Modelling the FIR-line emission of the ISM by a clumpy PDR-model

J. Stutzki, M. Akyilmaz, M. Cubick, Y. Okada, V. Ossenkopf, M. Röllig
Universität zu Köln, I. Physikalisches Institut, KOSMA, Germany

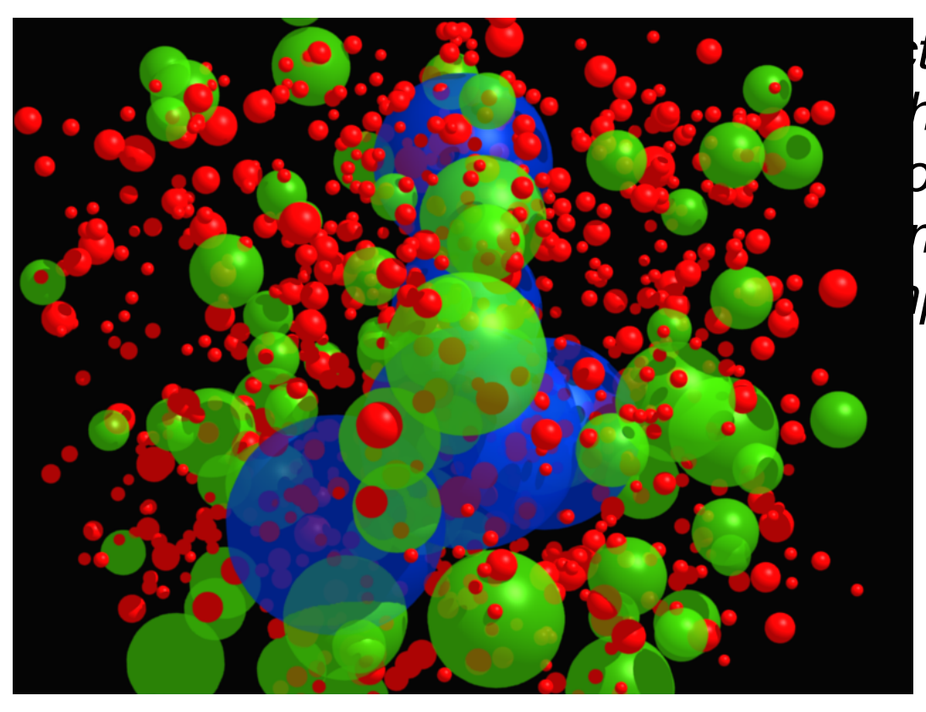
Motivation

One of SOFIA's unique capabilities is the mapping of velocity resolved line emission throughout the FIR spectral range. This wavelength regime covers many important cooling lines which are excited in the UV-illuminated, dense interstellar clouds either through the intense FUV photons from young embedded massive stars, or through the general interstellar radiation field.

Due to the fractal structure of molecular clouds, these surface regions dominate the bulk of the molecular cloud material. Hence, proper modeling of clumpy, UV-irradiated clouds is essential in order to derive the physical and chemical properties of the ISM from observations. The FIR cooling lines are the prime diagnostic tools.

Clumpy, UV-irradiated clouds

It is by now generally accepted that ISM clouds show structure on all scales, generated by turbulence and characterized either by clump mass spectra and mass-size relations, or by power-law distributions of the power spectrum of the structure. Stutzki et al., 1998, realized that these apparently disjunct scenarios are actually just two different aspects of the same beast. The power-law indices of the mass spectrum and the mass-size relation determine the power-law exponent of the fractional Brownian-motion power spectrum: the mass-size relation specifies at which spatial scale each clump contributes to the power spectrum of the projected image; the mass spectrum specifies how many of these structures are present, i.e. how much intensity the power spectrum has at these spatial scales. The random positioning of the individual clumps in the ensemble corresponds to the random distribution of the phases in the amplitude spectrum of the image.


tal clumpy cloud ensemble by hard spheres. The clump mass ow power-laws with indices characteristic mp density (high-medium-log: red-green- p size.

