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Ion Specific Effects on the Mutual Solubilities of Water and Hydrophobic Ionic Liquids

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Ion specific effects on the mutual solubilities between hydrophobic ionic liquids (ILs) and water are complex and not fully understood. The aim of this work is to obtain further evidence about the molecular mechanism behind this phenomenon by evaluating the effect of a large series of inorganic and organic salts on the mutual solubilities of water and the ionic liquid 1-butyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide, [C$_4$mim][Tf$_2$N]. The magnitudes of the salting-in and salting-out effects were assessed by changing either the cation or the anion, in a series of salts, as well as the salt concentration. It was observed that the influence of the ions on the solubility followed the Hofmeister series. Both salting-in and salting-out effects were observed and they showed to be dependent on both the nature of the salt and its concentration, while the pH had only a marginal effect on the studied solubilities. On the basis of the solubility changes of the ionic liquid in water in the presence of salts and on NMR spectroscopic data, it will be shown that salting-out inducing ions (high charge density) and salting-in inducing ions (low charge density) act through different mechanisms. While the former act mainly through an entropic effect resulting from the formation of water-ion hydration complexes which cause the dehydration of the solute and the increase of the surface tension of the cavity, the salting-in results from a direct ion binding of the low charge density ions to the hydrophobic moieties of the solute.

Introduction

In recent years ionic liquids (ILs) have earned special attention from the scientific community and an exponential increase of studies involving different features, properties, and applications of ILs have been presented hitherto. Their particular physico-chemical characteristics, such as high solvation ability and coordination properties, general nonflammability, wide liquidus range, wide electrochemical window, high thermal stability, and negligible vapor pressures make them suitable candidates for a large range of applications.[1,2] The possibility of controlling their properties by the adequate manipulation of the cation and/or the anion allows the design of these solvents to present selective solubilities for particular components in fluid mixtures. These characteristics make ionic liquids excellent alternative solvents for extraction purposes and potential green solvents of industrial interest.[3]

In particular, the use of ILs with low mutual solubilities with water as biphasic extraction media for the removal of organics from aqueous media is an active area of research.[4−8] The chemical versatility of ILs makes them interesting for biotechnological separations as shown by their successful application in the recovery of butan-1-ol from fermentation broths,[6] for the extraction of antibiotics,[7] and as solvents for multiphase biotransformation reactions.[8] The optimization of these extraction and purification processes requires a detailed understanding of the phase behavior between aqueous phases and IL systems. Despite our contributions for the characterization of the mutual solubilities between water and hydrophobic ILs,[9−12] there are still many gaps in what concerns the knowledge and understanding of the equilibrium between the aqueous phase of a fermentative medium (that usually contains common salts, sugars, substrates and fermentation metabolites and/or products in their composition) and the IL solvent. In previous works,[9−12] we observed that even those ILs considered hydrophobic present a significant solubility in water leading to water contamination problems. A possibility to overcome this difficulty is the promotion of salting-out by the addition of salts and therefore decreasing the IL solubility in water.

The first attempt to promote IL salting-out in aqueous solutions made use of supercritical carbon dioxide.[13−19] This fluid has shown antisolvent effects inducing liquid−liquid phase separation between ILs and organic or water liquid mixtures as well as the precipitation of solid solutes dissolved in ILs.[13−19] Scurto et al.[14] showed that the phase separation of water and ILs in the presence of CO$_2$ can partly result from the formation of carbonate in solution. In addition, the enhancement of liquid−liquid phase separation in systems involving ILs and aqueous phases using inorganic salts was firstly qualitatively studied by Dupont et al.[20] followed by Gutowski et al.[21] who confirmed those results quantitatively. Trindade et al.[22] described the entire liquid−liquid temperature-composition phase diagram between aqueous salt solutions and an hydrophilic IL, [C$_4$mim][BF$_4$], where significant upward shifts of the liquid−liquid demixing temperatures of those systems were observed. On the other hand, Najdanovic-Visak et al.[23] presented ternary phase diagrams describing the large salting-out effect produced by the

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addition of potassium phosphate to aqueous solutions of water-miscible ionic liquids. Moreover, recently, Canongia Lopes and Rebelo[24] reviewed the salt effects of hydrophilic IL-containing systems and some of their applications.

Currently the ILs mostly used in biocatalysis are hydrophobic since they can remove the water internally bonded from the enzymes more efficiently than hydrophilic ILs.[25] Moreover, the enzymes become suspended rather than dissolved in hydrophobic media preventing their denaturation due to the high ionic strength of the organic phase.[25] To the best of our knowledge, only one report of the effect of salts on hydrophobic ILs aqueous solubility was presented by us.[26]

From a theoretical point of view, and although the ionic strength and the electrolyte nature are recognized important factors, the specific ions effects are not embraced by classical and electrostatic theories of physical chemistry. The ability of ions to induce changes in a broad range of physical properties typically follows the well-known Hofmeister series.[27] This series was initially explained based on the ordering of bulk water and on the ability of the ions to increase or decrease the water structure by a simple hydration phenomena. This has long been known to be not correct, and recently a large number of authors have been addressing this subject trying to find an explanation for the observed effects produced by ions in aqueous solution.[28−31] Results by Zhang et al.[32] for the poly(N-isopropylacrylamide), PNIPAM, solubility in aqueous salt solutions indicate that direct interactions between the solute and the salt ions in the first hydration shell are present. The model proposed by these authors[32] is based on three types of interactions to explain the specific ion effects observed: (i) the destabilization of the hydration of the solute polar groups through polarization by the ion; (ii) enhanced surface tension of the solvent modulated by the salt; (iii) direct binding of the ion to the polar groups of the molecule. Interactions (i) and (ii) would cause salting-out while (iii) would be responsible for the salting-in effects. Zangi et al.[33] recently presented molecular dynamic simulation results indicating that the hydrophobic particles salting-out results from purely hydrophobic effects due to the formation of hydration complexes by the high charge density ions that reside away from the hydrophobic surfaces. The salting-in, caused by the low charge density ions, results from a more complex interplay of enthalpic/entropic effects but seems to be essentially induced by the binding of the ions to the hydrophobic surface. The ions specific effects seem thus to be dominated by the ions-solute versus ions-water-solute interactions, through a complex interplay of factors and not by the water-structure modification as classically accepted.[27,32,33] Both bulk and surface effects may play a role in describing the salting-in and salting-out effects.[32] The Hofmeister series,[27] although an excellent qualitative approach to predict the ions influence on the solute solubility, still requires the development of a theoretical framework that would allow the complete understanding of the ion-specific effects.

