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Published in:
Astronomy & astrophysics

DOI:
10.1051/0004-6361/201015878

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2011

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Aalto, S., Costagliola, F., van der Tak, F., & Meijerink, R. (2011). H3O+ line emission from starbursts and AGNs. Astronomy & astrophysics, 527, [A69]. https://doi.org/10.1051/0004-6361/201015878

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H$_3$O$^+$ line emission from starbursts and AGNs

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Received 6 October 2010 / Accepted 15 December 2010

ABSTRACT

Context. The H$_3$O$^+$ molecule probes the chemistry and the ionization rate of dense circumnuclear gas in galaxies.

Aims. We use the H$_3$O$^+$ molecule to investigate the impact of starburst and AGN activity on the chemistry of the molecular interstellar medium.

Methods. Using the JCMT, we have observed the $3_2^+–2_1^+$; 364 GHz line of p-H$_3$O$^+$ towards the centres of seven active galaxies.

Results. We have detected p-H$_3$O$^+$ towards IC 342, NGC 253, NGC 1068, NGC 4418, and NGC 6240. Upper limits were obtained for IRAS 15250 and Arp 299. We find large H$_2$O$^+$ abundances ($N$(H$_2$O$^+$/N(H$_2$) $\gtrsim 10^{-4}$) in all detected galaxies apart from in IC 342 where it is about one order of magnitude lower. We note, however, that uncertainties in $N$(H$_2$O$^+$) may be significant due to lack of definite information on source size and excitation. We furthermore compare the derived $N$(H$_3$O$^+$) with $N$(HCO$^+$) and find that the H$_3$O$^+$ to HCO$^+$ column density ratio is large in NGC 1068 (24), moderate in NGC 4418 and NGC 253 (4–5), slightly less than unity in NGC 6240 (0.7) and lowest in IC 342 (0.2–0.6). We compare our results with models of X-ray and photon dominated regions (XDRs and PDRs).

Conclusions. For IC 342 we find that a starburst PDR chemistry can explain the observed H$_3$O$^+$ abundance. For the other galaxies, the large H$_3$O$^+$ columns are generally consistent with XDR models. In particular for NGC 1068 the elevated $N$(H$_2$O$^+$)/$N$(HCO$^+$) ratio suggests a low column density XDR. For NGC 4418 however, large HC$_3$N abundances are inconsistent with the XDR interpretation. An alternative possibility is that H$_3$O$^+$ forms through H$_2$O evaporating off dust grains and reacting with HCO$^+$ in warm, dense gas. This scenario could also potentially fit the results for NGC 253. Further studies of the excitation and distribution of H$_3$O$^+$ – as well as Herschel observations of water abundances – will help to further constrain the models.

Key words. galaxies: evolution – galaxies: starburst – galaxies: active – radio lines: galaxies – ISM: molecules

1. Introduction

Molecular line emission is an important tool for probing the highly obscured inner regions of starburst galaxies and buried AGNs. Line ratios within and between species help determine physical conditions and chemistry of the gas, which provide essential clues to the type and evolutionary stage of the nuclear activity. Important extragalactic probes of cloud properties include molecules such as HCN, HCO$^+$, HNC, CN, and HC$_3$N (e.g. Costagliola & Aalto 2010; Krips et al. 2008; Graciá-Carpio et al. 2008; Loenen et al. 2008; Imanishi et al. 2004; Gao & Solomon 2004; Aalto et al. 2002) that trace the dense ($n \gtrsim 10^4$ cm$^{-3}$) star forming phase of the molecular gas. HCN, HNC, HCO$^+$, CN and CN are all species that can be associated both with photon dominated regions (PDRs) (e.g. Tielens & Hollenbach 1985) in starbursts and X-ray dominated regions (XDRs) (e.g. Maloney et al. 1996; Meijerink & Spaans 2005) surrounding active galactic nuclei (AGN). In contrast, HC$_3$N requires shielded dense gas to survive in significant abundance since it is destroyed by UV and particle radiation (e.g. reactions with the ions C$^+$ and He$^+$) (Prasad & Huntress 1980; Rodriguez-Franco et al. 1998, e.g.). These ions are expected to be abundant in for example XDRs. Thus HC$_3$N line emission may identify galaxies where the starburst is in the early, embedded, stage of its evolution. There is still, however, substantial dichotomy in the interpretation of the line emission from the above molecules and therefore new tracer species to combine with existing information are important.

The hydronium ion H$_3$O$^+$ is a key species in the oxygen chemistry of dense molecular clouds, and useful as a measure of the ionization degree of the gas (Phillips et al. 1992). Since H$_3$O$^+$ formation requires H$_2$O to exist in the gas-phase, the H$_3$O$^+$ molecule acts as a natural filter to select hot ($T > 100$ K) molecular gas, and therefore traces more specific regions than molecules usually surveyed towards other galaxies. The chemistry of this filtering is the evaporation of icy grain mantles at $T \approx 100$ K (van der Tak et al. 2006b), or that H$_2$O forms in the gas phase at high ($T > 300$ K) temperatures.