This allows straightforward modeling of the emission from UV-irradiated, fractal clouds by using a spherical symmetric PDR-clump model and average the emission of a clump ensemble with the appropriate distribution functions in mass and size. This approach has been implemented by the Cologne group within its KOSMA-tau PDR model framework. In a first application, we demonstrated, that the global emission of the Milky Way in the submm- and FIR cooling lines as well as the continuum dust emission as observed at low angular resolution with COBE, can successfully be reproduced this way (Cubick et al. 2007).

Application1: Orion Bar

The Orion Bar is one of the prototype PDRs. Hogerheijde et al. 1995 realized, that its geometry is not a simple edge on PDR-layer, but the warped edge of the molecular cloud/HII region interface. By adopting the clumpy/fractal cloud scenario sketched above, we presently study to what degree this scenario can help to reproduce the intensity distribution across the Bar in a large number of observed spectral lines within a single physical scenario.

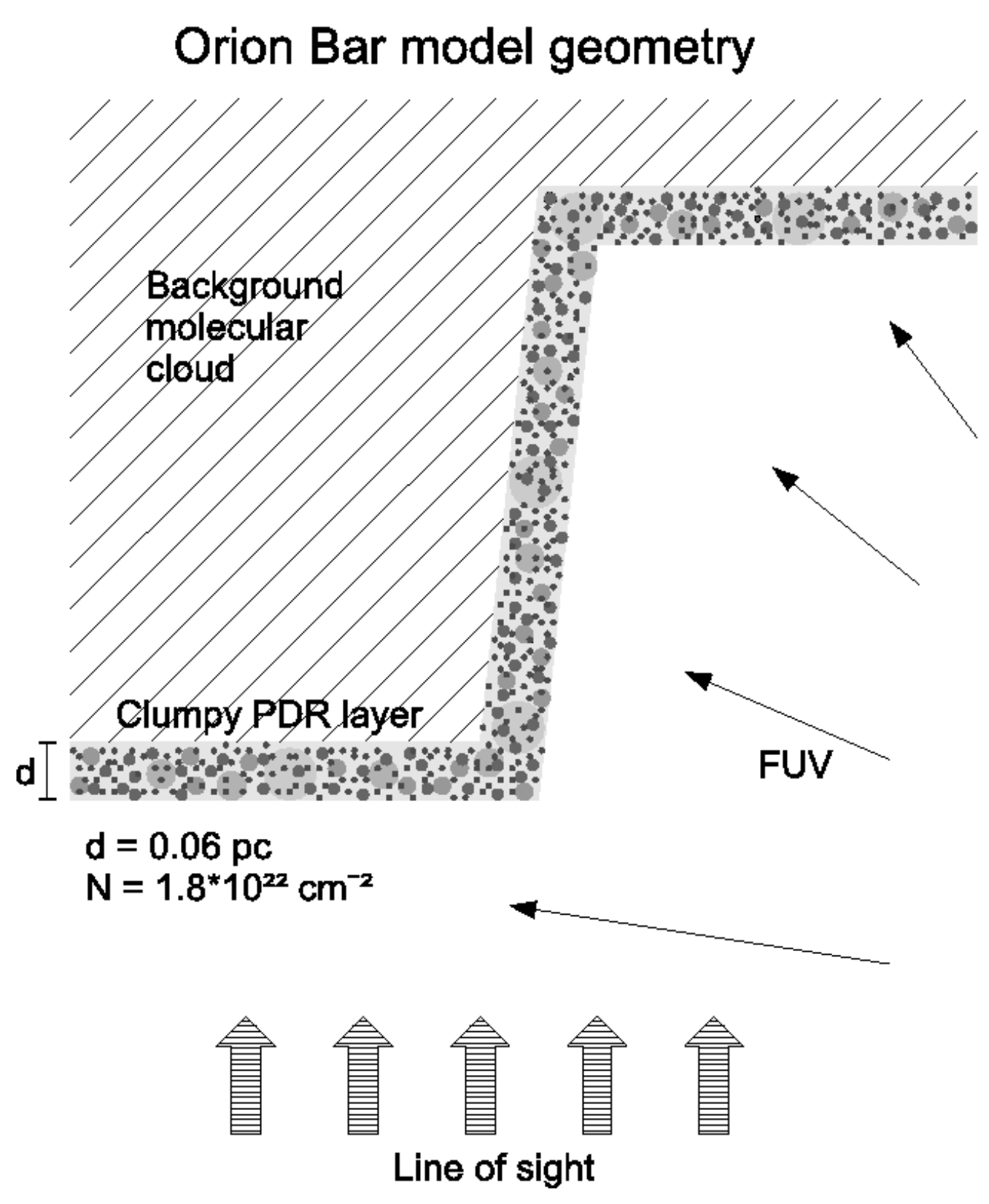


Figure 2: Sketch of the Orion Bar geometry adopted from Hogerheijde et al. 1995, but representing the PDR layer by a clumpy, UV-illuminated cloud.

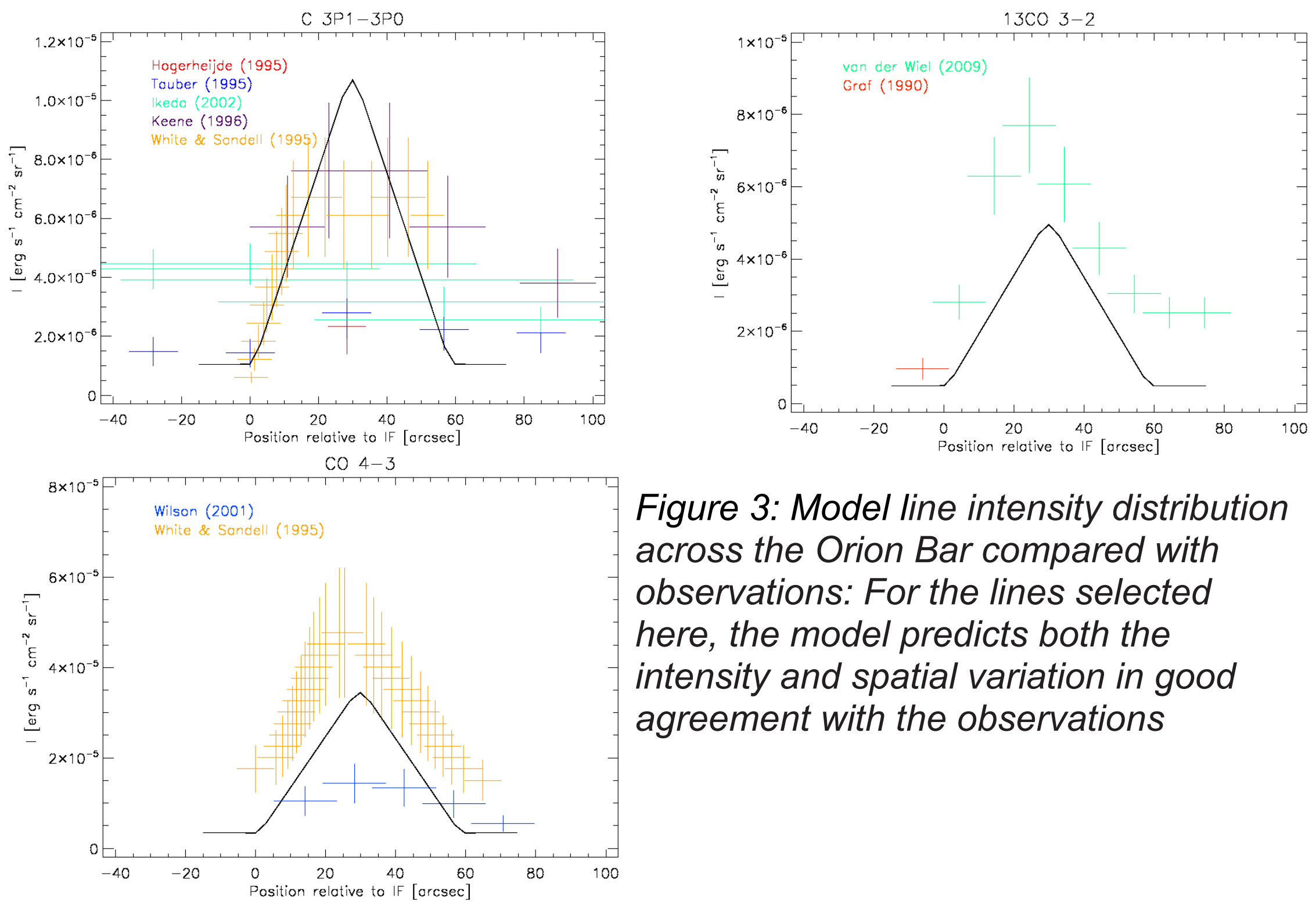


Figure 3: Model line intensity distribution across the Orion Bar compared with observations: For the lines selected here, the model predicts both the intensity and spatial variation in good agreement with the observations