The main goal of this study is to determine the effect of a large series of inorganic and organic ions and their concentrations in the mutual solubilities of water and 1-butyl-3-methylimidazolium bis(trifuoromethylsulfonyl)imide, $[C_4mim][Tf_2N]$, a model commonly used liquid salt. These data will then be used to try to foster our understanding within the ion specific effects on the solubility of charged molecules, such as the ILs, on aqueous salt solutions. The bis(trifluoromethylsulfonyl)imide-based ILs were chosen for this work because they are one of the most interesting imidazolium-based ionic liquids for various

applications due to their high hydrophobicity, high thermal and aqueous stability, relatively low viscosity, and high densities.[34−37]

It will be shown that both salting-in and salting-out effects are obtained depending on the salt nature and concentration and that the salts influence on the water-ionic liquid mutual solubilities qualitatively follows the Hofmeister series.[27] The influence of the pH of the aqueous solutions on the mutual solubilities is shown to be marginal and in agreement with the $[C_4mim]^+$ acidity and the $[Tf_2N]^-$ basicity. The salting-out effect will be shown to be essentially entropically driven, as suggested before,[32,33] while the salting-in is controlled by the direct binding of the low charge density ions to the hydrophobic moiety of the IL cation as implied by the NMR spectroscopic information.

Experimental Section

Materials. Mutual solubilities measurements were performed between water and $[C_4mim][Tf_2N]$ in the presence of the following inorganic and organic salts: NaCl > 99.5 w/w % pure from Panreac, NaNO₃ > 99.5 w/w % pure from Himedia, NaSCN ≥ 98.0 w/w % pure from Fluka, NaCH₃CO₂ > 99.8 w/w % pure from Pronalab, NaOH > 98.0 w/w % pure from Panreac, NaHCO₃ > 99.5 w/w % pure from Merck, NaHSO₄·H₂O > 99.0 w/w % pure from Panreac, NaH₂PO₄ > 99.0 w/w % pure from Panreac, Na₂SO₄ > 99.0 w/w % pure from Panreac, Na₂CO₃ > 99.7 w/w % pure from Carlo Erba, Na₃C₆H₅O₇·2H₂O > 99.5 w/w % pure from Panreac, Na₃PO₄·12H₂O > 98 w/w % pure from Riedel-de Haën, KCl > 99 w/w % pure from Pronalab, NH₄Cl > 99.5 w/w % pure from Panreac, HCl 37 w/w % solution from Riedel-de Haën, (CH₃)₄NCl ≥ 98 w/w % pure from Fluka, LiCl > 98 w/w % pure from VWR/Prolabo, MgCl₂·6H₂O > 99 w/w % pure from Riedel-de Haën, CaCl₂·2H₂O > 99 w/w % pure from Riedel-de Haën, SrCl₂·6H₂O > 99 w/w % pure from Merck. All the salts were used without further purification steps.

1-Butyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide was prepared as reported elsewhere.[34] The reagents $[C_4mim][Br]$ and $[Li][Tf_2N]$ were acquired at IoLiTec with mass fraction purities >99% and >98%, respectively. To reduce the water content and specially the volatile compounds to negligible values, the IL was dried at vacuum and at 353 K, using continuous stirring, for a minimum of 48 h. After that procedure, the IL purity was checked by ¹H, ¹³C, and ¹⁹F NMR spectroscopy and found to be >99%. The bromide content was quantified by ion chromatography and found to be inferior to 100 ppm mass fraction. The water used was double distilled, passed by a reverse osmosis system, and further treated with a Milli-Q plus 185 water purification apparatus. It has a resistivity of 18.2 MΩ·cm, a TOC smaller to 5 μg·L⁻¹, and it is free of particles greater than 0.22 μm. The anolyte used for the coulometric Karl-Fischer titration was Hydranal - Coulomat AG from Riedel-de Haën. The deuterium oxide used was acquired at Aldrich with >99.96% D atom. The 3-(trimethylsilyl)propionic-2,2,3,3-d4 acid sodium salt (TSP) was from Aldrich with >98% D atom.

Experimental Procedure. The mutual solubilities measurements between water and ILs for aqueous salt concentrations ranging from (0 to 1.5) mol·kg⁻¹ were carried out at 298.15 K and atmospheric pressure. The aqueous salt solutions were prepared gravimetrically in ultrapure water with an associated uncertainty of ±10⁻⁴ g. The IL and the salt aqueous phases were initially vigorously stirred and allowed to reach mutual saturation by the equilibration of both phases for at least 48 h. This period was found to be the minimum time required to guarantee a complete separation of the two phases and that no further variations in mole fraction solubilities occurred.[34−37]

The glass vials containing the two visible phases were in equilibrium at 298.15 K inside an aluminum block that is placed in an isolated air bath capable of maintaining the temperature within ±0.01 K. The temperature was achieved with a PID temperature controller driven by a calibrated Pt100 (class 1/10) temperature sensor inserted in the aluminum block. The solubility of water in the IL-rich phase was determined using a Metrohm 831 Karl-Fischer (KF) coulometer and the solubility of the IL in the aqueous phase was determined by UV-spectroscopy using a SHIMADZU UV-1700 Pharma-Spec Spectrometer at a wavelength of 211 nm (using calibration curves previously established and discounting for the salts absorbance whenever present). This wavelength was found to be the maximum UV absorption length for the studied imidazolium-based IL. Both rich-phases were sampled from the equilibrium vials using glass syringes maintained dry and at the same temperature of the measurements, a procedure which is feasible by the use of an air bath. For the IL-rich phase, samples of ≈(0.1 to 0.2) g were taken and directly injected in the KF coulometric titrator while for the aqueous phase, samples of ≈0.5 g were taken and diluted by a factor of ≈(1:500 to 1:2000) (w/w) in ultra pure water. The mutual solubilities results for each salt solution and at each salt concentration were determined gravimetrically and are an average of at least five independent measurements.

For NMR spectra results, a solution of [C$_4$mim][Tf$_2$N] at approximately 0.012 mol·kg^{-1} in D$_2$O (below the IL saturation limit and low enough to assure completely dissociation in aqueous solution), using TSP as a reference, was prepared gravimetrically with an associated uncertainty of ±10^{-4} g. The salt solutions were further prepared gravimetrically in the D$_2$O−IL−TSP initial solution with salt concentrations ranging from (0 to 1.0) mol·kg^{-1}. For each salt effect analysis, the IL concentration is at exactly the same concentration than the pure IL−D$_2$O−TSP solution used to determine the chemical shifts deviations. Due care was taken to avoid contamination of the solutions with moisture. The ^{1}H NMR spectra were recorded using a Bruker Avance 300 at 300.13 MHz using D$_2$O as solvent and TSP as internal reference.

Experimental Results

For each salt solution in equilibrium and at specific salt concentrations ranging between (0 and 1.5) mol·kg^{-1}, the mutual solubilities of water and [C$_4$mim][Tf$_2$N] were experimentally measured at 298.15 K and atmospheric pressure. Preliminary studies showed that the NaCl only has marginal effects on the mutual solubilities of the [C$_4$mim][Tf$_2$N] as also observed for other organic compounds. For that reason, a large series of salts based on either Cl$^-$ or Na$^+$ were used in this work to individualize the effect of the anion and the cation. The measured mutual solubilities data and respective standard deviations are presented in the Supporting Information of this manuscript. The experimental results obtained are also depicted in Figures 1 to 6.