Observations of H$_2$O$^+$ emission will therefore help probe the location of dense, warm and active gas in galactic nuclei. Combined with information on the H$_2$O abundance, these observations may further be used to trace the ionization rate by cosmic rays (produced in supernovae, i.e., starbursts) and/or X-rays (from an AGN). Studies by van der Tak et al. (2006a) have demonstrated this use of H$_2$O$^+$ for Sgr B2 in the Galactic centre. Furthermore, recent Herschel observations of Galactic sources show 984 GHz 0$_{15}$–1$_{14}$ H$_2$O$^+$ absorption in the diffuse gas towards G10.6-0.4 (Gerin et al. 2010) and 1.03–1.63 THz H$_3$O$^+$ emission from the high mass star forming region W3IRS5 (Benz et al. 2010). In general H$_3$O$^+$ abundances agree well with expectations from PDR models and – together with H$_2$O$^+$ and...
OH* – provide important further insight into gas phase oxygen chemistry.

Recently we have detected $\nu_2^+ - \nu_2^- \text{H}_2\text{O}^+$ in the nearby starburst M 82 and the ultraluminous galaxy Arp 220 (van der Tak et al. 2008). Derived column densities, abundances, and $\text{H}_2\text{O}^+/\text{H}_2\text{O}$ ratios indicate ionization rates similar to or even exceeding that in the Galactic centre. In M 82 the extended evolved starburst (PDR) is a likely source of this ionization rate while, for NGC 253 is estimated to 50 K (Melo et al. 2002).

We have used the James Clerk Maxwell Telescope (JCMT) in Hawaii to observe the $J_{K} = 3_2^+ - 2_1^- \text{H}_2\text{O}^+$ line (upper level energy $E_u = 139$ K) in seven starburst and active galaxies which cover a range of environments. Our goal is to use $\text{H}_2\text{O}^+$ as a tracer of gas properties in galactic nuclei and to see if $\text{H}_2\text{O}^+$ can serve as a diagnostic tool to distinguish AGN from starburst activity. In Sects. 2–4 the sample, observations and their results are presented. $\text{H}_2\text{O}^+$ line parameters are presented in Sect. 4.1 and in Sect. 4.2 $\text{H}_2\text{O}^+$ column densities and fractional abundances are calculated. In Sects. 5.1 and 5.2 $\text{H}_2\text{O}^+$ abundances in the context of X-ray and UV irradiated models are discussed and in 5.3 the potential importance of grain chemistry. In the last Sect. 5.5, we present a brief future outlook.

2. The sample

We have selected a sample consisting of seven nearby luminous starburst and AGNs – and one distant ULIRG. The galaxies are selected from their bright HCN line emission. From our previous experience with extragalactic $\text{H}_2\text{O}^+$ we knew that the line is weaker than the standard high density gas tracers such as HCN and HCO$^+$ so we restricted ourselves to a relatively small sample of seven objects (coordinates, FIR luminosities and distances are presented in Table 1):

IC 342 is a nearby barred Scd galaxy of moderate luminosity (central 400 pc has $L_{\text{FIR}}$ of $6 \times 10^8 L_\odot$) with a central starburst. Within its central 300 pc (30") two molecular arms end in a clumpy central ring of dense gas (e.g. Downes et al. 1992) which surrounds a young star cluster. The ring is suggested to outline the X orbits in a larger-scale bar. The chemistry of IC 342 has been investigated in detail in a high-resolution study by Meier & Turner (2005). They find that the chemistry in the ring is a mixture of PDR-dominated regions and regions of younger star-forming clouds. The chemistry in the bar/arms is dominated by shocks as shown by CH$_3$OH (Meier & Turner 2005) and SiO (Usero et al. 2006). Five (A–E) giant molecular clouds (GMCs) are found in the ring and arms. The 13$\text{C}$ JCMT beam of our H$_2$O$^+$ observations is pointed towards the region of GMC B – but also includes GMCs A and E. GMCs B and C are the sites of young (a few Myr) star formation and are also the regions where incoming molecular clouds meet the ring. GMC A has more PDR-like characteristics. The dust temperature of IC 342 is estimated to 42 K (e.g. Becklin et al. 1980).

NGC 253 is also a nearby barred galaxy located in the Sculptor group with a compact nuclear starburst and a IR luminosity that appears to originate in regions of intense massive star formation within its central few hundred parsecs (Strickland et al. 2004). From their 2 mm spectral scan Martín et al. (2006) suggest that the chemistry of NGC 253 shows strong similarities to that of the Galactic centre molecular region, which is thought to be dominated by low-velocity shocks. High resolution SiO observations show bright emission resulting from large scale shocks as well as gas entrained in a nuclear outflow (García-Burillo et al. 2000). Note also that it is suggested that NGC 253 is a galaxy in which a strong starburst and a weak AGN coexist (e.g. Weaver et al. 2002; Müller-Sánchez et al. 2010). High resolution observations of HCN and HCO$^+$ 1–0 (Knudsen et al. 2007) show strongly centrally concentrated emission. The 13$\text{C}$ JCMT beam covers the bulk of the nuclear emission from HCN and HCO$^+$. The central dust temperature of NGC 253 is estimated to 50 K (Melo et al. 2002).