Application 2: HIFI/Herschel DR21

Recent HIFI/Herschel observations (Ossenkopf et al. 2010) provide the full range of FIR cooling lines in DR21. For DR21 two ensembles with different properties have to be superimposed, a hot component, close to the inner HII region with strong FUV illumination, but only a small fraction of the total mass , and a cooler component that provides the bulk of the material .

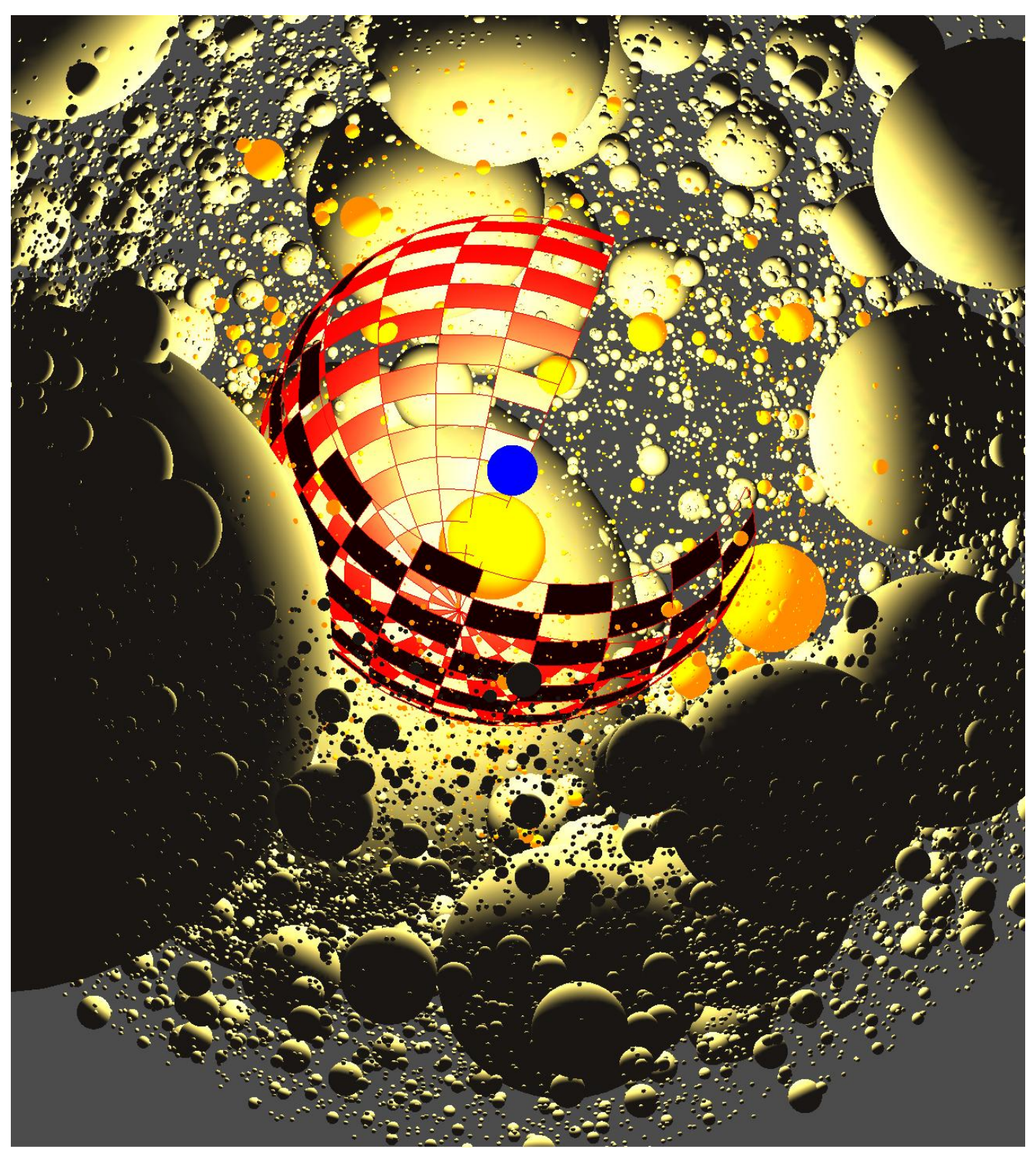


Figure 4: Examplary illustration of a two-ensemble model configuration. All dimensions are plotted to scale. The position of the central OB cluster is indicated by a blue sphere. The edge of the surrounding HII region is shown by the red wireframe sphere. The hot component clumps are shown as orange spheres. They populate the inner shell. The cool component clumps are shown in beige populating the outer shell. All clumps are randomly positioned and assumedly embedded in a diffuse inter-clump gas.

