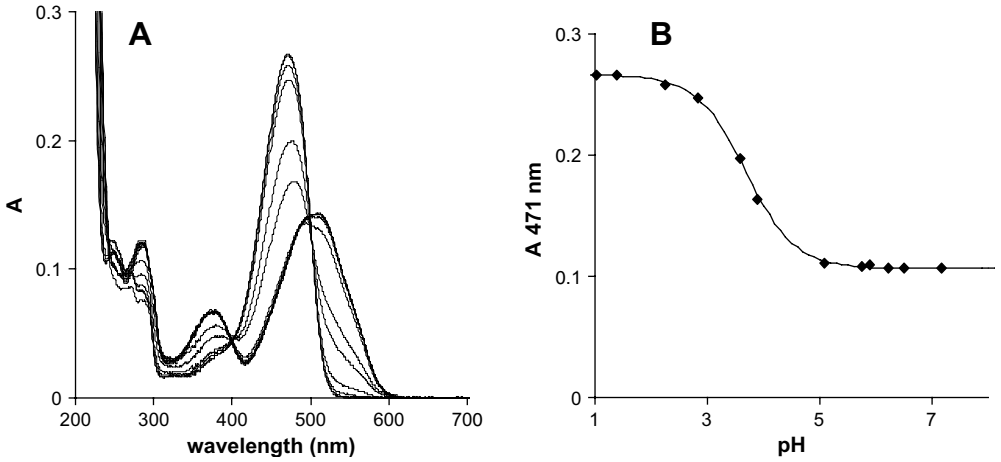


Fig. 2. (A) Spectra run immediately after a pH jump from a 2.5×10^{-5} M solution at pH 1 to 1.03, 1.4, 2.24, 2.84, 3.59, 3.9, 5.09, 5.75, 5.89, 6.21, 6.5 and 7.16. (B) Changes in absorption at 471 nm, fitted with a $pK_a = 3.7 \pm 0.1$.

$$\frac{[A]}{C_0} = \frac{K_a}{K'_a} \tag{7}$$

In order to study the kinetic properties of the system, pH jumps from 1 to more basic pH values were performed and followed by UV–vis absorption spectroscopy. In Fig. 4, the example of a pH jump to 4.53 is presented. It is possible to distinguish that immediately after adding the base, the quinoidal base, A, is formed and then converted into the *trans*-chalcone, Ct. It is worth of note that A only communicates with the rest of the system through AH^+.

It was seen previously [12] that the system could be represented as follows:

$$A \overset{K_a}{\rightleftharpoons} AH^+ \underset{k_{-h}[H^+]}{\overset{k_h}{\rightleftharpoons}} B \overset{K_T}{\rightleftharpoons} Cc \underset{k_{-i}}{\overset{k_i}{\rightleftharpoons}} Ct \tag{8}$$

Assuming that B and Cc are in fast equilibrium, we can simplify the problem:

$$A \overset{K_a}{\rightleftharpoons} AH^+ \underset{k_{-h}[H^+]}{\overset{k_h}{\rightleftharpoons}} X \underset{k_{-i}}{\overset{k_i}{\rightleftharpoons}} Ct \tag{9}$$

$$[X] = [B] + [Cc] \tag{10}$$

$$[X] = [B] + K_T[B] \tag{11}$$

$$\chi_B = \frac{1}{1 + K_T} \tag{12}$$

$$\chi_{Cc} = \frac{K_T}{1 + K_T} \tag{13}$$

and obtain the following differential equations:

$$\frac{d\left(\left[AH^+\right] + [A]\right)}{dt} = -k_h \frac{\left[H^+\right]}{\left[H^+\right] + K_a}\left(\left[AH^+\right] + [A]\right) + k_{-h}\left[H^+\right]\chi_B[X] \tag{14}$$

$$\frac{d[X]}{dt} = k_h \frac{\left[H^+\right]}{\left[H^+\right] + K_a}\left(\left[AH^+\right] + [A]\right) + k_{-i}[Ct] - \left(k_{-h}\left[H^+\right]\chi_B + k_i\chi_{Cc}\right)[X] \tag{15}$$