NGC 1068 is the nearest example of a type 2 Seyfert galaxy luminous in the infrared. Surrounding the AGN there is a 4$''$ circumnuclear molecular ring or -disk (CND) and on a larger scale there is a NIR stellar bar 2.3 kpc long. This bar is connected to a large-scale, molecular starburst ring that contributes about half the bolometric luminosity of the galaxy (e.g. Telesco et al. 1984; Scoville et al. 1988; Tacconi et al. 1994; Helfer & Blitz 1995; Tacconi et al. 1997). Bright HCN 1–0 line emission is observed towards the CND while the HCO$^+$ 1–0 emission is relatively fainter by a factor of 1.5 (e.g. Kohno et al. 2001). Only the CND and a fraction of the bar is covered by our JCMT beam and we adopt a source size of 2$''$ for the CND. The dust of the inner 4$''$ appears to show a strong temperature gradient – from about 800 K in the very inner region to 150–275 K at a distance of 0.8' or greater (Tomono et al. 2006). Alloin et al. (2000) find temperatures of about 150 K 200 pc from the nucleus. There is also a radio jet from the nucleus which falls into our JCMT beam (e.g. Wilson & Ulvestad 1983).

NGC 4418 is a luminous, edge-on, Sa-type galaxy with a deeply dust-enshrouded nucleus (Spoon et al. 2001). NGC 4418 is a FIR-excess galaxy with a logarithmic IR-to-radio continuum ratio (q) of 3 (Roussel et al. 2003). This excess may be caused by either a young pre-supernova starburst or a buried AGN (Aalto et al. 2007; Roussel et al. 2003; Imanishi et al. 2004). Unusually luminous HCN:N line emission (Aalto et al. 2002, 2007; Costagliola & Aalto 2010) has been interpreted as a signature of young starburst activity. Mid-IR intensities are indicative of dust temperatures of 85 K (Evans et al. 2003) inside a radius of 50 pc (0.5$'$. The IR luminosity-to-molecular gas mass ratio is high for a non-ULIRG galaxy indicating that

![Table 1. Sample galaxies*](image-url)
intense, compact activity is hidden behind the dust. Recent high resolution imaging of CO 2–1 (Costagliola et al., in prep.) indicate a molecular source size of 0″.5.

NGC 6240 is an infrared luminous merger of two massive spiral galaxies. Two AGN/LINER nuclei are separated by 1″ and the bulk of the molecular gas has piled up between the two nuclei (Iono et al. 2007; Tacconi et al. 1999). Luminous HCO+ 4–3 emission is also emerging from in between the two nuclei where the H2 emission is also located. The mid-IR sources (24.5 μm) are associated with the two X-ray nuclei – the brightest by far being the southern nucleus (T = 55–60 K) (Egami et al. 2006). It has been suggested that the medium between the two nuclei is dominated by starburst superwinds from the southern nucleus (Ohyama et al. 2000) and the molecular gas is indeed highly turbulent (Iono et al. 2007; Tacconi et al. 1999). The JCMT beam encompasses the entire molecular structure of this galaxy and we adopt a source size of 1″ for the H3O+ emission.

IRAS 15250+3609 is a relatively distant ultraluminous galaxy – probably a major merger with a dominant bright nucleus. A tidal feature appears to emerge from the southwest side of the nucleus and turns around on the eastern side to create an enormous closed ring, 27 kpc in diameter. The optical spectrum is a composite of H II and LINER features (Veilleux et al. 1999). IRAS 15250 exhibits deep silicate absorption features (Spoon et al. 2006) indicating a deeply enshrouded nucleus. Our JCMT beam covers the whole optical galaxy.

Arp 299 is an IR-luminous merging system of two galaxies, IC 694 and NGC 3690. Strong 12CO emission has been detected from the nuclei of IC 694 and NGC 3690 and from the interface between the two galaxies (e.g. Sargent & Scoville 1991; Aalto et al. 1997). The two nuclei, as well as the western overlap region, currently undergo intense star formation activity (e.g. Gehrz et al. 1983). Bright HCN 1–0 emission is emerging from both nuclei as well as from the overlap region (e.g. Aalto et al. 1997). Water emission from NGC 3690 suggests that it also harbours an AGN (Tarchi et al. 2007). To cover all three regions a map was carried out.

