Modeling of clumpy dust tori around AGN with CLUMPY

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Introduction.
A big class of extragalactic objects, the Active Galactic Nuclei (AGN), has been known since a few decades as one of the most luminous radiation sources in the universe. Several subtypes of AGN have been established. In an attempt to interlink the different observational findings (spectra, variabilities, polarization measurements), a nowadays widely accepted unification scheme (Antonucci, 1993) has emerged. It predicts that one physical object - a dust torus around a central black hole that generates very energetic radiation via gas accretion - accounts for two different types of observational sources, the so-called Type-1 and Type-2 AGN. Viewing the torus pole-on the observer has unobscured view of the black hole and its hard radiation. On the other hand the central engine's radiation is blocked from direct view when observing the torus edge-on. In such cases the radiation is reprocessed by the dust via absorption and re-emission, typically in the infrared (IR) bands. The spectral energy distributions (SED) of these two cases differ significantly.

The clumpy torus.
- Dust was detected close to AGN. If smoothly distributed, it would have been destroyed by AGN radiation (Krolik & Begelman, 1988)
- Dust can survive if enclosed in dense clouds shielding their interior

Goals.
- model SED for given dust cloud distribution around AGN
- 2nd step: fit interferometric data of NGC1068 (by Jaffe et al.) with CLUMPY models. Try to determine physical size of dust-free inner region, and other parameters.

The method of modeling.
Two basic types of clouds: with and without direct AGN view.

Directly illuminated clouds
- bright and dark face; phases, depending on cloud distance *r* and position angle *α* within torus (see Fig. 2)
- 'direct' source function: $S_{d,\lambda}(r,\alpha)$.
- dust radiative transfer for 1D-slab: code '*DUSTY*' (Ivezić, Nenkova, & Elitzur 1999); averaging slab solutions over all slab inclination angles mimics cloud phases (code '*SFN*', Sirocky).

Clouds without direct AGN view
- affected only by radiation processed by directly illuminated clouds
- cloud placed in isotropic radiation bath at given temperature (at *r*)
- 'indirect' source function: $S_{i,\lambda}(r)$.

Cloud source function at given location within torus:

$$S_{c,\lambda}(r,\alpha,\beta) = p(r,\beta)\, S_{d,\lambda}(r,\alpha) \; + \; (1 - p(r,\beta))\, S_{i,\lambda}(r) \qquad \textbf{(1)}$$

with probability $p(r,\beta)$ of direct AGN view at given location (*β* angular height over torus equatorial plane)

Intensity generated in segment *ds* of a path to observer: $S_{c,\lambda} N_c ds$
with N_c number of clouds / unit length

Probability for radiation to escape along rest of path (if number of clouds along rest of path Poisson-distributed; Natta & Panagia, 1984):

$$P_{esc} = e^{-(1-e^{-\tau_\lambda})\int_s N_c\, ds} \qquad \textbf{(2)}$$

AGN brightness for position (*x*,*y*) in Cartesian coordinate system (*x, y* in plane of sky, *z* from AGN to observer) at inclination angle *i*:

$$H_\lambda(x,y;i) = \int P_{esc,\lambda}(\vec{r}) S_{c,\lambda}(\vec{r}) N_c(\vec{r})\, dz \qquad \textbf{(3)}$$

Calculating H_λ for all (*x*,*y*) and normalizing properly gives SED. Calculations performed by code '*CLUMPY*'.