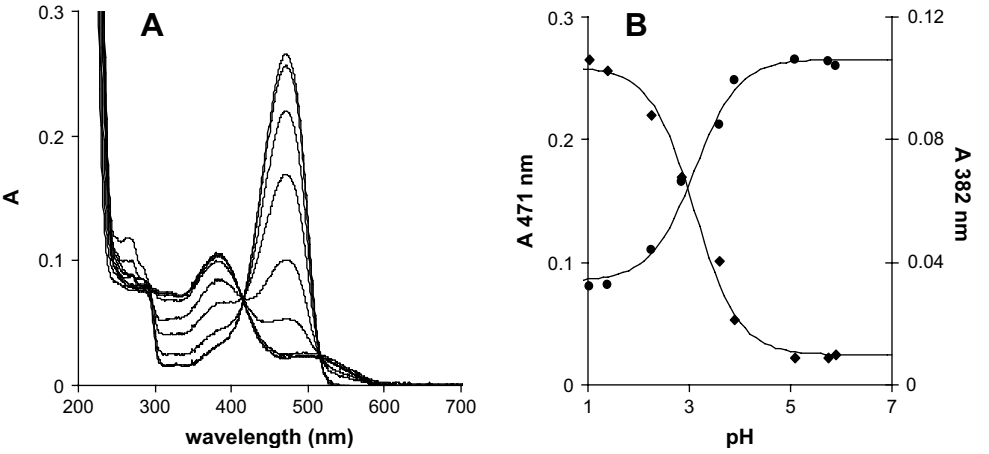


Fig. 3. (A) Thermal equilibrated solutions in the dark upon a pH jump from 1 to 1.03, 1.4, 2.24 2.84, 3.59, 3.9, 5.09, 5.75 and 5.89. (B) Changes in absorption at 471 (squares, left scale) and 382 nm (circles, right scale) simultaneously fitted with a $pK'_a = 3.1 \pm 0.1$.

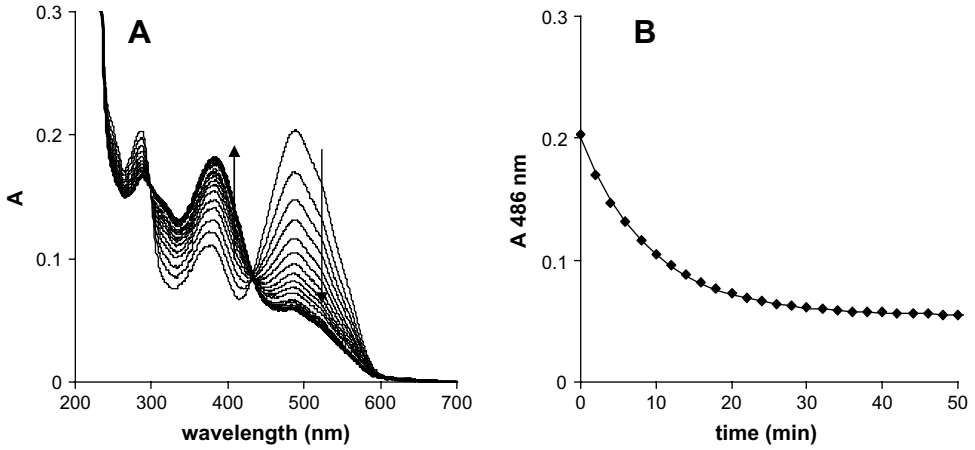


Fig. 4. (A) Spectral evolution after a pH jump from pH 1 to 4.53 followed every 2 min. The pH jump was performed as previously mentioned. (B) Fitting of the decay of absorption at 486 nm was achieved with $k_{obs} = 1.8 \times 10^{-3}\ s^{-1}$.

$$\frac{d[Ct]}{dt} = k_i \chi_{Cc}[X] - k_{-i}[Ct] \tag{16}$$

Applying the steady state approximation:

$$[X] = \frac{k_h \frac{[H^+]}{[H^+]+K_a}\left(\left[AH^+\right] + [A]\right) + k_{-i}[Ct]}{k_{-h}\left[H^+\right]\chi_B + k_i \chi_{Cc}} \tag{17}$$

Substituting [X] in Eqs. (14) and (16) one obtains,

$$\frac{d\left(\left[AH^+\right] + [A]\right)}{dt} = -k_h \frac{\left[H^+\right]}{\left[H^+\right] + K_a}\left(\left[AH^+\right] + [A]\right) + k_{-h}\left[H^+\right] \frac{k_h \frac{[H^+]}{[H^+]+K_a}\left(\left[AH^+\right] + [A]\right) + k_{-i}[Ct]}{k_{-h}\left[H^+\right]\chi_B + k_i \chi_{Cc}} = \frac{k_i \chi_{Cc} k_h \frac{[H^+]}{[H^+]+K_a}\left(\left[AH^+\right] + [A]\right)}{k_{-h}\left[H^+\right]\chi_B + k_i \chi_{Cc}} + \frac{k_{-i} k_{-h}\left[H^+\right]\chi_B [Ct]}{k_{-h}\left[H^+\right]\chi_B + k_i \chi_{Cc}} \tag{18}$$

$$\frac{d[Ct]}{dt} = k_i \chi_{Cc} \frac{k_h \frac{[H^+]}{[H^+]+K_a}\left(\left[AH^+\right] + [A]\right) + k_{-i}[Ct]}{k_{-h}\left[H^+\right]\chi_B + k_i \chi_{Cc}} - k_{-i}[Ct] = \frac{k_i \chi_{Cc} k_h \frac{[H^+]}{[H^+]+K_a}\left(\left[AH^+\right] + [A]\right) + k_{-i} k_{-h}\left[H^+\right]\chi_B [Ct]}{k_{-h}\left[H^+\right]\chi_B + k_i \chi_{Cc}} \tag{19}$$

Now it is simple to account for first order kinetic constant observed:

$$k_{obs} = \frac{\frac{[H^+]}{[H^+]+K_a} k_i \chi_{Cc} k_h + k_{-i} k_{-h}\left[H^+\right]\chi_B}{k_{-h}\left[H^+\right]\chi_B + k_i \chi_{Cc}} \tag{20}$$

which rearranges to:

$$k_{obs} = \frac{\frac{[H^+]}{[H^+]+K_a} K_h K_t k_i + k_{-i}\left[H^+\right]}{\left[H^+\right] + \frac{k_i K_t}{k_{-h}}} \tag{21}$$

Fig. 5 reports the best fitting of the k_{obs} values determined upon pH jumps *versus* pH, together with the fitting obtained for the constants reported in the literature for 7-hydroxyflavylium (HF) [27] for comparison purposes.