The solubility of a compound in water is generally affected by the presence of an electrolyte. The decrease of solubility is known as salting-out or Setchenov effect and the increase is known as salting-in effect.[37] The solubility data of the ILs in water displays both salting-in and salting-out effects, depending on the cation and anion of the electrolyte used and their concentration. For most ions, it is possible to observe salting-in at low salt concentrations followed by the IL salting-out at higher salt concentrations. For the IL-rich phase the presence of a salt seems to induce mainly salting-out of water. The
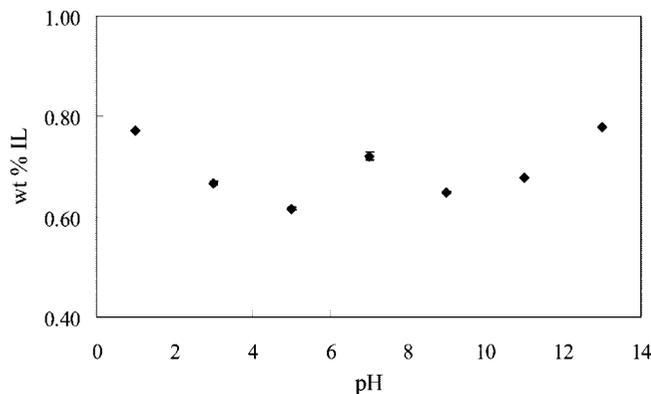

Figure 1. Solubility of [C$_4$mim][Tf$_2$N] in water as a function of the aqueous phase pH before equilibration.
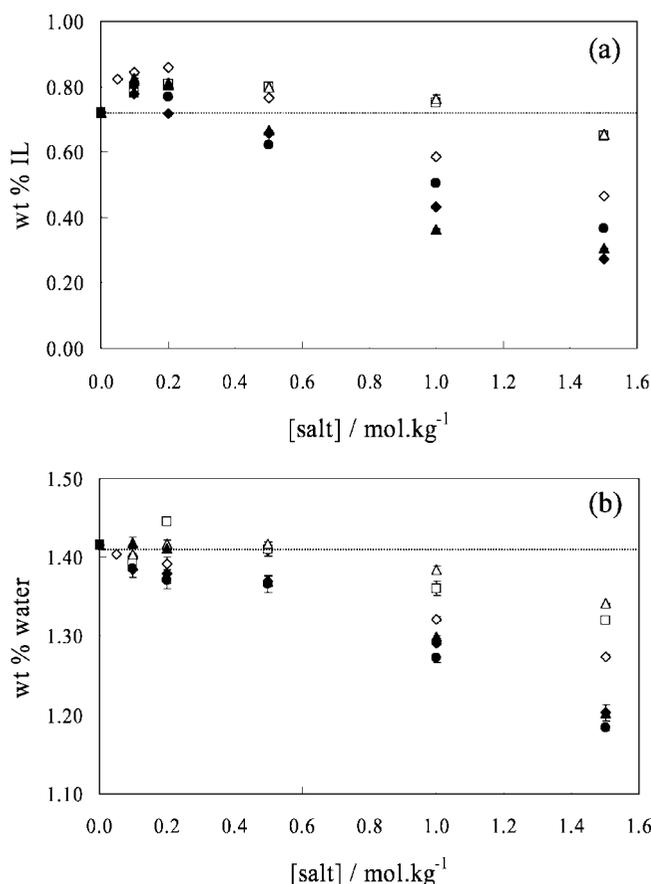

Figure 2. Solubility of [C$_4$mim][Tf$_2$N] in water (a) and solubility of water in [C$_4$mim][Tf$_2$N] (b) for the aqueous salt solutions: ◇, NaCl; □, LiCl; △, KCl; ●, MgCl$_2$; ◆, SrCl$_2$; ▲, CaCl$_2$.

influence of the pH on the mutual solubilities was also studied using HCl or NaOH and two shallow minima were observed in the IL solubility in water; see discussion below.

The addition of salts to ionic aqueous systems leads to a more complex phase equilibria than for non-electrolyte systems, where different mechanisms as ion exchange and ion-pairing may occur.[38−42] Since the prime goal of this work is to analyze the influence of salts addition, and to discuss their relative effects in the mutual solubilities between water and hydrophobic ILs, no speculations about possible ion-exchange mechanisms will be carried here. However, a complete understanding of the ions partitioning process in those systems is of major importance before an accurate judgment about the ILs prospective and potential applications is made.
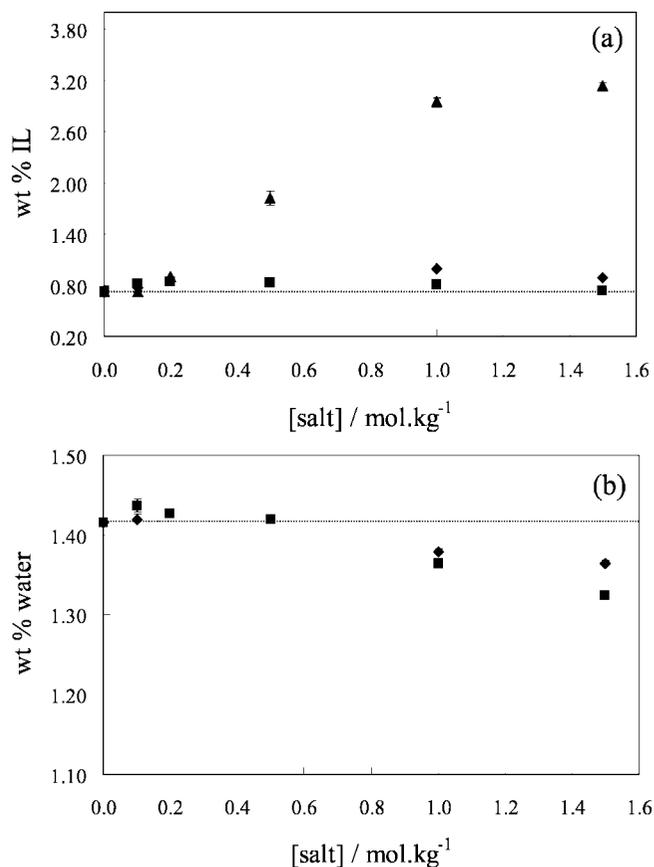
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Figure 3. Solubility of [C$_4$mim][Tf$_2$N] in water (a) and solubility of water in [C$_4$mim][Tf$_2$N] (b) for the aqueous salt solutions: ◆, HCl; ■, NH$_4$Cl; ▲, (CH$_3$)$_4$NCl.

pH Influence. Several organic and inorganic ions used in this work have a non-negligible acidic or basic character and could play a role in the solubility of the ionic liquid through the modification of the pH of their aqueous solutions. To evaluate this effect, the pH influence on the IL solubility in water was addressed by preparing aqueous solutions of HCl or NaOH with pH values ranging from 1 to 13. The results obtained are presented in Figure 1.