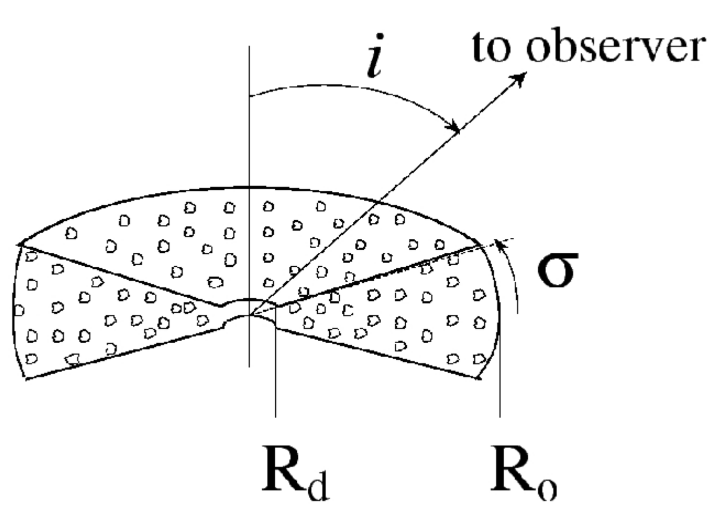

Fig. 1: Torus geometry (from Nenkova et al., in preparation)

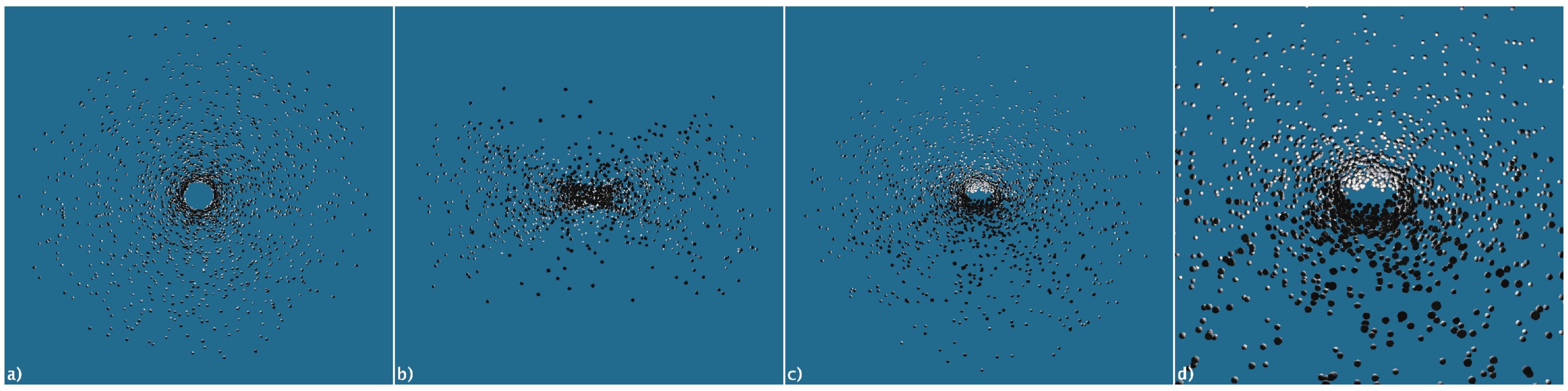

Fig. 2: Visualization of a clumpy torus as modeled by CLUMPY. All clouds are illuminated by a single isotropic source of light at the very center (the AGN, not depicted). Their individual optical depths are identical (here, the clouds are opaque). The finite cloud size in this figure is just for illustration purposes. In CLUMPY, the size enters only by means of the volume filling factor and probabilities. The cloud distribution is axially symmetric, the torus has a wedge angle of σ = 30 deg, the radial cloud distribution follows $1/r^2$, and extends from $R_{in} = 1\ R_d$ up to $R_{out} = 10\ R_d$ (R_d = dust sublimation radius). **a)** The cloud configuration observed pole-on (viewing angle 0 deg). The inner, cloud-free cavity of radius 1 R_d and the concentration of clouds toward small radii can be clearly seen. **b)** Edge-on view (viewing angle 90 deg) of the same configuration. Most clouds present only their dark face to the observer. Some clouds - not obscured by other clouds in the foreground - can still show their illuminated side. Some off-center clouds show both their dark and illuminated sides partially (phases). **c)** View at an angle of 45 deg. The observer clearly sees more illuminated clouds from the far side of the inner cavity, since being above the torus wedge angle of σ = 30 deg he now has a clear view of the inner regions. The upper part of the image appears brighter in total than the lower part. **d)** Same view as **c)**, but two times closer. Only the central part is visible in the panel, but the phases of individual clouds are clearly recognizable.