3. Observations
The 364.7974 GHz JK = 32–22 line of H3O+ was observed towards the sample galaxies in February and August 2008, with the James Clerk Maxwell Telescope (JCMT1) on Mauna Kea, Hawaii. We used the 16 elements heterodyne array HARP. Each of the receptors of the array has a beam size of 14″ at 345 GHz and the sources were placed in the receptor labeled H052. The back end was the Auto-Correlation Spectrometer and Imaging System (ACSIS), providing 1.0 GHz bandwidth in 2048 channels and a maximum resolution of 0.4 km s−1. In order to optimize baseline stability, double beam switching at a rate of 1 Hz was used with an offset of 120″. Weather conditions were optimal, with about 1 mm of precipitable water vapor, leading to a typical noise rms of 2 mK at 10 km s−1 resolution. Telescope pointing was checked every hour on the CO line emission of nearby AGB stars and always found to be within 2″. Data were extracted into fits files with the starlink software and analyzed in CLASS. Linear baselines were subtracted, line parameters were calculated by fitting Gaussian profiles to the spectra. The resulting spectra are shown in Fig. 1. Throughout this paper, velocities are in the heliocentric frame and redshift is computed using the radio convention.

4. Results
4.1. Line intensities and line widths
Integrated line intensities, line widths and fitted velocities (heliocentric) for the seven observed galaxies can be found in

1 The JCMT is operated by the Joint Astronomy Centre on behalf of the Science and Technology Facilities Council of the United Kingdom, the Netherlands Organization for Scientific Research, and the National Research Council of Canada.
2 For more information see: www.jach.hawaii.edu/JCMT/spectral_line/Instrument_homes/HARP/HARP.html
Table 2. H$_3$O$^+$ line results$^a$.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>( \int T_A^* )</th>
<th>( V_{\text{loc}} )</th>
<th>( \delta V )</th>
<th>( T_A^\ast )</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC 342</td>
<td>08–2008$^b$</td>
<td>0.30 ± 0.07</td>
<td>39 ± 10</td>
<td>75 ± 18</td>
</tr>
<tr>
<td></td>
<td>02–2008$^b$</td>
<td>0.22 ± 0.06</td>
<td>40 ± 5</td>
<td>39 ± 13</td>
</tr>
<tr>
<td>H$_3$O$^+$</td>
<td>(U-line)</td>
<td>0.38 ± 0.05</td>
<td>263 ± 2</td>
<td>30 ± 5</td>
</tr>
<tr>
<td>NGC 253</td>
<td>9.35 ± 0.18</td>
<td>221 ± 2</td>
<td>180 ± 4</td>
<td>48.8</td>
</tr>
<tr>
<td>NGC 1068$^d$</td>
<td>0.52 ± 0.05</td>
<td>1120 ± 8</td>
<td>160 ± 20</td>
<td>3.0</td>
</tr>
<tr>
<td>NGC 4418</td>
<td>1.02 ± 0.06</td>
<td>2129 ± 5</td>
<td>171 ± 11</td>
<td>5.6</td>
</tr>
<tr>
<td>NGC 6240</td>
<td>0.32 ± 0.05</td>
<td>7179 ± 15</td>
<td>177 ± 27</td>
<td>1.7</td>
</tr>
<tr>
<td>IRAS 15250</td>
<td>&lt;0.012$^c$</td>
<td>...</td>
<td>...</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td>Arp 299</td>
<td>&lt;0.020$^d$</td>
<td>...</td>
<td>...</td>
<td>&lt;2.0</td>
</tr>
</tbody>
</table>

Notes. (a) Integrated line intensities and peak line intensities are given in \( T_A^* \), \( \eta_{\text{mb}} \) is 0.65–0.7 and we have adopted 0.7 here for conservative values of \( N(H_2) \). (b) Data reduction of H$_3$O$^+$ and U-line taken at JCMT 02-2008 and 08–2008. (c) \( 1\sigma \) upper limit for a FWHM linewidth of 500 km s$^{-1}$. (d) \( 1\sigma \) upper limit for a FWHM linewidth of 300 km s$^{-1}$. The pointing centre of HARP was in between the two nuclei. We added the spectra in the three emission regions of Arp 299 covered by HARP to produce a spectrum with a 1$\sigma$ upper limit of 2 mK.

4.2. Column densities, excitation and abundances

Since we have no direct information on the excitation of the H$_3$O$^+$ molecule we make some assumptions that will have to be tested in future observations. The critical density of the H$_3$O$^+$ transition is high (about \( n_{\text{crit}} = 10^6 \text{ cm}^{-3} \), Phillips et al. 1992) and the low reduced mass of the H$_3$O$^+$ molecule makes its excitation very sensitive to radiative pumping by dust. We therefore assume that the coupling between the colour temperature of the IR emission and the excitation temperature of H$_3$O$^+$ holds as long as the dust colour temperature is above 30 K (see discussion in van der Tak et al. 2008).

For each galaxy we ran a RADEX model (van der Tak et al. 2007) with temperatures ranging from \( T = 10$–500 K. In these calculations, the volume density is set to an arbitrary large value, so that the excitation of H$_3$O$^+$ is thermalized. The adopted excitation temperature is essentially the radiation temperature and a radiative excitation with one excitation temperature is simulated. We therefore do not use the full non-LTE capacity of RADEX.

The results are shown in Fig. 2. Each plot has temperature (kinetic or radiation) on the x axis and H$_3$O$^+$ column on the y axis. The contour line corresponds to the observed brightness temperature. This depends on our assumption for the source size.