Two minima in the solubility of IL in water were observed. These two minima are in agreement with the basic character of the [Tf$_2$N] anion (aqueous solutions of Na[Tf$_2$N] present pH between 8 and 10) and the acidic character of the [C$_4$mim] cation (aqueous solutions of [C$_4$mim]Cl present pH between 4 and 6). The pH influence in the solubility of [C$_4$mim][Tf$_2$N] in water can be considered negligible when compared with the effect of the added salts in those solubilities, as will be shown below. Note that for pH 1 and pH 13, the solubility trend shown in Figure 1 has inherently to follow very closely that presented when the HCl salt molality is 0.10 mol·kg^{-1} (Figure 3a) and NaOH salt molality is 0.10 mol·kg^{-1} (Figure 6a), respectively. For this reason, in the results presented hereafter no pH adjustment of the aqueous phase was done. This study was performed without the addition of a buffer salt to the solution, a procedure that would lead to changes in the global salt concentration and mask the effects of the primary salt under studied on the IL-water mutual solubilities.

Cation Influence. In order to infer about the cation effect on the mutual solubilities, several chloride-based salts were used in different concentrations. These cations were divided into two classes according to the salting-in/salting-out behavior that they induce. Figures 2 and 3 present the results obtained for both the [C$_4$mim][Tf$_2$N]-rich and the water-rich phases. Both salting-in and salting-out effects were observed depending on the salt employed, its concentration and the phase under study. The results show that the solubilities at the aqueous phase are more affected by the presence of a salt than the solubilities at the IL-rich phase.

In Figures 2 and 3, it is possible to observe that most salts promote the IL salting-in at low salt concentrations followed by salting-out at higher salt concentrations. This effect is analogous to that observed for the aqueous solubility of other charged molecules such as proteins.[43] As more salt is added, the solubility of the charged molecules in aqueous solution starts to decrease. The salting-in followed by salting-out effect is the behavior observed for the majority of the salts used at the water-rich phase and besides the current [C$_4$mim][Tf$_2$N] case, it was also observed by us for both hydrophobic ionic liquids, such as [C$_4$mim][PF$_6$], and hydrophilic ones, such as [C$_8$mim][BF$_4$].

In Figure 2, it can observed that different salts (NaCl, LiCl, KCl, MgCl$_2$, CaCl$_2$, and SrCl$_2$) induce salting-out of the [C$_4$mim][Tf$_2$N] from the aqueous phase at moderate concentrations. At a salt concentration of 1.5 mol·kg^{-1}, the IL solubility salting-out decreasing order is following the sequence: Sr^{2+} > Ca^{2+} > Mg^{2+} > Na$^+$ > Li$^+$ ≈ K$^+$. On the contrary, in Figure 3 it can be observed that there are three salts, HCl, NH$_4$Cl, and mainly (CH$_3$)$_4$NCl, that at 1.5 mol·kg^{-1} salt molality promote an increasing salting-in of the IL in water following the cation increasing order effect: NH$_4^+$ < H$^+$ < (CH$_3$)$_4$N$^+$.

At the highest salt molality studied and maintaining the Cl$^-$ anion in common, the strongest salting-out inducing cation studied was Sr^{2+} and the strongest salting-in inducing cation was found to be (CH$_3$)$_4$N$^+$. In general, the cation influence in the water solubility of [C$_4$mim][Tf$_2$N] here reported seems to closely follow with some minor deviations the Hofmeister series.[27,44] The Hofmeister series[27] was established to evaluate the ionic effects on the aggregation or stabilization phenomena of particles immersed in aqueous solutions. The ionic effects on different properties such as polymer cloud points, protein solubility, chromatographic selectivity, critical micelle concentration, surface tension, gel-coagel transitions, molecular forces, and colloid stability have been intensively investigated since then.[45] Interestingly, it was also found that depending on the system and on the salt concentration some deviations of this well-established series can exist as is also verified in this work. The most remarkable discrepancy relative to the Hofmeister series is observed here for the cation H$^+$ that presents an opposite trend of what was expected since it promotes the salting-in of the IL in the aqueous phase. The bis(trifluoromethylsulfonyl)imide anion basic character is the major responsible for this result.

For the water solubility in [C$_4$mim][Tf$_2$N], presented in Figure 2 and 3, only minor effects were observed when compared to the deviations observed for the aqueous phase. The cation influence in the water solubility at a salt concentration of 1.5 mol·kg^{-1} follows the order: Mg^{2+} > Ca^{2+} ≈ Sr^{2+} > Na$^+$ > Li$^+$ > K$^+$. No relevant salting-in of water into the IL was observed. It seems that the change in the water activity in the aqueous phase plays a dominant role on the phase equilibria of the IL-rich phase. The increase of the salt concentration in the water-rich phase reduces the chemical potential of water resulting thus in the decrease of the solubility of water in the IL.

Anion Influence. To infer about the anion effect on the mutual solubilities, several sodium-based salts were used in different concentrations. Since anions are typically more
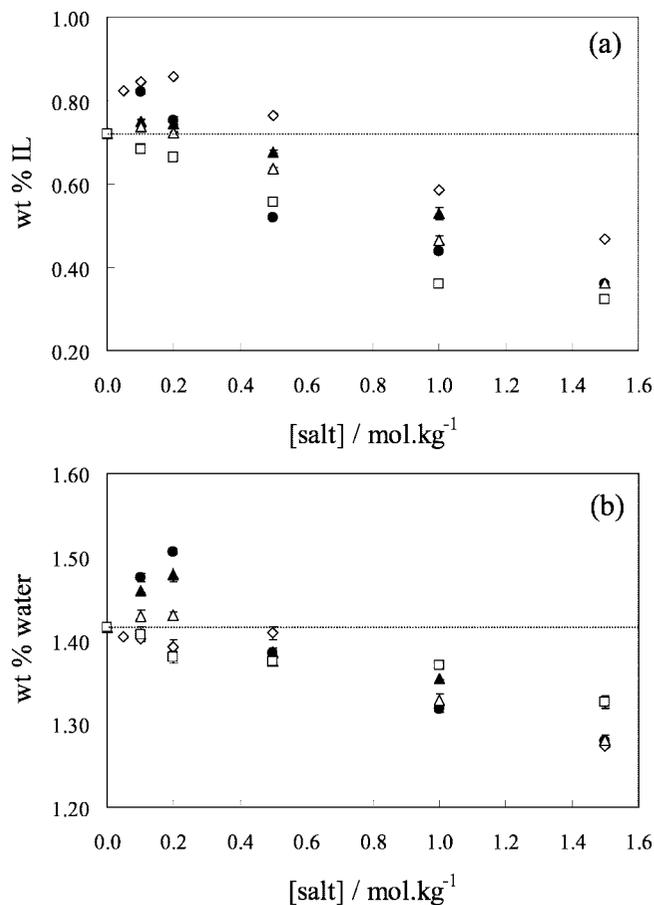
Figure 4. Solubility of [C$_4$mim][Tf$_2$N] in water (a) and solubility of water in [C$_4$mim][Tf$_2$N] (b) for the aqueous salt solutions: ◇, NaCl; △, NaHSO$_4$; ☐, NaH$_2$PO$_4$; ▲, NaHCO$_3$; ●, NaCH$_3$CO$_2$.

