A non-equilibrium ortho-to-para ratio of H$_2$O in the Orion PDR

Y. Choi$^{1,2,*}$, F. F. S. van der Tak$^{2,1}$, E. A. Bergin$^3$, R. Plume$^4$, and the HEXOS team

$^1$Kapteyn Astronomical Institute, Groningen, The Netherlands
$^2$SRON, Groningen, The Netherlands.
$^3$Department of Astronomy, University of Michigan, Ann Arbor, USA
$^4$Department of Physics and Astronomy, University of Calgary, Calgary, Canada
* y.choi@astro.rug.nl

The ortho-to-para ratio (OPR) of H$_2$O

- Two species of molecular hydrogen: para-H$_2$ (1$^1$) and ortho-H$_2$ (1$^2$)
- The OPR is expected to be ~3 at high temperature (>40 K).
- The OPR is lower than 1 at low temperature (<15 K).
- OPR ~ 2 - 3 in solar system comets and interstellar medium (Mumma & Charnley 2011; Lis et al. 2010; Flagey et al. 2013)
- OPR ~ 0.77 in the protoplanetary disk TW Hya (Hogerheijde et al. 2011)

The ortho-to-para ratio of H$_2$O is useful to study the formation mechanism of water.

Sources & Observations

We observed the ground-state lines of ortho- and para-H$_2$O in the Orion PDR (Photon-dominated region), at the Orion Bar and Orion S positions, as part of the HEXOS (Herschel/HIFI Observations of EXTRAOrdinary Sources, PI: E. A. Bergin) key program for the HiFi instrument onboard the Herschel Space Observatory.

Orion Bar
- Nearly edge-on morphology
- Clumpy structure
- Distance ~ 414 pc
- Temperature ~ 85 K
- Mean density ~ 10$^5$ cm$^{-3}$

Orion S
- A star formation region located 2' south of Orion KL.
- Younger and more quiescent.

Discussion

The OPR of water in the Orion PDR is much lower than interstellar value.
- Beam size effect?
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- Gas-phase formation of water?
  - H$_2$O dissociative recombination is exothermic (OPR ~ 3).
- Water formation on grains, recent evaporation?
  - dust temperature is too low (<100 K).
- Effect of photodesorption?
  - recombinaton of H + OH -> H$_2$O (OPR ~ 3)
  - kick-out mechanism (low OPR)
  - ice thickness & ice temperature

This low OPR is inconsistent with gas phase formation and with thermal evaporation from dust grains. But it may be explained by photodesorption.

LTE Calculations

We assumed that
- the lines are optically thin (we do not see H$_2$O lines),
- the gas is not warm (<150 K, we do not see excited-state lines of H$_2^{16}$O).

Orion Bar
- For $T_e$ = 50 - 100 K
  - $N$(o-H$_2$O) = 3.0x10$^{10}$ cm$^{-2}$
  - $N$(p-H$_2$O) = 1.0x10$^{11}$ cm$^{-2}$
  - OPR ~ 0.3

Orion S
- $N$(o-H$_2$O) = 2.0x10$^{11}$ cm$^{-2}$
  - for $T_e$ = 50 - 100 K
  - $N$(p-H$_2$O) = 2.0x10$^{12}$ cm$^{-2}$
  - from absorption depth
  - OPR ~ 0.1

- The OPR in LTE condition ~ 0.1 - 0.3
- much lower than the OPR in TW Hya.

Non-LTE Calculations

We carried out non-LTE calculations of water using the RADEX code (van der Tak et al. 2007).

Orion Bar
- At $T_{kin}$ = 20 K and n(H$_2$) = 10$^4$ cm$^{-3}$
  - OPR ~ 0.1
- At $T_{kin}$ = 60 K and n(H$_2$) = 10$^6$ cm$^{-3}$
  - OPR ~ 0.1
- At $T_{kin}$ = 100 K and n(H$_2$) = 10$^8$ cm$^{-3}$
  - OPR ~ 0.5

Orion S
- At $T_{kin}$ = 60 K and n(H$_2$) = 10$^8$ cm$^{-3}$
  - OPR ~ 4
- At $T_{kin}$ = 100 K and n(H$_2$) = 10$^8$ cm$^{-3}$
  - OPR ~ 0.3

- Non-LTE results for the Orion Bar (OPR ~ 0.1 - 0.5) are in good agreement with LTE calculations.
- The OPR in the Orion S (~ 0.3 - 4) depends on conditions.

References
- Arce et al. 2012, JORP, 126, 184106
- Hogerheijde et al. 2011, Sci, 333, 529
- Lis et al. 2010, A&A, 521, 205