4.2.1. Errors in H$_3$O$^+$ column density and abundances

Our assumptions on the excitation and spatial extent of H$_3$O$^+$ introduce errors in the column density estimates. For IC 342 in particular the source size error can be significant. We assume that the source fills the beam which gives us an average column density for GMCs A, B and E, but the real column density towards a particular cloud should be higher. For NGC 253 the double peaked line shape suggests that the H$_3$O$^+$ emission is emerging from both dense-gas peaks in the centre and is filling the JCMT beam. For NGC 1068 the H$_3$O$^+$ source size in the CND could be anything from <1$''$ to 4$''$. We have assumed a source size of 2$''$. For NGC 4418 and NGC 6240 the source sizes are <1$''$, which means that the beam dilution is significant, but no H$_3$O$^+$ emission is missed.

In Fig. 2 the impact of the assumption of the excitation temperature on the resulting H$_3$O$^+$ column density is illustrated. Note the strong dependence of \( N(H_3O^+) \) for \( T_{\text{ex}} \leq 60 \text{ K} \). For NGC 253 (for example) \( N(p-H_3O^+) \) changes from \( 9 	imes 10^{14} \text{ cm}^{-2} \) when \( T_{\text{ex}} = 50 \text{ K} \) to \( 7 	imes 10^{13} \text{ cm}^{-2} \) when \( T_{\text{ex}} = 25 \text{ K} \). When \( T_{\text{ex}} \) exceeds 60 K, however, the temperature dependence on \( N(H_3O^+) \) is almost gone. Thus for all galaxies, except IC 342, we are not likely to overestimate \( N(H_3O^+) \) by more than a factor of 2 since the adopted \( T_{\text{ex}} \geq 50 \text{ K} \). It is possible that H$_3$O$^+$ could be collisionally excited. In this case the excitation temperature is likely significantly lower than the ones we assume here (because of the high critical density). In Fig. 2 it is evident that the \( N(H_3O^+) \) would go up considerably with decreasing temperature. With the assumed \( T_{\text{ex}} \) the resulting \( N(H_3O^+) \) is already quite large for all galaxies – even larger H$_3$O$^+$ columns would be an interesting result indeed, but very difficult to explain with current models. The excitation can be constrained through observing multiple transitions and Requena-Torres et al. (in prep.) are currently studying the 307 and 364 GHz line of H$_3$O$^+$ in a sample of starburst galaxies.

We conclude that the source size uncertainties dominate the errors in the column density calculations. To improve future \( N(H_3O^+) \) calculations it is necessary to determine source sizes through high resolution observations and to obtain information on \( T_{\text{ex}}(H_3O^+) \) through multi-transition observations.

In addition it should be noted that the estimates of the H$_3$O$^+$ relative abundances are dependent on the reliability of the conversion factor from CO luminosity to H$_2$ mass.
Fig. 2. On the x axis we find the temperature of the exciting background radiation and on the y axis the column density of H$_3$O$^+$. For each galaxy, the brightness temperature of the H$_3$O$^+$ transition is shown in a gray scale map. The thick black contour marks the observed value, with one sigma errors marked by dashed lines. Background temperatures estimated by IR observations are also reported and used to derive a column density consistent with the observed brightness temperature. Note that the column density fits include only the para column.
5. Discussion

5.1. H$_3$O$^+$ abundances and PDR/XDR models

We compare the column densities of H$_3$O$^+$ and H$_2$ in Table 3 to chemical models of clouds irradiated by either far-UV, photon dominated regions (PDRs) or X-ray photons (XDRs). In general, we expect the XDRs to dominate in molecular ISMs surrounding an AGN. The XDR and PDR models we use are presented in Meijerink & Spaans (2005) and Meijerink et al. (2007). In general, the thermal and chemical structure of XDRs and PDRs are different. Larger parts of an XDR can be maintained at high temperature and the ionization fraction of an XDR can be up to two orders of magnitude higher ($x_e = 10^{-2}$–$10^{-1}$) than in a PDR. In an XDR H$_2$O may form in the gas phase at high temperatures (200–300 K) and then react with either H$_3^+$ or HCO$^+$ to form H$_3$O$^+$.

Source averaged HCO$^+$ abundances are typically $\approx 10^{-8}$ for all detected galaxies except for IC 342. A general result of the models presented in van der Tak et al. (2008) is that the $X$(H$_3$O$^+$) does not exceed $3 \times 10^{-9}$ in PDRs – even in the models with an extremely high cosmic-ray ionization rate of $\zeta = 5.0 \times 10^{-15}$ s$^{-1}$. H$_3$O$^+$ abundances approaching $10^{-8}$ and beyond are more likely to occur in X-ray dominated regions and we conclude that the XDR scenario fits the $X$(H$_3$O$^+$) values of NGC 253, NGC 1068, NGC 4418 and NGC 6240. For IC 342, the results are consistent with a PDR, but a model with a high $\zeta$ of $5.0 \times 10^{-15}$ s$^{-1}$.