Figure 5. Solubility of [C$_4$mim][Tf$_2$N] in water (a) and solubility of water in [C$_4$mim][Tf$_2$N] (b) for the aqueous salt solutions: ☐, Na$_2$CO$_3$; ▲, Na$_2$SO$_4$; ●, Na$_3$PO$_4$; ◇, Na$_3$C$_6$H$_5$O$_7$.

polarizable than cations (α(Na$^+$), 0.12 Å^3; α(K$^+$), 0.78 Å^3; α(Cl$^-$), 4.00 Å^3)[46] due to their more diffuse valence electronic configuration, their hydration is usually stronger than that of cations and, therefore, their salting-in/salting-out effects are more pronounced. For that reason a larger series of anions was studied to classify them accordingly to the behavior they induce on the ILs/water phase equilibria.

The results obtained for both phases with sodium-based several salts investigated (NaCl, NaCH$_3$CO$_2$, NaHCO$_3$, NaHSO$_4$, NaH$_2$PO$_4$, Na$_2$SO$_4$, Na$_2$CO$_3$, Na$_3$PO$_4$ and Na$_3$C$_6$H$_5$O$_7$) are reported in Figures 4 and 5. As observed before for the cations, an IL salting-in region is observed at low salt concentrations with the salts NaCl, NaCH$_3$CO$_2$, NaHCO$_3$, NaHSO$_4$, Na$_2$CO$_3$ and Na$_3$C$_6$H$_5$O$_7$, followed by salting-out at higher concentrations. The effect of the anion on decreasing the IL solubility at a 1.5 mol·kg^{-1} salt molality follows the order: C$_6$H$_5$O$_7^{3-}$ > CO$_3^{2-}$ > SO$_4^{2-}$ > H$_2$PO$_4^-$ > CH$_3$CO$_2^-$ $\approx$ HSO$_4^-$ > Cl$^-$. Because of the low solubility of Na$_3$PO$_4$ in water, it is impossible to directly compare the effect of this salt at this concentration, but for the 0.50 mol·kg^{-1} concentration the PO$_4^{3-}$ displays a salting-out inducing capacity stronger than C$_6$H$_5$O$_7^{3-}$. This indicates that citrates, phosphates, carbonates, and sulfates may be used to reduce the solubility of ionic liquids in water with possible application in the treatment of aqueous effluents contaminated with ILs. This impact on the solubility leads also to the formation of aqueous two phase systems that may be used in liquid−liquid extraction of biologic molecules and allows for the recovery and purification of ionic liquids from aqueous solutions.

The experimental data for the salting-in inducing salts studied (NaOH, NaSCN, and NaNO$_3$) are summarized in Figure 6.
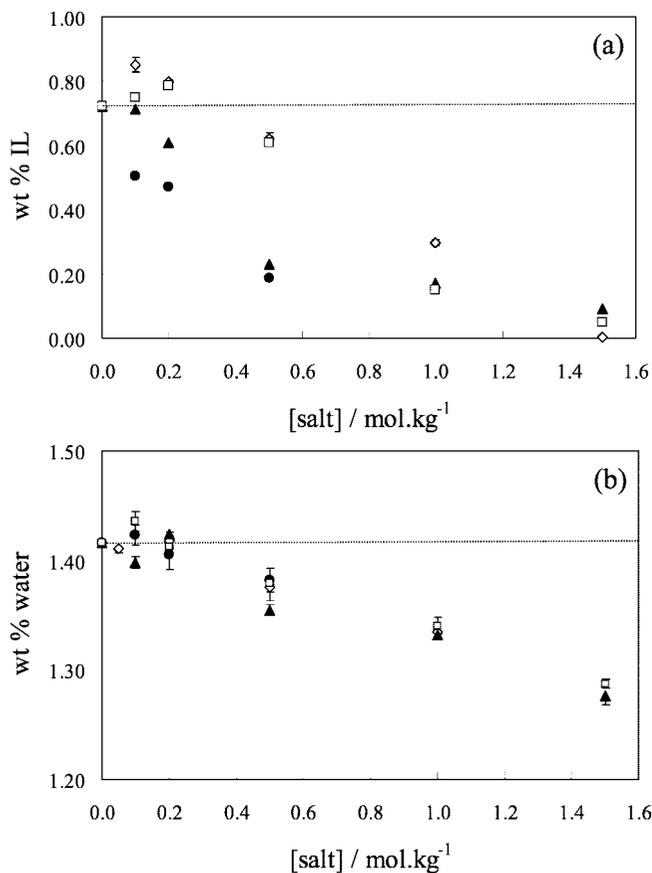
These salts were found to promote the salting-in of the IL following the increasing order effect: NO$_3^-$ < OH$^-$ < SCN$^-$.

The results indicate that the anion that induces the strongest salting-out effect was PO$_4^{3-}$ and the anion that brings on the strongest salting-in effect is SCN$^-$. As observed for the cations, the effect of the anions on the water solubility of ionic liquids obeys the Hofmeister series.[27,46] The exception is the OH$^-$ ion that induces salting-in at moderate concentrations of NaOH. This is similar to the behavior observed before for the HCl influence and it is related with the 1-butyl-3-methylimidazolium cation acidity.

In the IL-rich phase only a minor decrease of the water solubility in the ionic liquid is observed, when compared with the aqueous phase. All anions induce a decrease in the solubility of water in [C$_4$mim][Tf$_2$N] at salt concentrations higher than 0.20 mol·kg^{-1}. At a salt concentration of 1.5 mol·kg^{-1}, the effect of the anions on the decrease of the solubility of water follows the order C$_6$H$_5$O$_7^{3-}$ > SO$_4^{2-}$ > CH$_3$CO$_2^-$ > HSO$_4^-$ > OH$^-$ > CO$_3^{2-}$ > SCN$^-$ > H$_2$PO$_4^-$ > NO$_3^-$.

Discussion

Debates about the ionic species ability to alter the hydrogen bonding network of water and the adequacy of the concepts of "kosmotrope" ("water structure makers") and "chaotrope" ("water structure breakers") have been going on during the last few years.[27−32,46−49] Studies of the orientational correlation function of the water molecules in salt solutions have demonstrated that most anions, outside their direct vicinity, have no influence on the dynamics of the water structure, even at
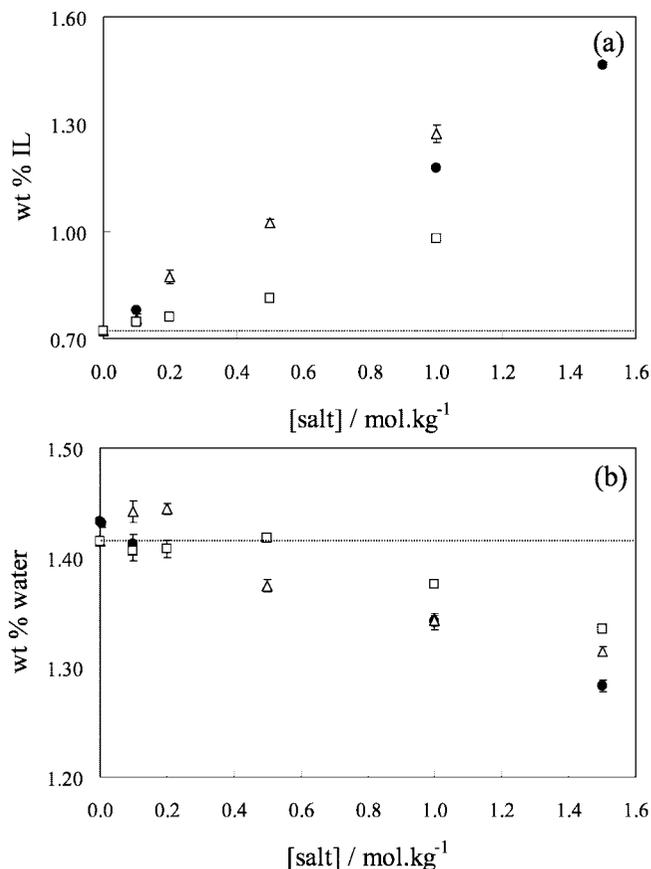
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Figure 6. Solubility of [C$_4$mim][Tf$_2$N] in water (a) and solubility of water in [C$_4$mim][Tf$_2$N] (b) for the aqueous salt solutions: ●, NaOH; Δ, NaSCN; □, NaNO$_3$.