From Fig. 5, it is clearly seen that the behaviour of HF and HS is very similar, although the rates observed are *ca.* 5-fold higher for the flavylium ion.

Concerning the photochemistry of the system, it was observed that an equilibrated solution at pH 3.95 essentially suffers no changes when irradiated in a solar lamp for 30 min. At pH 5.75, there seems to be a degradative photochemical process, because the observed final state does not recover after several days; moreover, when the irradiated solutions are acidified only a very small percentage of flavylium is recovered.

In basic media, ionized *trans*-chalcones can be obtained. Starting from an equilibrated solution at pH 12 and titrating back to acid, the successive protonations of the Ct^{n-} species can be achieved.

$$Ct + H_2O \leftrightharpoons Ct^- + H_3O^+ \quad K_{Ct1} \tag{22}$$

$$Ct^- + H_2O \leftrightharpoons Ct^{2-} + H_3O^+ \quad K_{Ct2} \tag{23}$$

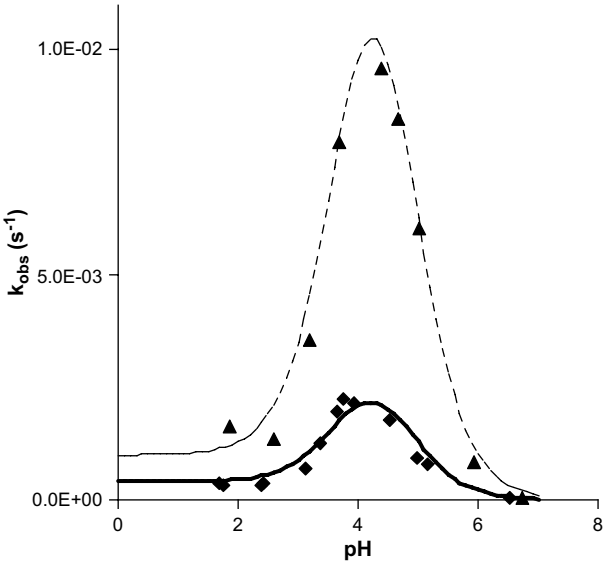


Fig. 5. Observed rate constants *versus* pH (◆) for HS (this work) and (▲) for HF [27]. Fitting of experimental data with Eq. (21) was achieved with constants reported in Table 2.

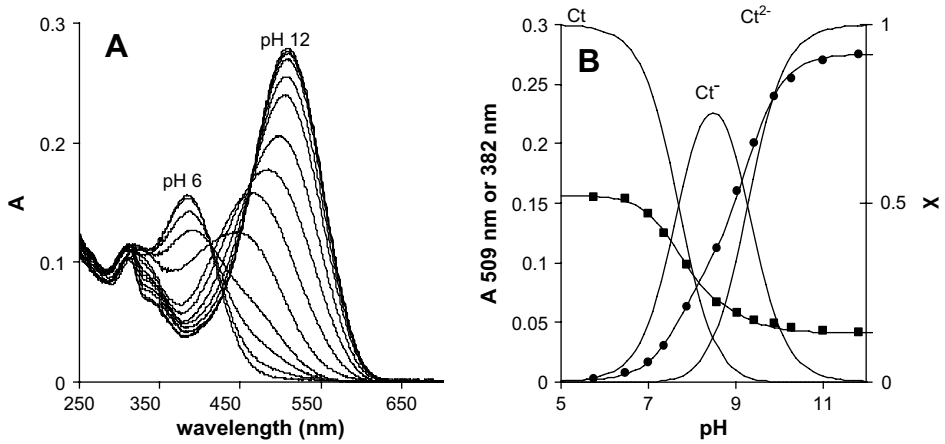


Fig. 6. (A) Spectrophotometric titration of the *trans*-chalcones of HS; pH values 12.4, 12.19, 11.84, 11.00, 10.28, 9.89, 9.43, 9.04, 8.58, 7.88, 7.37, 6.99, 6.47 and 5.76. (B) Changes in absorption at 509 and 382 nm, simultaneously fitted with $pK_{Ct1} = 7.7 \pm 0.1$ and $pK_{Ct2} = 9.3 \pm 0.1$.

By inspection of Fig. 6 and the simultaneous fitting of absorptions at 509 nm (main absorbing species Ct^{2-}) and 382 nm (Ct), $pK_{Ct1} = 7.7 \pm 0.1$ and $pK_{Ct2} = 9.3 \pm 0.1$ were obtained.