5.1.1. Water abundances

The H$_3$O$^+$/H$_2$O ratio is an even better probe of the ionization rate, and potential nature of the emitting source. It is straight forward to obtain H$_3$O$^+$/H$_2$O abundance ratios as large as $10^{-2}$ in XDR models, while for PDR models ratios are generally $10^{-3}$ or less. Herschel has already measured water abundances in M 82 (Weiβ et al. 2010) (see also Sect. 5.4) and results for other galaxies will follow soon.

5.2. Relative H$_3$O$^+$ and HCO$^+$ abundances and XDR/PDR models

Kohno et al. (2001) and Imanishi et al. (2004) find HCN/H$_3$O$^+$ 1–0 line intensity ratios greater than unity in several Seyfert nuclei – where also the HCN/CO 1–0 line ratio is high. Furthermore, Graciá-Carpio et al. (2006) find elevated HCN/H$_3$O$^+$ 1–0 line ratios in ULIRGs. This is often interpreted as a sign of an underabundance of HCO$^+$ compared to HCN due to X-ray chemistry. (Although it is important to remember that an abundance difference cannot be unambiguously deduced from a single-transition line ratio). Underabundant HCO$^+$ in XDRs has been proposed in theoretical work by Maloney et al. (1996). However, more recent models by Meijerink & Spaans (2005) suggest that HCO$^+$ may be underabundant in moderate column density ($N_{\text{HII}} < 10^{22.5}$ cm$^{-2}$) XDRs – but for larger columns the reverse is true and $X$(HCO$^+$) generally exceeds $X$(HCN). Here we compare our derived $N$(H$_3$O$^+$)/$N$(HCO$^+$) for the sample galaxies to see if large H$_3$O$^+$ abundances are paired with a particularly low HCO$^+$ abundance, and to compare $N$(H$_3$O$^+$)/$N$(HCO$^+$) with the expectations from current models.

In the XDR/PDR models, the formation of both H$_3$O$^+$ as well as HCO$^+$ is mainly driven by reactions with H$_2$, H$_3^+$, and H$_2^+$, and destruction by electrons, unless the electron fractional abundance is very low ($x_e \approx 10^{-7}$–$10^{-9}$). However, the interpretation of an $N$(H$_3$O$^+$)/$N$(HCO$^+$) abundance ratio in an XDR/PDR scenario is not entirely straightforward, but the models provide some useful limits. For example, in the PDR models H$_3$O$^+$/HCO$^+$ ratios are unlikely to become larger than 3 (Meijerink et al. 2010), while for the XDR models it is quite straightforward to obtain $N$(H$_3$O$^+$)/$N$(HCO$^+$), but the obtained ratio is very column density dependent. When the column densities are small (e.g. $N$(H) $< 10^{22}$ cm$^{-2}$) ratios as large as 20 can be obtained, but abundances (and associated brightness temperatures) are small, and in order to obtain significant HCO$^+$ and H$_3$O$^+$ column densities larger clouds are needed. However, when increasing the column, the H$_3$O$^+$/HCO$^+$ column density ratio slowly decreases, but moderate ratios around 4–5 are easy to reproduce with the XDR model.

5.2.1. $N$(H$_3$O$^+$)/$N$(HCO$^+$) in the sample galaxies

In Table 4 we list $N$(HCO$^+$) and $N$(H$_3$O$^+$)/$N$(HCO$^+$) for the sample galaxies. The largest $N$(H$_3$O$^+$)/$N$(HCO$^+$) value is found in NGC 1068 which has a Seyfert nucleus and its inner few hundred pc has been suggested to be an XDR (e.g. Usero et al. 2004; Pérez-Beaupuits et al. 2009; García-Burillo et al. 2010). The large abundance ratio of $\approx 24$ suggested for NGC 1068 is consistent with (a low column density) XDR.

For NGC 4418 and NGC 253 XDR models can explain the H$_3$O$^+/HCO^+$ ratios (but we note that the values with errors are also within the range of PDR models). For NGC 253 there is evidence that both an AGN and a young starburst is present while for NGC 4418 the nuclear activity is so obscured that the nature of the activity cannot be discerned (see Sect. 2). The H$_3$O$^+$/HCO$^+$ ratio for IC 342 is consistent with a PDR model as is the relative H$_3$O$^+$ abundance.

For NGC 6240 the H$_3$O$^+$/HCO$^+$ ratio is consistent with both XDR and PDR models while the H$_3$O$^+$ relative abundance favours an XDR. It is interesting to note that even if the molecular gas of NGC 6240 is collected in-between the two nuclei, their radiation could still impact the gas. The two AGNs are separated by 1.5″ which means that the molecular gas is irradiated.

