HERSCHEL/HIFI observations of water in nuclei of actively star forming galaxies

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on behalf of the HexGal consortium

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The HexGal project:

**HexGal**: Aims to study the physical and chemical composition of the ISM in galactic nuclei using HIFI spectroscopy

- ISM in the galactic center region
  - detailed investigation of the GC region

- Gas excitation in starbursts and ULIRGs
  - CO & fine structure line excitation
  - The extragalactic water trail

- Chemical complexity of extragalactic nuclei
  - Line surveys of selected sources
  - Absorption line study in selected source

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**Extragalactic Water so far:**
SWAS & ODIN not sensitive enough

ISO: detections of H$_2$O in extragalactic objects, but no observations below 1.5 THz

=> only high excitation lines

**HexGal water trail:**
First systematic survey for H$_2$O low-level transitions in active galaxies
Water trail sample:

Sample:
all flavors of nuclear activity in different evolutionary stages:

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<th>Obj.</th>
<th>Type</th>
<th>Stage</th>
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<td>LIRG</td>
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Lines:

- $p$-H$_2$O $(1_{11}^{-}0_{00})$ 1113 GHz
- $p$-H$_2$O $(2_{02}^{-}1_{11})$ 988 GHz
- o-H$_2$O $(1_{10}^{-}1_{01})$ 557 GHz
- $(p$-H$_2^{18}$O $(1_{11}^{-}0_{00})$ 1102 GHz)
Water observations in M82:

Lines:

- $p$-H$_2$O (1$_{11}$-0$_{00}$) 1113 GHz
- $p$-H$_2$O (2$_{02}$-1$_{11}$) 988 GHz
- o-H$_2$O (1$_{10}$-1$_{01}$) 557 GHz yesterday
- (p-H$_2^{18}$O (1$_{11}$-0$_{00}$) 1102 GHz) pending

CO(1-0) OVRO+30m Walter et al. 2002

SUBARU multi color optical image

VLA HI
Yun et al. 1998
HIFI p-H$_2$O 1113 GHz results:

Chop/Nod observations (fast chopping)
5600s (2280 on source)
rms: 1.6mK @ 8 km/s resolution (H+V)
HIPE level 2 reduction: OK

First detection of H$_2$O and H$_2$O$^+$
Surprise: H$_2$O$^+$ absorption stronger than H$_2$O
HIFI p-H$_2$O 988 GHz results:

Chop/Nod observations (fast chopping)
3680s (1510 on source)
rms: 2.0mK @25 km/s resolution (H+V)

Parts of the data affected by baseline instabilities - HIPE 1 level + Class processing

CO(1-0) beam: 3.5"

HIFI beam: 21”.5 for p-H$_2$O($2_02$-$1_{11}$)
Comparison to CO line profiles

$p$-H$_2$O (1$_{11}$-0$_{00}$) 1113 GHz

$p$-H$_2$O (2$_{02}$-1$_{11}$) 988 GHz

Water absorption detected in the line wings as well as red-wards of the systemic velocity

The lack of absorption is most likely due to geometry (e.g. located behind the continuum)

Water emission detected at all velocities where CO emission is detected.

$\Rightarrow$ H$_2$O abundant in the gas phase at all nuclear velocities
On the origin of the water absorption

Grey scale & white contours VLA 1.4GHz

H$_2$O/H$_2$O$^+$ line profiles

Grey scale & white contours VLA 1.4GHz
H$_2$O absorption region
Comparison to other wavelength

Dense Gas:
greyscale: H$^{13}$CO+ Garcia-Burillo etal 2002
contours: CO(1-0)

Continuum:
greyscale: 1.4GHz continuum Wills etal 1998
contours: 3mm continuum Weiss etal 1999

PDRs:
greyscale: HCO Garcia-Burillo etal 2002
contours: CO(1-0)

Shocks:
contours: SIO Garcia-Burillo etal 2001
Water continuum covering factor

Continuum: 61.9 Jy/b
(SED model & 3mm distribution: 66 Jy/b)

Absorption:
H$_2$O (1$_{11}$-0$_{00}$): 4.5 Jy/b
H$_2$O$^+$ (1$_{11}$-0$_{00}$): 8.0 Jy/b

for $\tau$$\gg$1 absorption depth $\sim$ fc

Continuum covering factor:
1) random distribution in beam
   => H$_2$O : fc = 7%
   => H$_2$O$^+$ : fc = 13%

2) Limited to the region determined from the CO line profiles:
   => H$_2$O : fc $\sim$ 45%
   => H$_2$O$^+$ : fc $\sim$ 80%
**Water excitation - first steps**

\[ T_{\text{line}} \sim f_c \left( J(\nu, T_{\text{ex}}) - J(\nu, T_{\text{bg}}) \right) (1-e^{-\tau}) \]

Line absorption => \[ J(\nu, T_{\text{ex}}) < J(\nu, T_{\text{bg}}) \]

Background derived from dust SED models

Siebenmorgen & Kruegel 2007

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Result depends on dust model, in particular the clumpiness of medium (this determines the opacity)

fit to the cold gas with \( \beta = 1.8 \) and a dust filling factor of 30\% yields:

\[ T_{\text{dust}} = 45 \text{ K} \] and
\[ \tau@1113\text{GHz} = 0.19 \]
\[ \tau = 1 \text{ @ } 120\mu\text{m} \] (quite long \( \lambda \), max. \( T_{\text{ex}} \))

\[ \Rightarrow T_{\text{ex}} < 20 \text{ K} \]

for \( \text{H}_2\text{O} \) (1\_11-0\_00) and
\( \text{H}_2\text{O}^+ \) (1\_11-0\_00)
Implications & Conclusions

p-H$_2$O ground transition sub-thermally excited
=> in agreement with spatial distribution of the H$_2$O absorption (avoids dense gas)

H$_2$O/H$_2$O$^+$ absorption in M82 associated with diffuse gas which could have a PDR origin. H$_2$O$^+$ more wide spread than H$_2$O

HIFIs spectral resolution highly required

Relation to H$_2$O emission not clear yet => o-H$_2$O will shed more light on its origin

But:
Water excitation is complex (IR pumping important). Higher excited H$_2$O line (e.g. from SPIRE) highly desirable.

Larger sample of galaxies required…