The results obtained for this compound, as well as for DSF and DAS, which will be presented in the next sections, are summarized in Tables 1 and 2. For purposes of easy comparison, data for the corresponding flavylium compounds are also shown.

In conclusion, the absorption maximum of the flavylium ion changes *ca.* 35 nm to higher wavelengths upon introduction of the double bond. On the other hand, the pK'_a value is 0.4 units higher for the styryl derivative, showing that the effective color loss is only slightly shifted to higher pH values. The benzopyrylium core is more stable towards hydration in HS than in HF as evidenced by k_h (Table 1 and Fig. 5). There is no evidence for the existence of an extra isomerisation and the usual reaction network for the flavylium ion could be applied to 7-hydroxy-2-styryl-1-benzopyrylium, with no restrictions. Although the values found for the kinetic constants are always higher for the flavylium compound, it is not yet fully understood why the styryl derivative presents no photochemistry in water; further investigation is being carried out to clarify this issue.

3.3.2. 7-Hydroxy-2-(4-hydroxystyryl-1)-benzopyrylium chloride (DHS)

In the case of the dihydroxy derivative, essentially the same results described above were found. In Fig. 7, the titration after immediate pH jumps, leading to the formation of A and in this case also A^-, is shown, as well as the situation in equilibrium and the protonation steps for the *trans*-chalcones.

The maximum absorption of DHS occurs at 510 nm ($\varepsilon = 32{,}000\ cm^{-1}\,M^{-1}$), which is ≈51 nm red shifted when compared with DHF analogue [27]. Taking into account that the absorption bands should be assigned to π–π^* transitions (with charge transfer character), the relatively large red shift observed can, once again, be attributed to the extended conjugation of the π system brought by the introduction of one more conjugated double bond.

When a pH jump on the AH^+ species is carried out to moderately acidic and basic pH values the spectra obtained immediately after are those of the quinoidal bases A ($\lambda_{max} = 515$ nm, $\varepsilon_{max} \approx 19{,}500\ cm^{-1}\,M^{-1}$) and A^- ($\lambda_{max} = 605$ nm, $\varepsilon_{max} \approx 30{,}000\ cm^{-1}\,M^{-1}$), also red shifted relatively to the DHF (495 nm and 535 nm, respectively [27]). In Fig. 8, the rate constants of the pH jumps *versus* pH are shown in comparison with those of DHF.

Tables 1 and 2 summarize the results obtained with the styryl derivatives HS, DHS and DAS together with the results of the

Table 1
Thermodynamic constants obtained in aqueous solutions at 298 K for HF, DHF, DAF, HS and DHS (constants for DAS were obtained in 29% acetonitrile)

Compound	pK_a	pK_{a+}	pK_{a1}	pK_{a2}	%A	pK_{Ct+}	pK_{Ct1}	pK_{Ct2}	$K_hK_tK_i$(M)
HS	3.1 ± 0.1	–	3.7 ± 0.1	–	24 ± 5	–	7.7 ± 0.1	9.3 ± 0.1	$(6 \pm 1) \times 10^{-4}$
HF [27]	2.7	–	3.6	–	14	–	N/A	N/A	1.71×10^{-3}
DHS	3.4 ± 0.1	–	4.1 ± 0.1	8.1 ± 0.1	20 ± 4	–	7.9 ± 0.1	9.4 ± 0.1	$(3.2 \pm 0.8) \times 10^{-4}$
DHF [28]	3.1	–	4.0	8.0	13	–	8.1	10.2	6.91×10^{-4}
DAS	4.0 ± 0.1	0.7 ± 0.1	5.1 ± 0.1	–	8 ± 2	2.9 ± 0.2	8.6 ± 0.1	10.4 ± 0.1	$(9 \pm 2) \times 10^{-5}$
DAF [29]	4.3 ± 0.1	−0.2 ± 0.2	5.4 ± 0.1	–	8 ± 2	2.3 ± 0.2	8.1 ± 0.1	9.6 ± 0.1	$(5 \pm 1) \times 10^{-5}$

Table 2
Kinetic constants obtained in aqueous solutions at 298 K for HF, DHF, DAF, HS and DHS (constants for DAS were obtained in 29% acetonitrile)