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### Table 3. Parameters for the RADEX modeling of the H$_3$O$^+$ Line.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Source size ($\prime$)</th>
<th>$T_{IR}$ [K]</th>
<th>$N$(H$_3$O$^+$) $^a$ fit</th>
<th>$X$(H$_3$O$^+$) $^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC 342</td>
<td>13</td>
<td>40</td>
<td>$1.25 \times 10^{14}$</td>
<td>$4 \times 10^{-9}$</td>
</tr>
<tr>
<td>NGC 253</td>
<td>13</td>
<td>50</td>
<td>$2.25 \times 10^{15}$</td>
<td>$1.5 \times 10^{-8}$</td>
</tr>
<tr>
<td>NGC 1068</td>
<td>2</td>
<td>150</td>
<td>$1 \times 10^{18}$</td>
<td>$1 \times 10^{-8}$</td>
</tr>
<tr>
<td>NGC 4418</td>
<td>0.5</td>
<td>80</td>
<td>$2.5 \times 10^{16}$</td>
<td>$3 \times 10^{-8}$</td>
</tr>
<tr>
<td>NGC 6240</td>
<td>1</td>
<td>5</td>
<td>$5 \times 10^{15}$</td>
<td>$2.5 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

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**Notes.** $^a$ The temperature range investigated for all galaxies was 10–500 K, but solutions were fixed where $T_{ex} = T_{IR}$. The $X$(H$_3$O$^+$) range searched was $10^2$–$10^3$ cm$^{-2}$. $^b$ For a discussion of adopted source sizes see Sect. 2. $^c$ The total beam-averaged column density of H$_2$O is 2–3 times higher than that of p-H$_2$O in Fig. 2, because the ortho to para ratio of H$_2$O drops from the high-temperature limit of $a_{op} = 1$ for $T > 100$ K to $a_{op} = 2$ when $T < 50$ K. Here we have corrected column densities for an $a_{op}$ ratio of 1.5. $^d$ IC 342: $N$(H$_3$) is estimated to be $3 \times 10^{22}$ cm$^{-3}$ (from the CO data of Eckart et al. 1990). NGC 253: $N$(H$_3$) is estimated to be $1.3 \times 10^{22}$ cm$^{-3}$ (using CO data from Mauersberger et al. 1996). NGC 1068: From Tacconi et al. (1994) the $N$(H$_2$) for the CND is estimated to be $2 \times 10^{22}$ cm$^{-3}$. If we take the CO–2 data from Planesas et al. (1989) and assume a source size of 2′′ we obtain $N$(H$_3$) = $1.35 \times 10^{21}$ cm$^{-2}$. NGC 4418: Column density for H$_2$ for a 0.5′ source is $N$(H$_2$) = $7.4 \times 10^{23}$ cm$^{-3}$ (Costagliola et al. in prep.). NGC 6240: Iono et al. (2007) estimate $N$(H$_2$) to be $1 \times 10^{23}$ cm$^{-3}$ from their CO–3 data.
5.3. Grain chemistry and the formation of H$_2$O

Above we have found that the XDR/PDR models can potentially explain the H$_3$O$^+$ and HCO$^+$ column densities and abundances we found for the observed galaxies. However, for NGC 4418 the problem with an XDR explanation is the large column densities of gas and dust observed towards its centre (see footnote of Table 3) where Costagliola & Aalto (2010) find global HC$_3$N abundances similar to those found towards hot cores in Sgr B2. Intense vibrational line emission suggest that the HC$_3$N indeed exists in warm-to-hot environments in the very centre of the galaxy. The HC$_3$N abundances are not consistent with either XDRs or PDRs.

Thus, we have searched for alternative explanations to the H$_2$O$^+$ line emission outside of the XDR and PDR models. Elevated HC$_3$N line emission is consistent with the conditions in warm, dense shielded gas associated with embedded star formation. Is it then possible to obtain relative H$_3$O$^+$ abundances of $\approx 10^{-8}$ without the X-ray chemistry?

In a scenario where grains are important, the H$_2$O can evaporate off the grains at temperatures $>100$ K and in Phillips et al. (1992) the destruction of HCO$^+$ through the reaction of H$_2$O is found to be an important formation process for H$_2$O$^+$ when the gas is dense and warm. For a water abundance X(H$_2$O) of $10^{-5}$ and a density $n$(H$_2$) of $10^5$ cm$^{-3}$ Phillips et al. (1992) find an H$_2$O$^+$ abundance, X(H$_2$O$^+$), of $\approx 10^{-8}$ and X(HCO$^+$) a factor 2–3 lower. It is unclear however, if the N(H$_2$O$^+$/N(H$_2$O) can be greater than $10^{-8}$ within the context of their model. van der Tak & van Dishoeck (2000) find the same effect in their study of the of Galactic protostar GL 2136. In their Fig. 1 the temperature and density structure is presented including calculated concentrations of HCO$^+$ both with and without destruction by H$_2$O.

