3D PDR Modelling: The Structure of the ISM in Star Forming Regions

S. Andree, M. Röllig and V. Ossenkopf

I. Physikalisches Institut, Universität zu Köln

Introduction

The interstellar medium (ISM) is permanently heated by the interstellar radiation field. Main cooling occurs through FIR continuum emission by dust grains, fine structure line emission by atoms and ions ([CII], [CI], [OI]...), and rotational and vibrational line emission by molecules (mainly CO).

A **PDR (photon-dominated region)** is a region in interstellar space where the interstellar FUV radiation field, with photon energies 6eV<hν<13.6eV, dominates the heating processes and the chemistry of the ISM. PDRs are the main source of IR emission lines in the ISM.

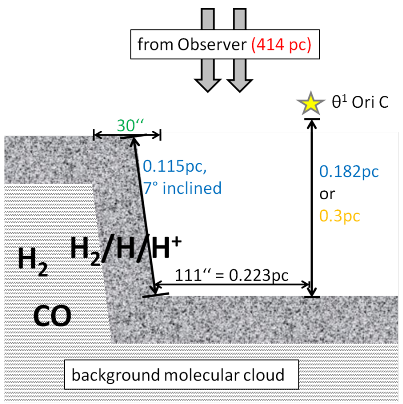
Observations of molecular clouds show **filamentary, turbulent structures and substructures** on all scales observed so far. Hence, a large part of the molecular material is located in surface structures and exposed to the interstellar radiation field, i.e. forms PDRs.

Stars form from the dense and cold regions of the ISM. **We investigate how the interstellar radiation field influences the physical and chemical processes within the ISM and whether it triggers star formation.**

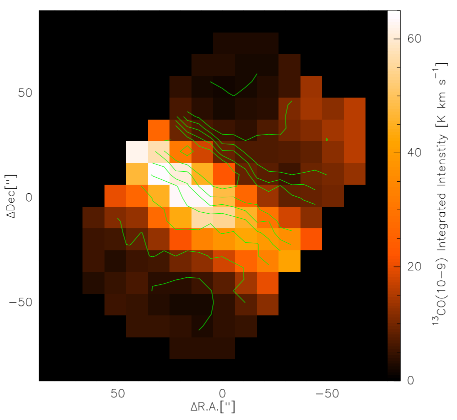
The Orion Bar PDR

The Orion Bar is the closest and hence most luminous PDR. It has been observed in various projects and forms an ideal test case for PDR modelling.

The **"face-on to edge-on to face-on" geometry**, with the Trapezium stars (represented by Θ^1Ori C) embedded in a HII-cavity in front of the Orion molecular cloud, was proposed by Hogerheijde et al. 1995 and can explain **emission peak and chemical stratification.**



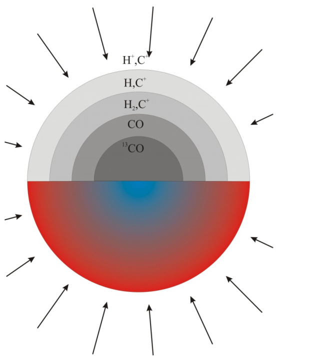
Orion Bar Geometry. Values are taken from: Hogerheijde et al. 1995 (green); Menten et al. 2007 (red); Pellegrini et al. 2009 (blue); and van der Werf et al. 2013 (orange).



Map of the Orion Bar observed with HIFI/Herschel in ^{13}CO 10-9 (colourscale) and in [CII] (green contours).

3D PDR Simulations

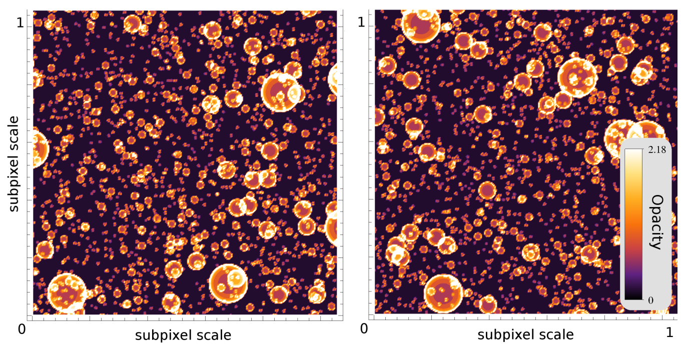
The presented PDR model aims for an extension of **the KOSMA-τ model** (`http://www.astro.uni-koeln.de/kosma-tau` or Röllig et al. 2006) to three dimensions.