Compound	$K_hK_tk_i$(M^{-1})	K_tk_i/k_{-h}(M)	k_{-i}(s^{-1})	k_h(s^{-1})	k_{-i+}(s^{-1})	k_{i+}/k_{-h+}(M)
HS	$(6 \pm 1) \times 10^{-7}$	$(1.5 \pm 0.3) \times 10^{-5}$	$(4 \pm 1) \times 10^{-4}$	0.04 ± 0.01	–	–
HF [27]	3.1×10^{-6}	1.5×10^{-5}	1.0×10^{-3}	0.21	–	–
DHS	$(2.9 \pm 0.5) \times 10^{-7}$	$(6 \pm 1) \times 10^{-5}$	$(1.5 \pm 0.4) \times 10^{-4}$	$(5 \pm 1) \times 10^{-3}$	–	–
DHF [28]	3.8×10^{-7}	2.1×10^{-5}	1.8×10^{-4}	0.02	–	–
DAS	$(1.0 \pm 0.4) \times 10^{-7}$	$(1.0 \pm 0.4) \times 10^{-3}$	$(1.0 \pm 0.4) \times 10^{-5}$	$(1.0 \pm 0.5) \times 10^{-4}$	$(4.0 \pm 0.8) \times 10^{-3}$	1.0 ± 0.2
DAF [29]	$(1.0 \pm 0.4) \times 10^{-7}$	$(1.0 \pm 0.4) \times 10^{-3}$	$(5 \pm 2) \times 10^{-4}$	$(1.0 \pm 0.5) \times 10^{-4}$	$(5 \pm 1) \times 10^{-3}$	0.25 ± 0.05

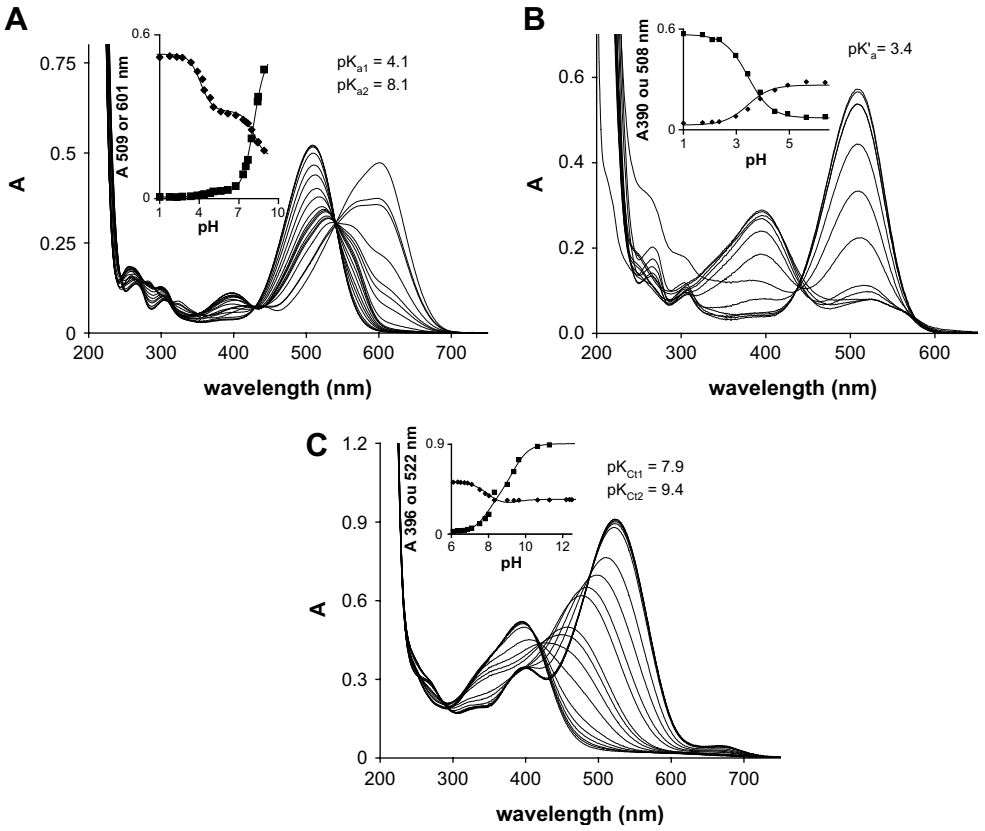


Fig. 7. (A) Immediate titration upon a pH jump from a stock solution of DHS 1.6×10^{-5} M at pH = 1.0 to basic pH values, inset, fitting of the absorptions at 509(◆) and 601 nm (■) with $pK_{a1} = 4.1 \pm 0.1$ and $pK_{a2} = 8.1 \pm 0.1$. (B) The same as A but upon equilibrium, inset, fitting of the absorptions at 508 (■) and 390 nm (◆) with $pK'_a = 3.4 \pm 0.1$. (C) Protonation steps of the *trans*-chalcones, inset, fitting of the absorptions at 396 (◆) and 522 nm (■) with $pK_{Ct1} = 7.9 \pm 0.1$ and $pK_{Ct2} = 9.4 \pm 0.1$.

corresponding flavylium compounds HF, DHF and DAF for comparison purposes.

The pK_as for the conversion of DHS into the quinoidal base and ionized quinoidal base are 4.2 ± 0.1 and 8.0 ± 0.1, which compare with 4.0 and 8.0 in the case of the analogue DHF. In terms of kinetic data, once more, the rate constants present the same trend but are slightly lower than in the case of DHF.