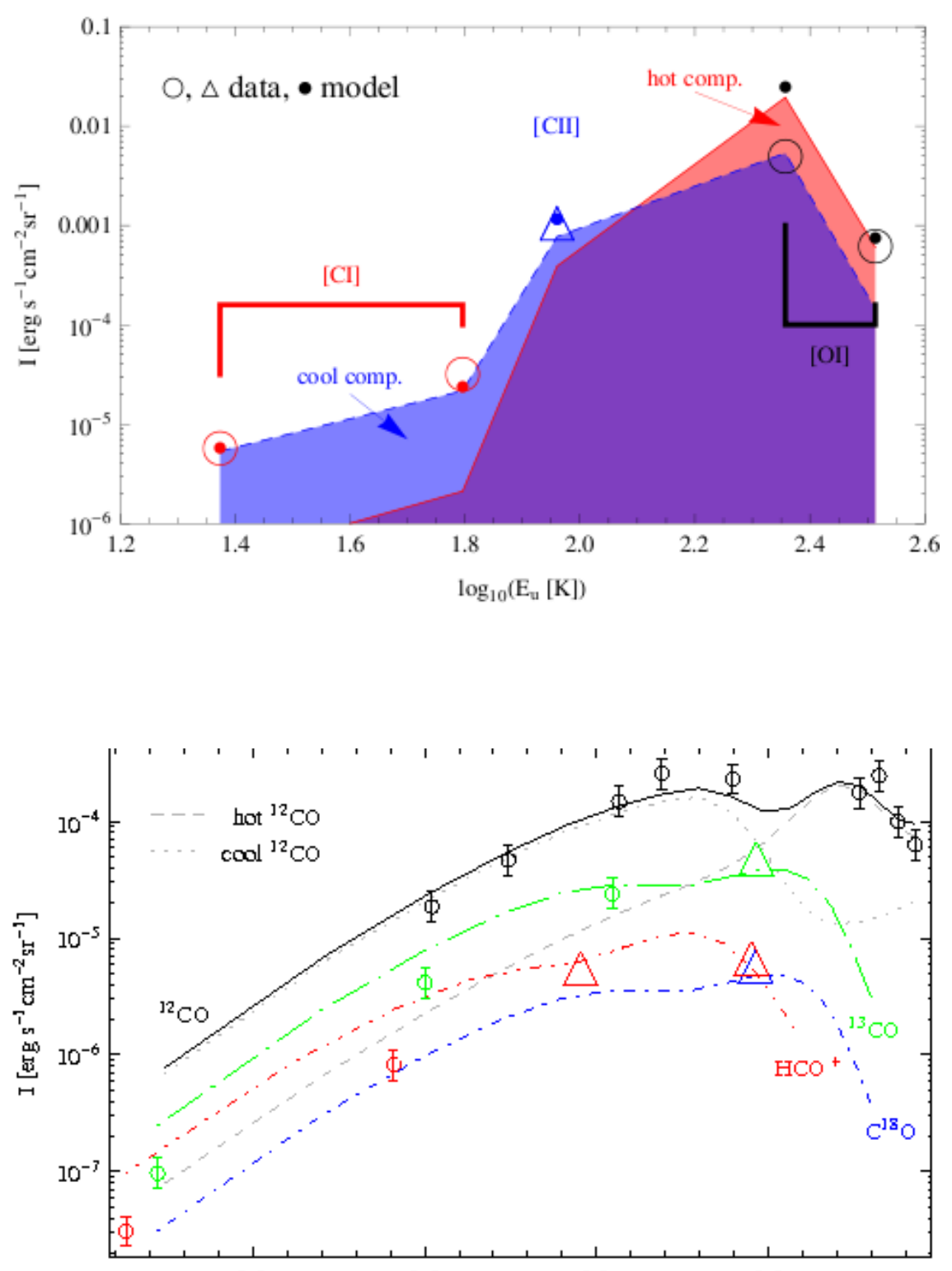


Figure 5: Two-ensemble PDR model fit to the observed CO, HCO⁺ , and fine structure line intensities, shown as function of the upper level energy. HIFI measurements are depicted as open triangles, complementary data points as open circles