The code CLUMPY.
- Fortran 90 code calculating SEDs from dust cloud distribution
- parallelized with message passing interface (MPI); generates SED in typically less than 30 seconds on 4-CPU-machine.

- The following can be specified:
  - dust composition (by means of available SFNs)
  - geometry (toroidal / spherical cloud distributions)
  - mean number N_0 of clouds along radial equatorial rays
  - optical depth τ of single cloud
  - radial and angular behaviors of cloud distribution
  - torus angular width σ
  - torus maximal radial extent $Y_{max} = R_{out} / R_d$

- Output: SED for 125 wavelengths *λ* and any viewing angle *i*. The direct AGN contribution can be added to the SED.

- SEDs for many model configurations (currently > 8,000) publicly available (after registration) from our web catalog:

http://www.pa.uky.edu/clumpy

- From **eq. (3)**: brightness can be calculated for any point (*x*,*y*) → Imaging mode of CLUMPY. Brightness maps for any *λ* can be stored as 3D-datacubes (*x*,*y*,*λ*) in FITS files.

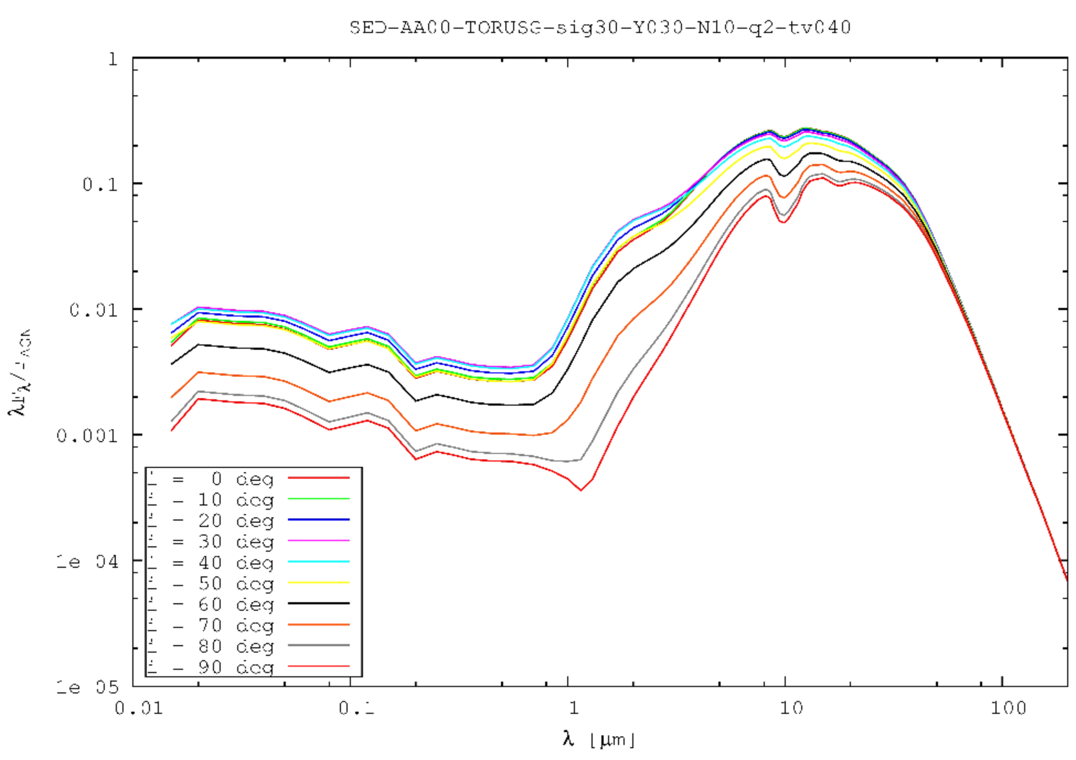

Fig. 3: The SED mode. For any cloud configuration, CLUMPY calculates the spectral energy distribution for all specified viewing angles *i*. Both scales in this figure are logarithmic. The parameters specifying the cloud distribution and cloud properties are given in the figure's title.