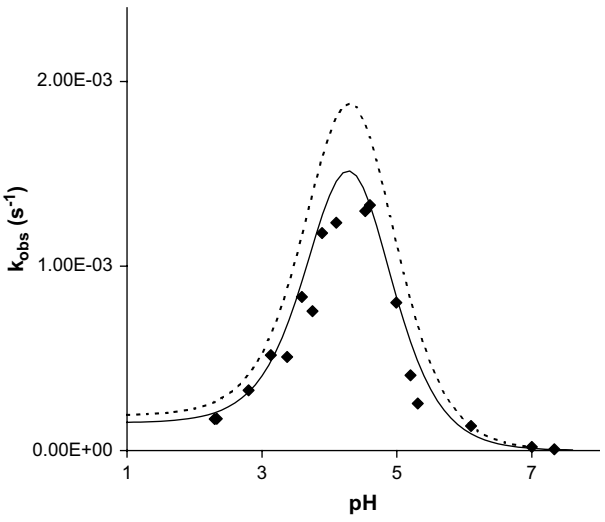


Fig. 8. Observed rate constants *versus* pH (◆) for DHS (this work) and for DHF (traced line) [27]. Fitting of experimental data with Eq. (21) was achieved with constants reported in Table 2.

3.4. 7-Hydroxy-2-(4-dimethylaminostyryl)-1-benzopyrylium chloride (DAS)

In the case of amino substituted flavylium ions, because of the presence of the nitrogen atom that can protonate, two more equilibria must be considered [8]:

$$AH_2^{2+} + H_2O \leftrightharpoons AH^+ + H_3O^+ \quad K_{a+} \tag{24}$$

$$CtH^+ + H_2O \leftrightharpoons Ct + H_3O^+ \quad K_{Ct+} \tag{25}$$

In Fig. 9, the titration obtained upon pH jumps from a mother solution at pH 1 to higher pH values shows the presence of three species: AH_2^{2+} ($\lambda_{max} = 464$ nm, $\varepsilon_{max} \approx 22{,}600\ cm^{-1}\,M^{-1}$), AH^+ ($\lambda_{max} = 639$ nm, $\varepsilon_{max} = 47{,}800\ cm^{-1}\,M^{-1}$), and A ($\lambda_{max} = 616$ nm, $\varepsilon_{max} = 28{,}200\ cm^{-1}\,M^{-1}$). In equilibrium, the species present are AH_2^{2+} (not shown in spectra), AH^+ and Ct. Finally, at basic pH values the ionized Ct species are once again the thermodynamically stable species. In this case, similarly to what occurs for the flavylium analogues, [8] if an equilibrated solution of Ct^{2-} is acidified to a very acidic pH value, the immediate formation of CtH^+ (spectrum not shown) is observed, which converts to the thermodynamically stable species AH^+ or AH_2^{2+}, depending on the final pH. Because the Ct of DAS is rather insoluble in water, all measurements were carried out in the presence of 29% acetonitrile.

To take into account the process in which AH^+ is formed from CtH^+, Eq. (27) must be introduced since Eq. (21) now longer explains all the kinetics. Eq. (27) is deduced through a similar process, in which X′ is considered to be CcH^+ and $B2H^+$ in fast equilibrium and the formation of AH^+ could be considered an irreversible reaction [8].