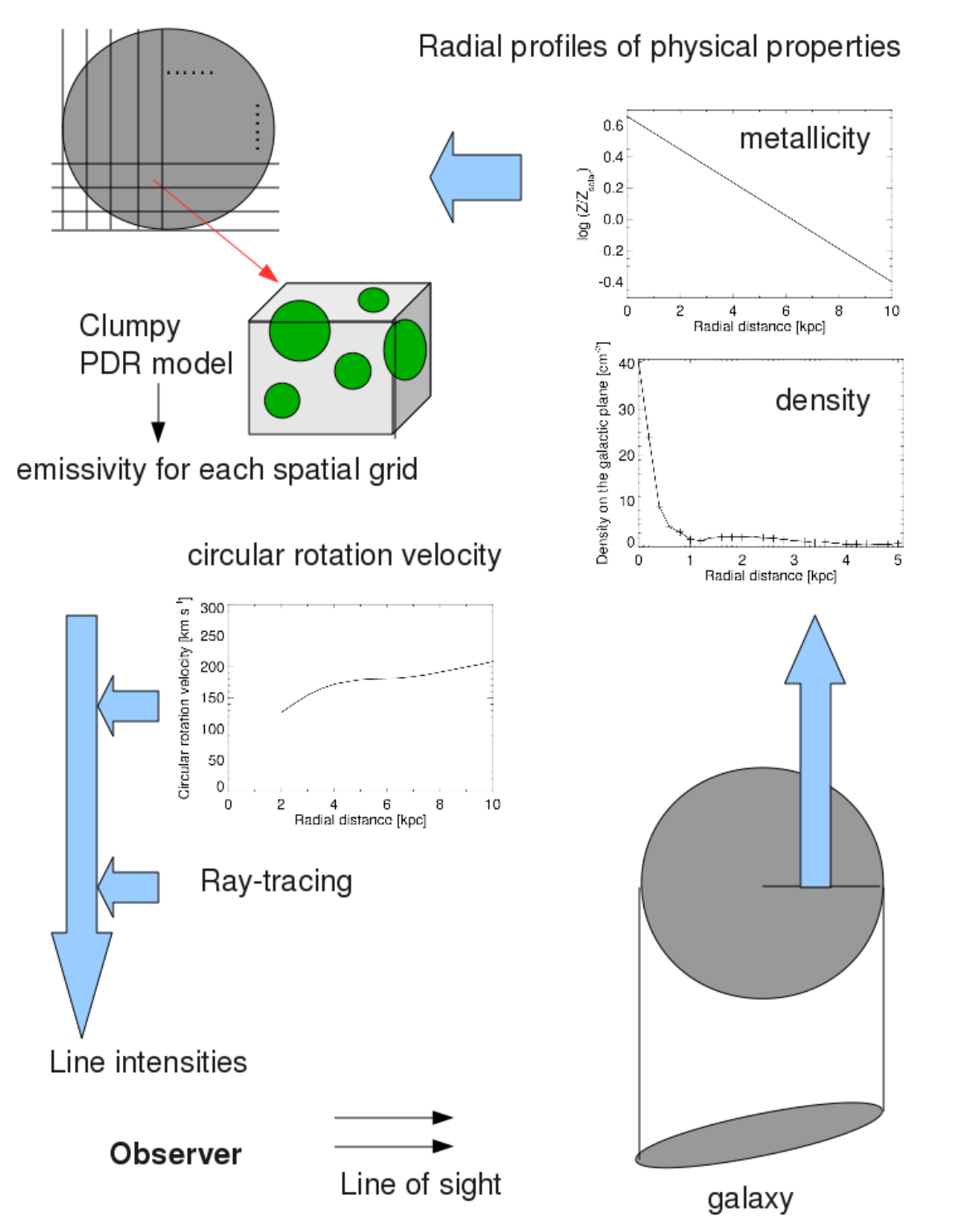
This two-ensemble PDR model is able to fit all the observed lines. We find no evidence for shock heating of the dense gas, in agreement with Lane et al. (1990). This seems to be in contradiction with the line profiles that show excited outflow material.