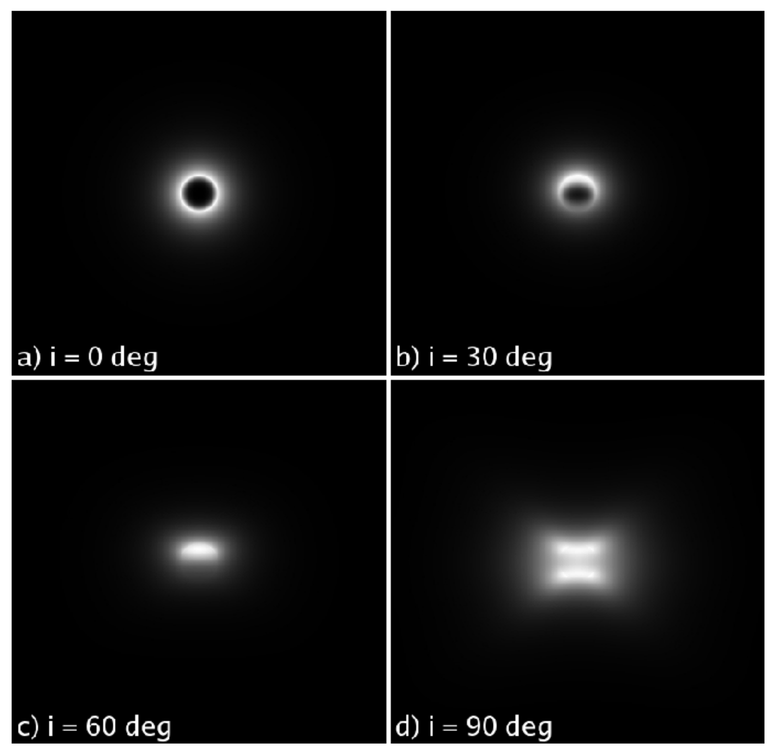

Fig 4: The imaging mode. For any cloud distribution CLUMPY can generate brightness maps. Depicted is a model with Gaussian angular cloud distribution (width σ = 30 deg), a radial distribution following $1/r^2$, a mean number of clouds along radial equatorial rays N_0 = 5, a cloud optical depth at visual wavelengths τ_V = 40, and a radial torus extent of $Y_{max} = R_{out} / R_{in} = 30\ R_d$. Only the central 10x10 R_d are shown, and all panels are for λ = 10 μm. In panels **a) - d)** the viewing inclination angle increases from 0 deg to 90 deg in 30 deg steps. The color scaling is linear black and white, with white showing the maximum brightness in a given panel.

CLUMPY and interferometric observations.
The ability to generate brightness maps allows to use CLUMPY for fitting interferometric data taken recently with the mid-infrared instrument (MIDI) connected to VLTI in Chile. The dataset was provided by the group of W. Jaffe (by D. Raban) and consists of correlated fluxes for 16 interferometric baselines in the N-band (8-13.5 μm) for the nearby AGN NGC1068. The longest projected baseline in that dataset is ~ 130 m, providing a maximum angular resolution of order ~ 10 mas at λ = 12 μm, or equivalently 0.7 pc at the distance of NGC1068 (14.4 Mpc, Mason et al. 2006).

Fourier-transforming the CLUMPY brightness maps in two dimensions for all wavelengths and selecting the Fourier components that correspond to the 16 baselines provides synthetic correlated fluxes for the given CLUMPY model. Comparing these correlated fluxes to the ones contained in the dataset may enable us to fix some parameters of NGC1068, most important being the true physical size of the dust-free inner region of the torus.

Knowing this size, by giving the dust sublimation temperature T_{sub} for the dust species contained in the torus (often known from laboratory measurements), one can calculate the luminosity of the AGN, which is a matter of many debates.