influence in several physical behaviors, the molecular level mechanism by which ions operate in aqueous solutions remains unclear[32] and an explanation based on changes of the bulk water structure is fundamentally flawed. Thus a new conceptual model to explain the interactions between salt ions and charged solutes in aqueous solutions is required. We believe this work constitutes a contribution towards that goal.

The results obtained in this work indicate, as detailed below, that the solubility of charged molecules, such as ILs, on aqueous salt solutions is determined by the following two major effects: (i) an entropic effect promoting salting-out, caused by the presence of high charge density ions due to the formation of hydration complexes away from the solute hydrophobic moieties and an increase on the surface tension of water, and, thus, on the energy of cavity formation; (ii) the direct binding of the ions of low charge density to the solute hydrophobic moieties, hence inducing salting-in.

In order to better understand the complex interplay of different solvation phenomena of 1-butyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide in aqueous salt solutions, chemical shift deviations for the protons of the IL cation on solutions of NaSCN and Na$_2$CO$_3$ in the concentration range (0.0 to 1.0) mol kg^{-1} were measured and reported in Figures 7 and 8. The experimental ^{1}H NMR chemical shifts obtained are reported in the Supporting Information of this manuscript. Positive deviations, resulting from the interaction between the salt ions and the solute, are observed in both cases for the protons on the ring and on carbon 6. However, while interactions between SCN$^-$ and the protons of the hydrophobic moiety of the IL (the side alkyl chain) are also observed, they are conspicuously absent for the CO$_3^{2-}$. Interestingly, the behavior depicted for SCN$^-$ is also observed for the other salting-in inducing salts while that of CO$_3^{2-}$ is observed for the salting-out inducing salts studied. NMR spectra proves to be a valuable tool in the understanding of the relative positioning of the ions that clearly reveals a complex solvation scheme that is present in this type of systems. This methodology will be fully explored in a future work. These findings are in agreement with the results by Zangi et al.[33] where the binding of the ions to the hydrophobic moiety of the solute is responsible for the salting-in in aqueous salt solutions.
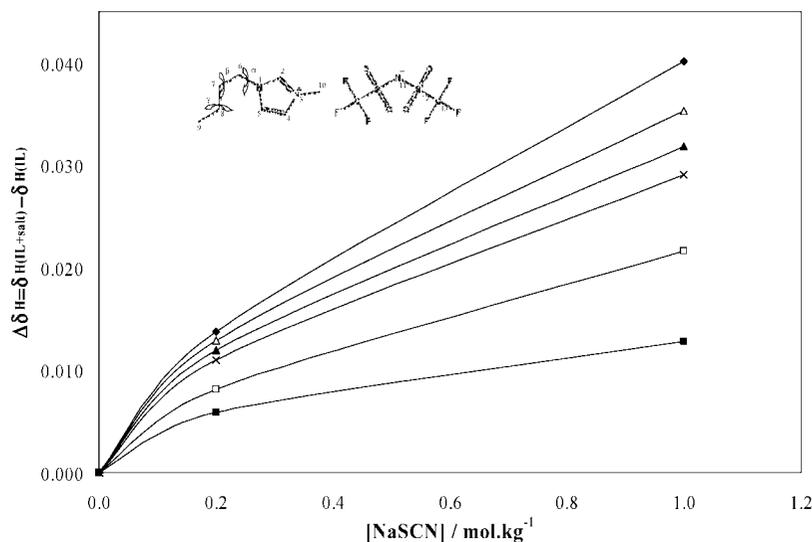
significantly high concentrations of salts.[28−30] There seem to be no long-range ion effects of structure-making or structure-breaking in bulk water for either chaotropes and kosmotropes.[27−33] Thermodynamic studies employing pressure perturbation calorimetry to aqueous ionic solutions also clearly indicate that there are no water structure makers or water structure breakers.[29] These experimental evidences show that although the Hofmeister series provides an adequate qualitative description of the salts

Figure 7. ^{1}H NMR chemical shifts deviations between the salt aqueous solutions and the pure [C$_4$mim][Tf$_2$N] as a function of the NaSCN concentration (relative to TSP in D$_2$O): □, H (4) and H (5); Δ, H (6); ▲, H (7); ×, H (8); ■, H (9); ◆, H (10).

Figure 8. ^{1}H NMR chemical shifts deviations between the salt aqueous solutions and the pure [C$_4$mim][Tf$_2$N] as a function of the Na$_2$CO$_3$ concentration (relative to TSP in D$_2$O): □, H (4) and H (5); Δ, H (6); ▲, H (7); ×, H (8); ■, H (9); ◆, H (10).
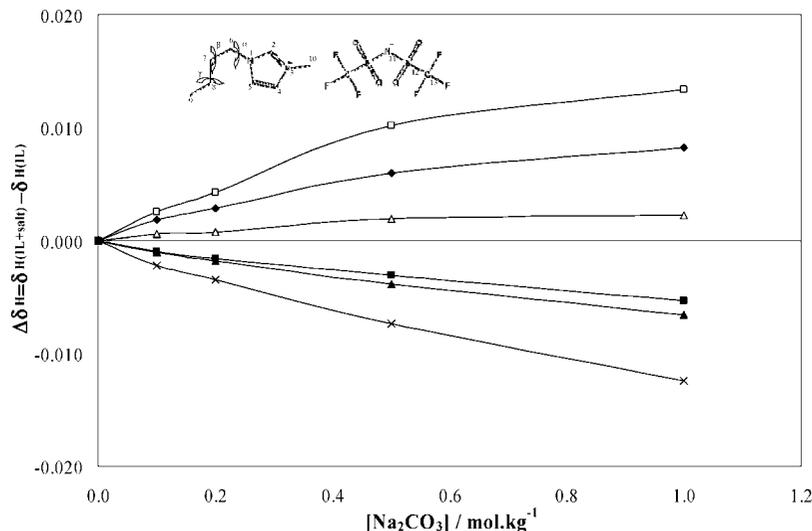
Following the approach of Zhang et al.[32] the effect of the different salts and their concentration on the [C$_4$mim][Tf$_2$N] solubility at constant temperature will be described as

$$IL = IL_0 + kc + \frac{B_{max}K_Ac}{1 + K_Ac} \qquad (1)$$

where IL is the [C$_4$mim][Tf$_2$N] solubility in the saline solution, IL$_0$ is the [C$_4$mim][Tf$_2$N] solubility in pure water, c the concentration of salt in molality, and k, B_{max}, and K_A are adjustable parameters that describe the phenomena that affect the solute solubility. This equation was developed based on the fact that the polarization of the water molecules at the first hydration shell and the interfacial tension of the water in contact

with an hydrophobic surface are linearly dependent on the salt concentration in diluted and moderately concentrated solutions and that the binding of the ion to the solute can be described by a Langmuir type of isotherm.[32] In order to evaluate the performance of the solvation model here proposed, eq 1 was used to correlate the solubility data measured in this work and the values of the fitted parameters are reported in Table 1. Note that the last term was only used for salts that induce ionic liquid salting-in in water.