We conclude that the material visible in the blue line wing, characterizing the blister outflow, is contained in dense clumps that are accelerated by the outflow, but that are chemically and energetically fully dominated by the UV and not by the associated shock.

Imaging 3D model structures

One important ongoing improvement of the clumpy/UV-penetrated cloud model is, to allow to calculate "observed" images from model structures which are specified by an arbitrary 3d-distribution of physical parameters characterizing the ISM, such as mean volume density, filling factor, UV-intensity. This includes the specification of a velocity field and local line widths, so that the model can also predict line profiles and their spatial variation.

Figure 6: Combining the clumpy cloud/PDR code with a proper ray-tracing technique, the predicted line intensities, profiles and their spatial variation can be derived from a specified 3d distribution of physical parameters of the ISM. The scketch outlines the series of steps necessary in combining the various tools.



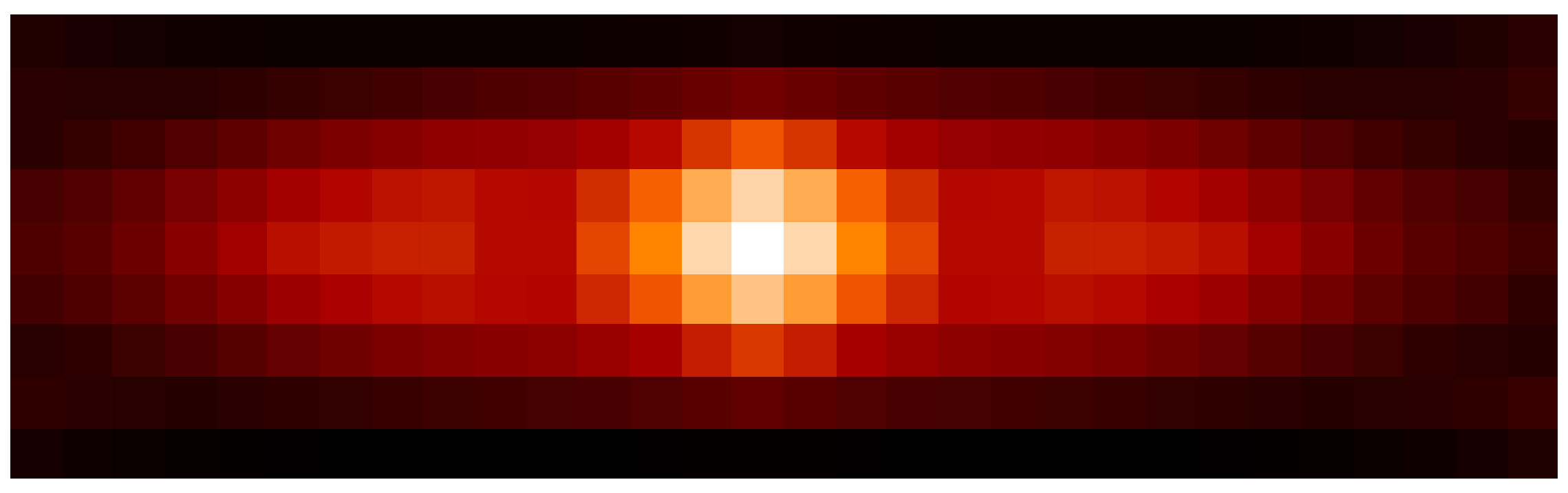


Figure 7: Simulated integrated intensity distribution of [CII] 158mm for NGC253.