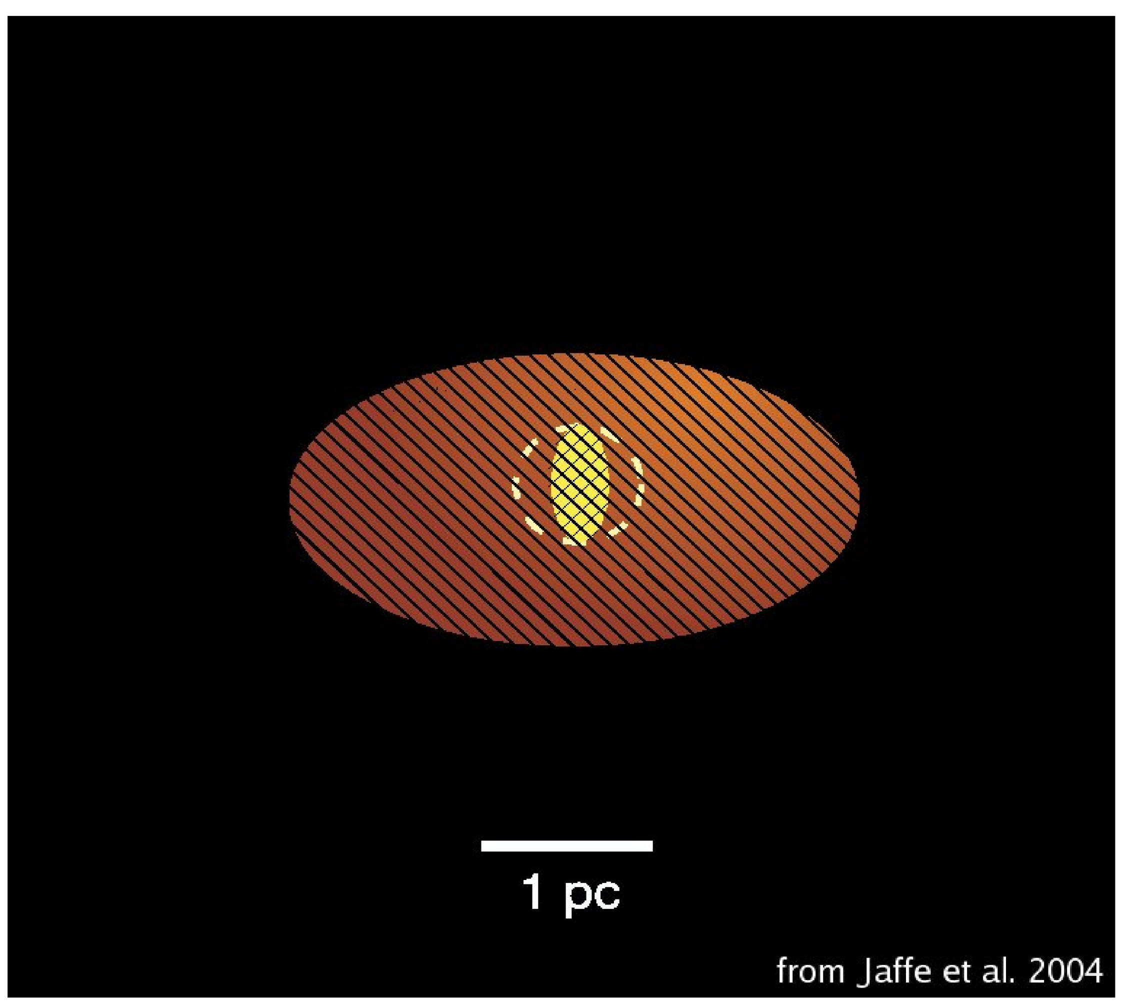

Fig. 5: A model of NGC1068 constrained by current interferometric observations. Through fitting the correlated fluxes from two baselines, Jaffe et al. (2004) suggested a model for the AGN consisting of two ellipsoidal Gaussian blackbody components. The central bright component is definitively smaller than 1 pc and hotter than 800 K. North is up in this figure.