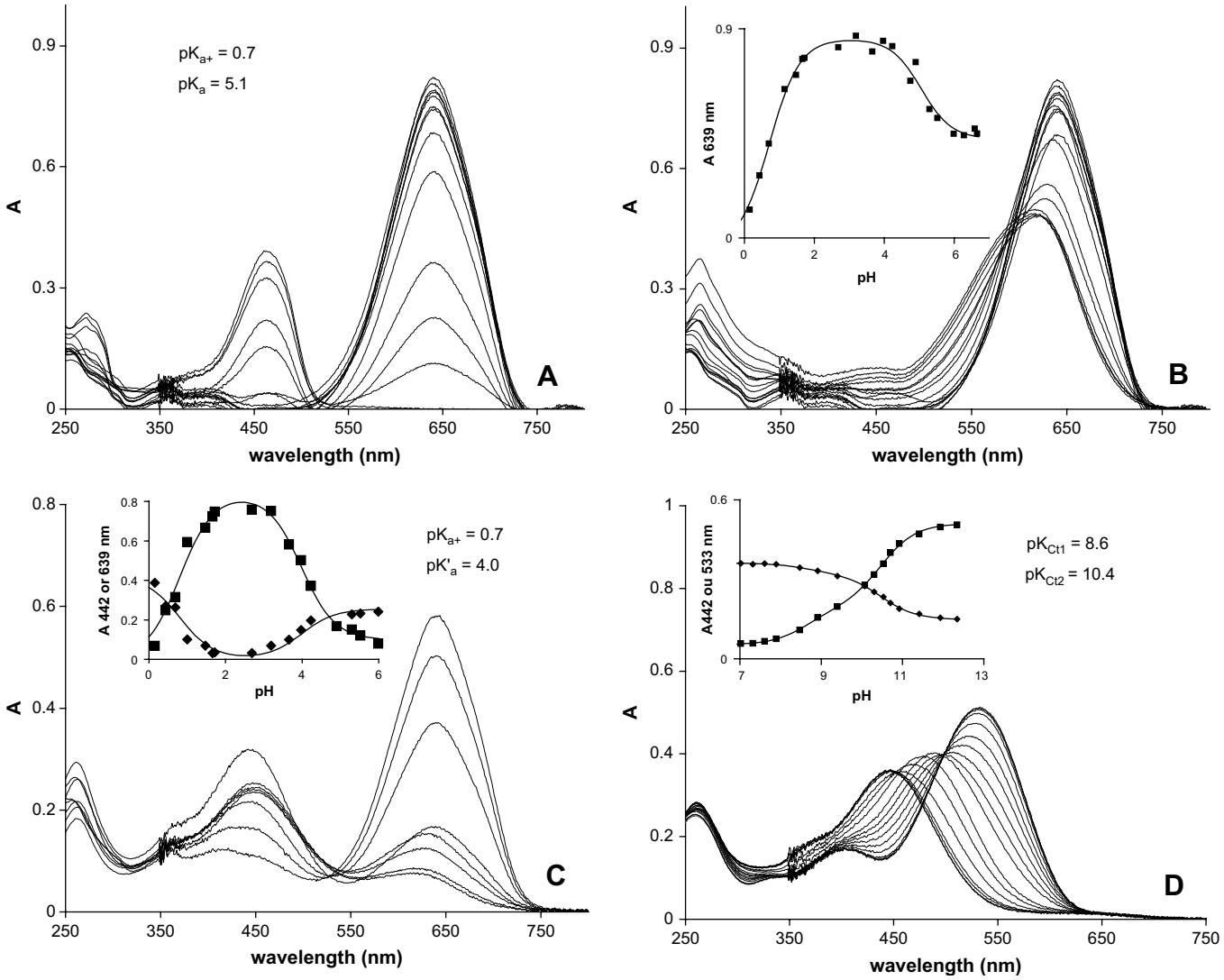


Fig. 9. Spectrophotometric titration upon pH jumps from a stock solution of DAS at pH = 1.0 to acidic pH values or basic pH values; final [DAS] = 1.7×10^{-5} M. (A) From pH 0 to pH 3. (B) From pH 3 to pH 7, inset, fitting of the absorption at 639 nm with $pK_{a+} = 0.7 \pm 0.1$ and $pK_a = 5.1 \pm 0.1$. (C) The same as B but upon equilibrium, inset, fitting of the absorptions at 442 (◆) and 639 nm (■) with $pK_{a+} = 0.7 \pm 0.1$ and $pK'_a = 4.0 \pm 0.1$. (C) Spectrophotometric titration of Ct^{2-}, inset, fitting of the absorptions at 422 (◆) and 533 nm (■) with $pK_{Ct1} = 8.6 \pm 0.1$ and $pK_{Ct2} = 10.4 \pm 0.1$.

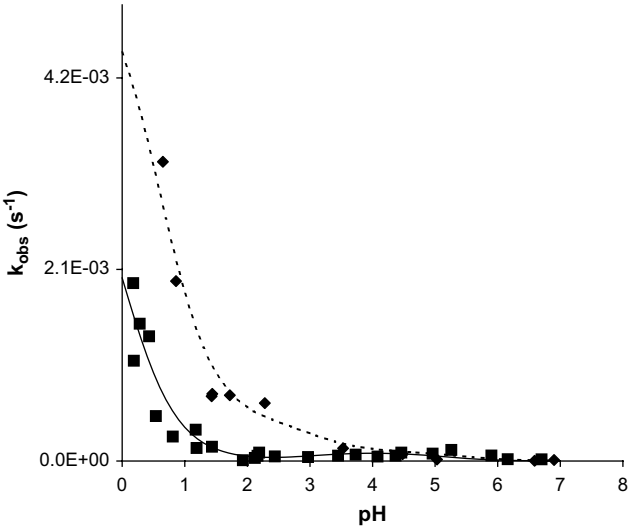


Fig. 10. Observed rate constants *versus* pH for (■) DAS and for (diamond symbol) DAF [29]. Fitting of experimental data with Eqs. (21) and (27) was achieved with constants reported in Table 2.

$$CtH^+ \underset{k_{-i+}}{\overset{k_{i+}}{\rightleftharpoons}} X' \overset{k_{-h}[H^+]}{\rightarrow} AH^+ \tag{26}$$

$$k_{obs} = \frac{\frac{[H^+]}{[H^+]+K_{Ct^+}} k_{-i+}[H^+]}{\frac{k_{i+}}{k_{-h+}} + [H^+]} \tag{27}$$

The fitting of the observed rate constant upon pH jumps *versus* pH for these cases is thus performed with a sum of Eqs. (21) and (27). Because there are many parameters to be adjusted, there is some uncertainty in the values obtained, particularly $K_h K_t k_i$, $K_t k_i / k_{-h}$, k_{-i} and k_h that are calculated through these adjusted parameters. Nevertheless, as shown in Fig. 10, once again the rate constants obtained for 2-styryl-1-benzopyrylium are lower than those of its flavylium counterpart – 4′-dimethylamino-7-hydroxyflavylium, DAF [29].

The summary of the results obtained for DAS in comparison with DAF are shown in Tables 1 and 2.