The molar Gibbs energy of hydration of the ions ($\Delta_{hyd}G$)[51] has been widely used to evaluate the ions influence on aqueous solubilities. The relationship between the constant k and $\Delta_{hyd}G$ for the experimental data measured in this work is presented in Figure 9 for both anions (a) and cations (b). On the other hand, Zhang et al.[32] have shown that the effect of various ions on

TABLE 1: Fitted Constants for Each Ion Studied Using Equation 1 (k, K_A, and B_{max}) and literature values for the ions molar entropy ($\Delta_{hyd}S$)[51] and Gibbs energy ($\Delta_{hyd}G$)[51] of hydration at 298 K and the surface tension increments (γ)[52]

cation	k/ (mol of IL·mol of salt^{-1})	K_A/ (kg·mol of salt^{-1})	B_{max}/ (mol of IL·kg^{-1})	$\Delta_{hyd}S$/ (J·K^{-1}·mol^{-1})	$\Delta_{hyd}G$/ (kJ·mol^{-1})	γ/ (mN·dm^3·m^{-1}·mol^{-1})
Na$^+$	−0.0038			−111	−375	1.64
H$^+$	−0.0143	0.1118	0.2291	−131	−1056	n.a.[a]
Li$^+$	−0.0006			−142	−481	1.69
K$^+$	−0.0004			−74	−304	1.38
NH$_4^+$	−0.0524	0.1847	0.4377	−112	−292	1.38
(CH$_3$)$_4$N$^+$	−0.0470	0.1561	0.6890	−144	−160	n.a.[a]
Mg^{2+}	−0.0054			−331	−1838	2.12
Ca^{2+}	−0.0069			−252	−1515	3.67
Sr^{2+}	−0.0067			−242	−1386	3.35

anion	k/ (mol of IL·mol of salt^{-1})	K_A/ (kg·mol of salt^{-1})	B_{max}/ (mol of IL·kg^{-1})	$\Delta_{hyd}S$/ (J·K^{-1}·mol^{-1})	$\Delta_{hyd}G$/ (kJ·mol^{-1})	γ/ (mN·dm^3·m^{-1}·mol^{-1})
Cl$^-$	−0.0038			−75	−347	1.64
OH$^-$	−0.0001	0.8953	0.0131	−161	−439	2.12
NO$_3^-$	−0.0003	0.6423	0.0091	−76	−306	1.06
SCN$^-$	−0.0006	0.2672	0.0623	−66	−287	0.45
CH$_3$CO$_2^-$	−0.0063			−170	−373	n.a.[a]
HCO$_3^-$	−0.0041			−137	−368	n.a.[a]
HSO$_4^-$	−0.0057			−129	−335	n.a.[a]
H$_2$PO$_4^{2-}$	−0.0071			−166	−473	2.30
SO$_4^{2-}$	−0.0118			−200	−1090	2.73
CO$_3^{2-}$	−0.0111			−245	−479	2.69
PO$_4^{3-}$	−0.0270			−421	−2773	2.66

[a] Not available in literature.

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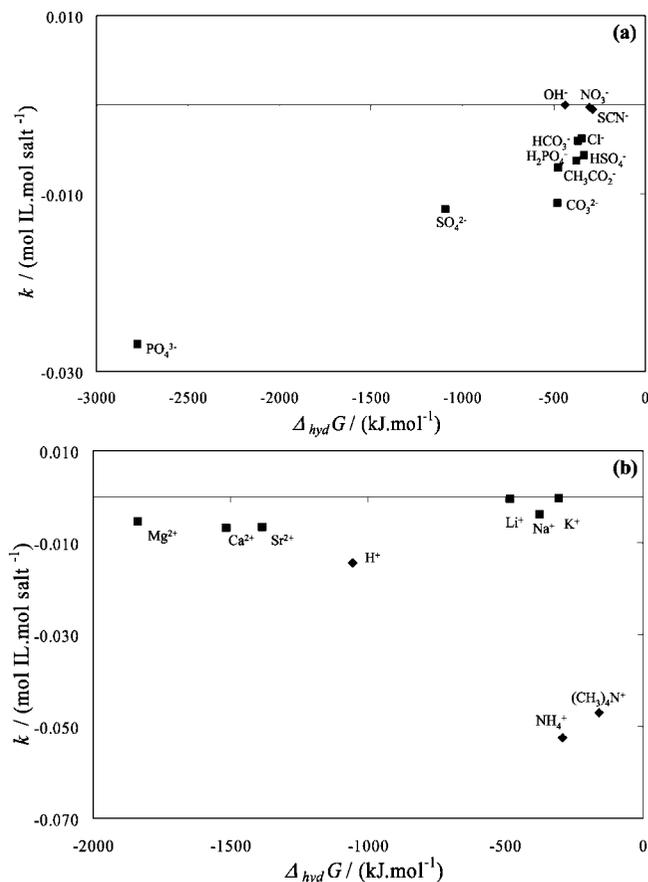*J. Phys. Chem. B, Vol. 113, No. 1, 2009* **209**

Figure 9. Relationship between the constant k from eq 1 and the molar Gibbs energy of the anions (a) and of the cations (b): ■, salting-out inducing ions; ◆, salting-in inducing ions.

Figure 10. Relationship between the constant k from eq 1 and the molar hydration entropy of the anions (a) and of the cations (b): ■, salting-out inducing ions; ◆, salting-in inducing ions.