As a first example of applying this, we show here the modeled PDR line emissions from NGC 253. We project the spatial grid with the inclination of the galaxy (78.5 degree for NGC253) and calculate the intensity using a ray-tracing code combined with the KOSMA-tau PDR model.

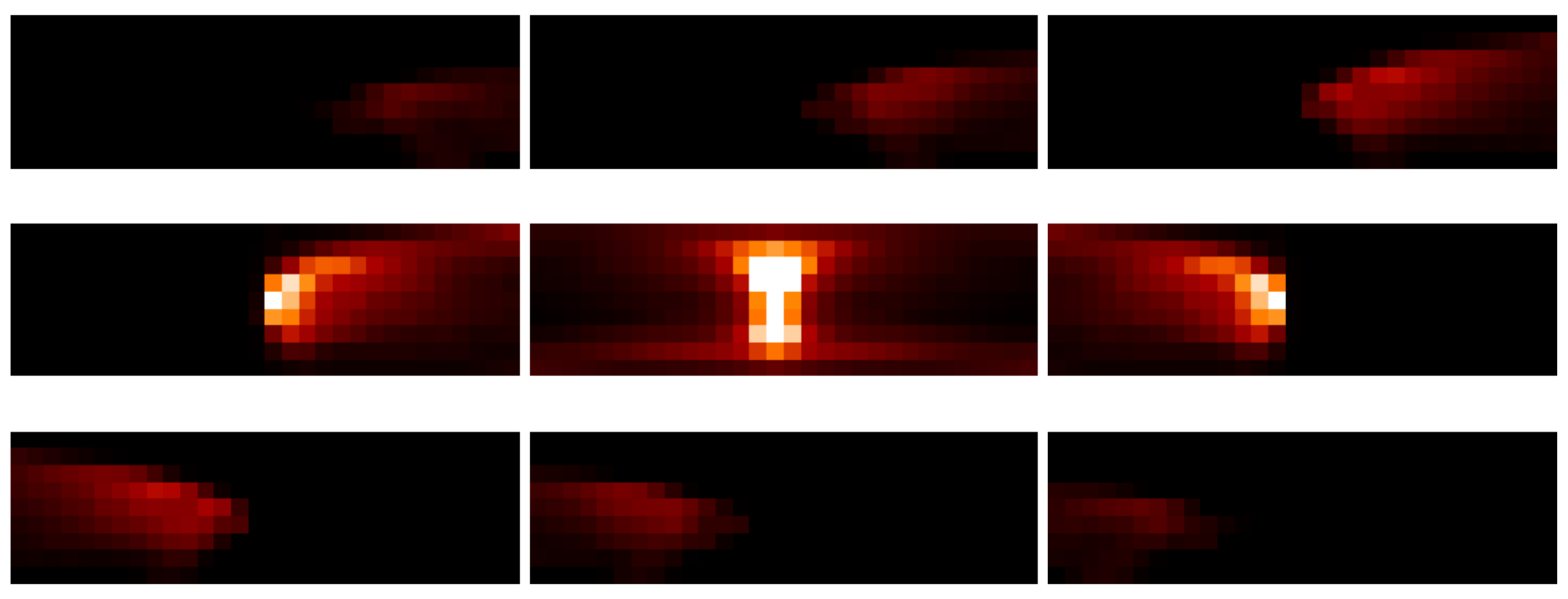


Figure 8: Channel map of the simulated [CII] 158mm for NGC253. The velocity bin is 20 km/s.

PDR-code improvements

Ongoing improvements of the clumpy cloud PDR-code include a self-consistent treatment of dust UV-heating and cooling, and of source intrinsic dust opacity in the radiative transfer modeling. The former is done in close collaboration with R: Sczerba, Torun, Poland; the latter by modifying the SimLine radiative transfer code to include dust opacities in a notation consistent with Sczerba's dust code.

References:

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