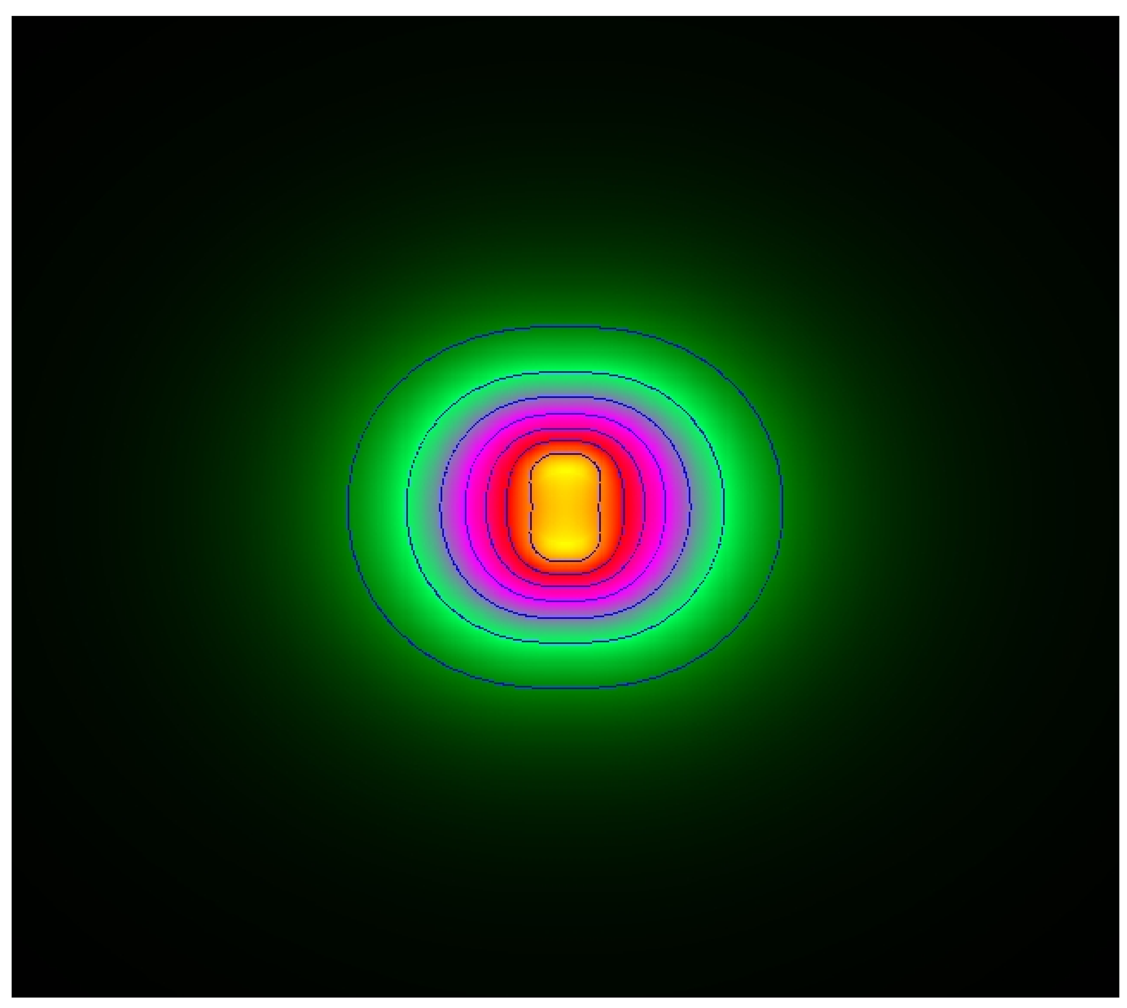

Fig. 6: A model by CLUMPY. For some combinations of cloud distribution parameters it seems possible to mimic the models of NGC1068 developed by observational astronomers (see Fig. 5). Shown are the central 7x7 R_d of a model in false-color, linear-scaling (viewing angle is 90 deg). Isophotes of that model are overplotted in blue color. They strikingly seem to resemble the North-South elongation of a bright component, and the East-West elongation of a cooler, less bright component.

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