PNIPAM solubility in aqueous salt solutions is directly correlated to their hydration entropy. Zangi et al.,[33] using molecular dynamics simulations, show the salting-out to be an entropic effect. In a previous work, we have also shown that the solubility of [C$_n$mim][Tf$_2$N] ILs in pure water is entropically driven.[9] In order to further investigate the ion specific effects observed on each system, the dependency of the k parameter on the entropy of hydration was also evaluated for both anions and cations and is presented in Figure 10. The ions molar hydration entropy and Gibbs energy of hydration used were taken from literature[51] and are reported in Table 1. Comparing Figures 9 and 10, a superior correlation is observed between the k parameter and the molar hydration entropy for the salting-out inducing (high charge density) cations and anions. Curiously and in agreement with Zhang et al.,[32] the salting-in inducing (low charge density) ions fall completely outside this trend. This straight dependence of the magnitude of the salting-out on the ions hydration entropy confirms that the salting-out of a charged molecule such as [C$_4$mim][Tf$_2$N] is basically entropically driven as previously suggested.[32,33,48,49]

The k parameter dependence on the aqueous surface tension increment induced by the salt ions is depicted in Figure 11. The surface tension increments used were taken from literature[52] and are presented in Table 1. Figure 11 indicates a direct correlation between the salting-out effect observed, as measured by the k parameter, and the surface tension increment for the salting-out inducing (high charge density) ions. Yet, no such relation was observed for the salting-in inducing ions. Since both salting-out inducing effects are coupled in eq 1, it is not possible to separate them. It is thus impossible at this point to know if the modification of the interfacial tension of the cavity
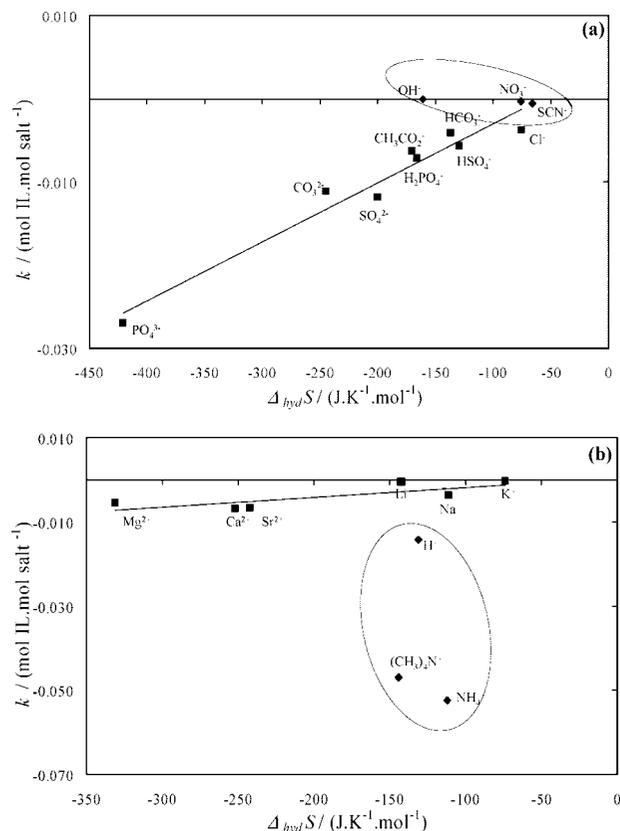
formed is a specific and autonomous contribution to the salting-out effect, or just another expression of the formation of hydration complexes between the high charge density ions and the water.

The results herein obtained indicate that salting-in and salting-out inducing ions operate essentially by different mechanisms, which can be linked to specific ion effects: while salting-in results from a direct ion binding between the ion and the hydrophobic moiety of the ionic liquid, salting-out results from an entropic effect related to the formation of hydration complexes and an increase in the interfacial tension of the aqueous salt solution. The results here reported provide an experimental evidence for the phenomena suggested by Zangi et al.[33] from molecular dynamic simulation data, to explain the effects of ions on the hydrophobic interactions between particles. They also show that although the effect of the ions on the solubility of hydrophobic ionic liquids in water qualitatively follows the Hofmeister series, this is a consequence of the direct, or indirect (water mediated), interactions between the salts ions and the solute and not of a rearrangement of the water structure caused by the ions.

As suggested by the confluence of the results here reported with those by Zhang et al.[32] and Zangi et al.,[33] the evidence here conveyed seems to be relevant not only for charged molecules such as ionic liquids but for hydrophobic and polymeric compounds. Similarly, it is anticipated to be also important in the effect of salts on the aqueous solubility of biomolecules such as peptides or proteins.

Conclusions

The influence of salts in the mutual solubilities between water and the hydrophobic [C$_4$mim][Tf$_2$N] ionic liquid at
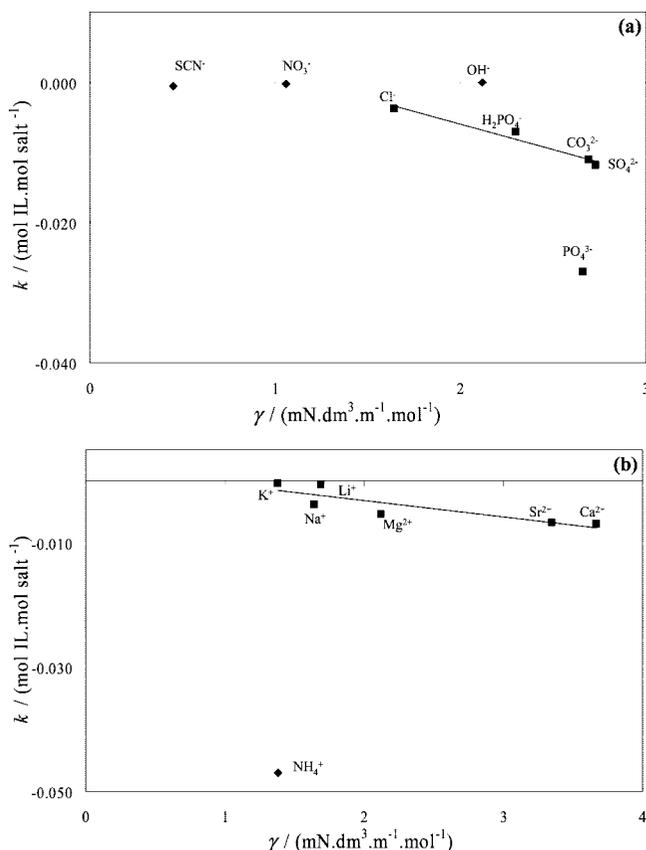
Figure 11. Relationship between the constant k from eq 1 and the surface tension increment of the anions (a) and of the cations (b): ■, salting-out inducing ions; ◆, salting-in inducing ions.

298.15 K and atmospheric pressure was accessed and discussed. The solubility of ILs in aqueous salt solutions is shown to follow a trend analogous to that obtained for other charged molecules such as proteins. At low salt concentrations, a salting-in region is observed while with increasing salt concentration a salting-out of the IL occurs. Both salting-in and salting-out effects were experimentally observed, and they depend on both the salt nature and its concentration. The influence of the pH in the mutual solubilities is marginal.

The influence of the ions in the solubility of water and IL qualitatively follows the Hofmeister series. It was verified that the IL solubility in aqueous salt solutions is ruled by the specific ions effects that result from the direct or indirect (water-mediated) interactions between the salts ions and the solute and not from a rearrangement of the water structure caused by the ions. The results presented herein show that salting-out (high charge density) and salting-in (low charge density) inducing ions act through different mechanisms. While the former have an entropic effect resulting from their tendency to form hydration complexes and to increase the surface tension of the cavity, the latter display a direct ion binding with the hydrophobic moiety of the solute stabilizing this species in solution.

Supporting Information Available: Experimental solubility data and ¹H NMR chemical shifts. This material is available free of charge via the Internet at http://pubs.acs.org.

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