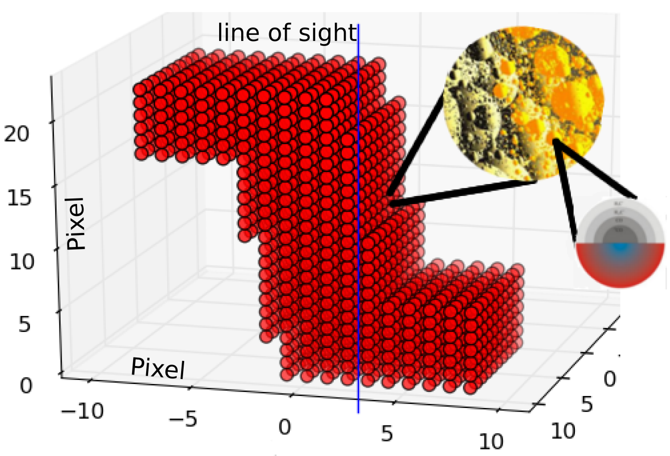
The KOSMA-τ model utilises a spherical geometry ("clumps") to calculate PDR emission. Chemical abundances change, depending on optical depth from the surface.

Observations of molecular clouds suggest a **fractal cloud distribution**. It has been shown that such a structure can be mimicked by an equivalent superposition of spherical clumps ("ensemble") following a well-defined mass spectrum and mass-size relation (Stutzki et al. 1998, Cubick et al. 2008).

For the 3D simulations the Orion Bar geometry has been assembled **using a different ensemble for each pixel.**



"Opacity maps" of two different random representations of the same clumpy ensemble (here: [CII] in the Orion Bar based on the column density given in Hogerheijde et al. 1995).



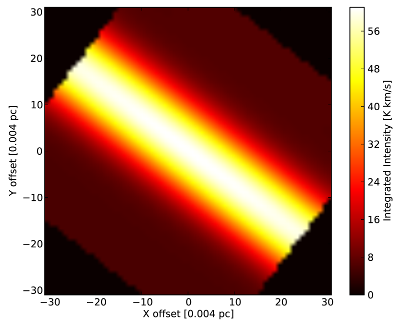
Set-up for Orion Bar simulations. Each red sphere represents a complete clumpy ensemble. The blue line indicates a line of sight towards the observer.

Acknowledgments

This project is supported by Deutsche Forschungsgemeinschaft (DFG) via grant SFB 956. S. Andree wishes to thank the Deutsche Telekom Stiftung and the Bonn-Cologne Graduate School of Physics and Astronomy for financial support.

Results

- The Orion Bar set-up has been used to simulate **line profiles and integrated intensity maps** of the Orion Bar PDR. Peak intensities could be reproduced for ^{13}CO 5-4, ^{13}CO 10-9 and [CII] emission.



A simulated integrated intensity map (here ^{13}CO 10-9) of the Orion Bar PDR (optically thin approximation).

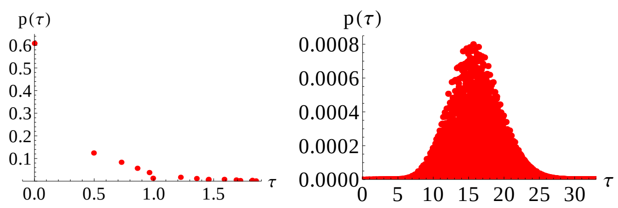
- Two methods to calculate the **averaged absorption coefficient for an ensemble** have been developed:

i) Use of random representations of the same ensemble (central column) to calculate the ensemble-averaged opacity. Performing this calculation for many different representations yields average and standard deviation of the opacity.

ii) Binomial distributions can be used:

$$p(\tau) = \sum_i \sum_{N_i=0}^{n_i} \delta[\tau - (N_1\tau_1 + ... + N_n\tau_n)] \cdot B_1(N_1, p_1, n_1) \cdot ... \cdot B_n(N_n, p_n, n_n)$$

Probability $p(\tau)$ to find a specific optical depth τ along a line of sight through an ensemble. Averaged opacities are determined using binomial distributions B_i describing that N_i clumps from mass interval i intersect a line of sight.



$p(\tau)$ for the Orion Bar (left, same set-up as the "opacity map" in the central column) and after increasing the column density by a factor 50 (right).

Method i) and ii) are found to be in excellent agreement for various setups.

Outlook

- After implementing absorption and emission of the clumpy ISM absorption and emission of the homogeneous inter-clump medium have to be added.
- In the presented simulations the FUV field attenuates $\propto \frac{1}{r^2}$ with distance to Θ^1 Ori C. In addition absorption effects due to dust grains need to be added enabling us to reproduce chemical stratification.
- The presented model can simulate integrated intensity maps and full line profiles, accounting for the velocity structure of the source. These will be used to study line profiles of species of different optical depth as well as star forming regions with complex velocity structures.

Poster by Silke Andree, email: sandree@ph1.uni-koeln.de