We suggest that for NGC 4418 it is possible that the H$_3$O$^+$ abundance and the N(H$_3$O$^+$/N(HCO$^+$) ratio can be explained by a model where the gas is warm and dense and water is coming off the grains to react with HCO$^+$ to form H$_3$O$^+$. This process could contribute to a reduction of the HCO$^+$ abundance in the gas phase which may result in a lower HCO$^+$ line intensity in any transition. Note that shocks may be responsible for removing the water from the grains making it available for further reactions including H$_2$O$^+$ formation. Flower & Pineau Des Forêts (2010) presents models where water abundances are related to the type and strength of shocks and there are a multitude of Galactic observational studies showing enhancement of water emission in shocks (Nisini et al. 2010; Lefloch et al. 2010; Wampfler et al. 2010; Melnick et al. 2008). Apart from causing H$_2$O to come off the grains, shocks can result in efficient gas-phase formation of H$_2$O from OH in the shocked high-temperature regime.

5.4. H$_2$O$^+$, H$_3$O$^+$, and H$_2$O

Weiβ et al. (2010) found a (potentially) surprisingly low N(H$_2$O)/N(H$_3$O$^+$) ratio of only a few which they attribute to H$_2$O evaporating off the grains through shocks, the H$_2$O then becomes photodissociated into O and OH. Ion-molecule reactions then make H$_2$O$^+$ while H$_2$O abundances remain low. It is furthermore noteworthy that X(H$_2$O$^+$) > X(H$_2$O) in M 82 (van der Tak et al. 2008; Weiβ et al. 2010). This is consistent with the low density ($n = 10^3$ cm$^{-3}$), high cosmic ray rate ($> 5 \times 10^{-15}$ s$^{-1}$) model (Model 2) of Meijerink et al. (2010). This model does however not include any grain processing.

In van der Tak (2010a) a photoevaporation-ionization hypothesis for the H$_3$O$^+/H$_2$O/H$_2$O$^+$ ratio is discussed for M 82 noting that testing this theory requires calculation of the photodissociation cross-section of H$_3$O$^+$. Whether this hypothesis holds for other galaxies, however, remains to be seen: the H$_2$O/H$_2$O$^+$ ratio in M 82 may well be unusually low. In the ULIRG Mrk 231 N(H$_2$O$^+$)/N(H$_2$O) and the H$_2$O$^+$ line emission feature is consistent with an XDR interpretation (van der Werf et al. 2010b).

5.5. Future studies

With this study we have confirmed that the 364 GHz line of p-H$_3$O$^+$ is feasible to detect in starburst and active galaxies and that H$_3$O$^+$ fractional abundances are substantial. The HIFI heterodyne spectrometer onboard ESA’s Herschel space observatory is currently obtaining H$_2$O and H$_3$O$^+$ data around 1 THz and more accurate estimates of the H$_2$O/H$_3$O$^+$ abundance ratios can be determined for many sources improving the understanding of the ionization rates of molecular regions. Determining the source size and excitation of H$_3$O$^+$ is essential to further improve the understanding of the impact of the nuclear activity on its surrounding interstellar medium and to facilitate a more accurate comparison with models. In the near future, grain chemistry and impact of shocks should be added to the interpretation of the data. In particular the results for NGC 4418 – and to some degree also NGC 253 – emphasizes this conclusion.

Acknowledgements. We are very grateful to the staff of the ICMT for their help and support and we thank the referee, Santiago Garcia-Burillo, for a thorough and very useful report which improved the paper. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References


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Table 4. HCO$^+/H_2$O$^+$ ratios.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>N(HCO$^+$)/N(H$_2$O$^+$)</th>
<th>N(H$_2$O$^+$)/N(HCO$^+$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC 342</td>
<td>2–6 \times 10^{14}</td>
<td>0.2–0.6</td>
</tr>
<tr>
<td>NGC 253</td>
<td>5 \times 10^{14}</td>
<td>4</td>
</tr>
<tr>
<td>NGC 1068</td>
<td>4 \times 10^{13}</td>
<td>24</td>
</tr>
<tr>
<td>NGC 4418</td>
<td>4.7 \times 10^{13}</td>
<td>5</td>
</tr>
<tr>
<td>NGC 6240</td>
<td>3 \times 4 \times 10^{13}</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Notes. IC 342: estimated from Nguyen et al. (1992) (Note that a low HCO$^+$/H$^1$CO$^+$ 1–0 line ratio of 7 suggests that HCO$^+$ columns may be higher. NGC 253: from Martin et al. (2006) (6.5 \times 10^{13} for T$_{ex}$ = 12 K and for 35° source size. Rescaled N(HCO$^+$) for the 10” by 14” H$_2$O$^+$ source size of Knudsen et al. (2007). NGC 1068: we used the data provided in Pérez-Beaupuits et al. (2009) and made a rotational diagram (assuming a 2” source size) finding T$_{ex}$(HCO$^+$) = 36 K. NGC 4418: column density for HCO$^+$ (based on data in Aalto et al. (2007) and unpublished JCMT HCO$^+$ 4–3 data) for a 0.5 source size. NGC 6240: We estimate the HCO$^+$ column density from the excitation information given in Iono et al. (2007) and for a source size of 1”.

by intense X-ray emission from two directions on only 370 pc distance. This scenario could possibly explain both the relatively high H$_3$O$^+$ and HCO$^+$ abundances.

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