The pK'_as obtained for the two compounds are hardly comparable, since acetonitrile is expected to stabilize the neutral form and so lower the pK'_a value. However, the pK_{a+} of the styryl is

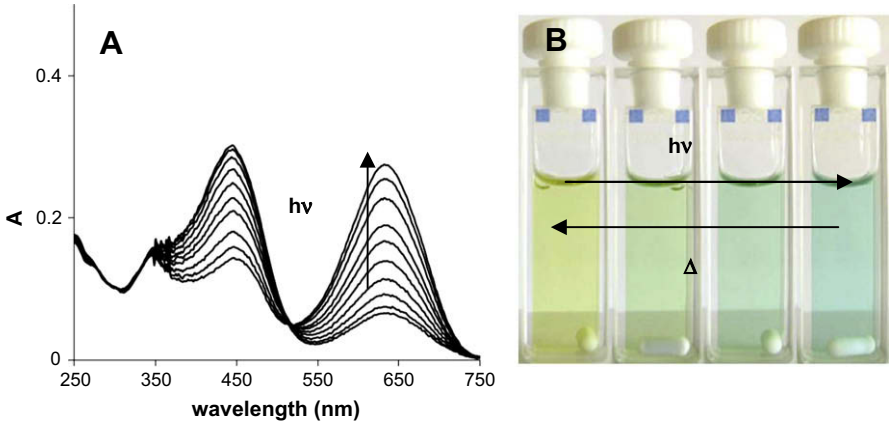


Fig. 11. (A) Irradiation of an equilibrated solution of DAS (Ct) at pH 1.9 in 0.2 M CTAB ($\phi = 0.02$, irradiating at 436 nm $I_0 = 2.8 \times 10^{-7}$ Einstein min^{-1}), $t = 0$, 1, 3, 6, 10, 15, 20, 30, 40 and 50 min. (B) Observed color at irradiation times $t = 0$, 15, 30 and 50 min. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

significantly higher than in the case of the corresponding flavylium (−0.2 in water), which is comprehensible on the basis of a longer charge separation in the AH_2^{2+} species of DAS, and consequent smaller repulsion between positive charges.

No photochemistry was detected in water either for DAS and DAF. However, as in the case of other aminoflavylium ions, an efficient photochromic system could be obtained in CTAB micelles [11]. While DAF is pink ($\lambda_{max} = 540$ nm in water), DAS is blue ($\lambda_{max} = 639$ nm in water/acetonitrile 71/29), which allows the exploitation of a strong color contrast upon irradiation, see Fig. 11. Although the quantum yields are low ($\phi = 0.02$ at 436 nm, pH = 1.9, 0.2 M CTAB; $I_0 = 2.8 \times 10^{-7}$ Einstein min^{-1}), this is, to our knowledge, the first time in which a photochromic system based on derivatives of natural anthocyanins is reported that shows such a deep change in λ_{max} upon irradiation. Furthermore, the change of color is relatively fast upon direct solar irradiation and it reverts to its initial state in the dark with a rate constant 1.0×10^{-4} s^{-1}.

3.5. Final comments

In Table 3, the most relevant parameters related to color loss are listed for HS, DHS and DAS.

The pK'_a is related to the thermodynamic stability of AH^+ (strongly colored) *versus* Ct (colorless or pale yellow) and eventually a low percentage of A (colored). The value of k_h accounts for the rate of hydration to form the colorless B, initiating the color loss process. Except for DAS, the pK'_as are slightly higher and the hydration rates are lower for 2-styryl-1-benzopyrylium than for their flavylium analogues. Taking into account that the studies for DAS were performed in a mixture containing approximately 30% of acetonitrile (due to insolubility), which is a more apolar solvent that stabilizes neutral forms such as Ct, B and A, the pK'_a could also be higher for DAS in water when compared to that of its flavylium counterpart.

Table 3
pK'_a and k_h (s^{-1}) obtained in aqueous solutions at 298 K for HF, DHF, DAF, HS and DHF (constants for DAS were obtained in 29% acetonitrile)

Compound	pK'_a	k_h (s^{-1})
HS	3.1 ± 0.1	0.04 ± 0.01
HF [27]	2.7	0.21
DHS	3.4 ± 0.1	(5 ± 1) × 10^{-3}
DHF [28]	3.1	0.02
DAS	4.0 ± 0.1	(1.0 ± 0.5) × 10^{-4}
DAF [29]	4.3 ± 0.1	(1.0 ± 0.5) × 10^{-4}

4. Conclusions

A series of 2-styryl-1-benzopyrylium salts were synthesized and thoroughly studied in comparison with flavylium analogues. Although the known network of reactions of flavylium salts could be applied and no evidence was found for the isomerisation of the second double bond, the absorption maxima are pronouncedly red shifted. 2-Styryl-1-benzopyrylium salts are also more stable towards color loss at slightly higher pH values and kinetically more inert towards hydration than their corresponding flavylium ions. Moreover, this family of compounds also allows the design of photochromic systems with significant color changes when in the presence of CTAB micelles that stabilize the Ct.

Acknowledgements

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