The radiative transfer code POLARIS

Introduction and examples

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An introduction to radiative transfer &
application in astrophysics and plasma physics

École Doctorale « Sciences physique et de l'ingénieur »

What is POLARIS?

Radiative transfer simulation code

- Numerical approaches to solve the RT equation
  - **Monte-Carlo** (temperature and scattering)
  - **Raytracing** (continuum and line emission)
- Analytical models and (M)HD simulations
- Emission maps and spectral energy distributions

Development

- C++ (main code) and Python (optional toolkit)
- By Stefan Reissl and Robert Brauer

History of POLARIS

Apr., 1999	MC3D in version 1 (basis for POLARIS, Wolf et al. 1999)
Feb., 2003	MC3D in version 2 (basis for POLARIS, Wolf 2003)
2010	MC3D in version 4 (basis for POLARIS)
2014	**Start of POLARIS development** (version 1.0)
June, 2014	$\Rightarrow$ Reissl et al. (2014)
July, 2015	Mol3D (basis for line RT in POLARIS version 2.0, Ober et al. 2015)
Apr., 2016	$\Rightarrow$ Brauer et al. (2016)
Sept., 2016	$\Rightarrow$ Reissl et al. (2016)
2017	Final merge of MC3D and Mol3D into POLARIS (version 3.0)
Sept., 2017	**First POLARIS workshop** (in Heidelberg)
May, 2017	$\Rightarrow$ Brauer et al. (2017a)
July, 2017	$\Rightarrow$ Reissl et al. (2017)
Nov., 2017	$\Rightarrow$ Brauer et al. (2017b)
Mai, 2018	$\Rightarrow$ Reissl et al. (2018)
Aug., 2018	**First public release of POLARIS** (version 4.0)
Jan., 2019	$\Rightarrow$ Seifried et al. (2019)
Jul., 2019	**Current stable release version 4.05.**

Download from our homepage

- `www1.astrophysik.uni-kiel.de/~polaris`
- Execute `./polaris.run` to start installation

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Download from our GitHub repository

- https://github.com/robertbrauer1988/Polaris.git
- Use git clone to download the POLARIS repository
- Execute ./install_polaris.sh to start installation

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- https://github.com/robertbrauer1988/Polaris.git
- Use git clone to download the POLARIS repository
- Execute ./install_polaris.sh to start installation

$\Rightarrow$ **Already installed on your training PCs**

Using POLARIS

ASCII command files

- Most fundamental way of using POLARIS
- Files in UML-like script language to start simulation
- First choice when using (M)HD simulations

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PolarisTools (Python scripts)

- Create grids, start simulations, and plot results
- Needs Python and other modules (e.g. numpy, matplotlib)
- First choice when using analytical models

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$\Rightarrow$ **The following exercises are based on PolarisTools**

PolarisTools (Python scripts)

polaris-gen

- Generates binary files that contain the grid/model

polaris-run

- Executes POLARIS simulations

polaris-plot

- Creates plots of POLARIS results

⇒ **Use the option** `--help` **for more information**

Continuum radiative transfer

Exercise I: Laser directed at a sphere
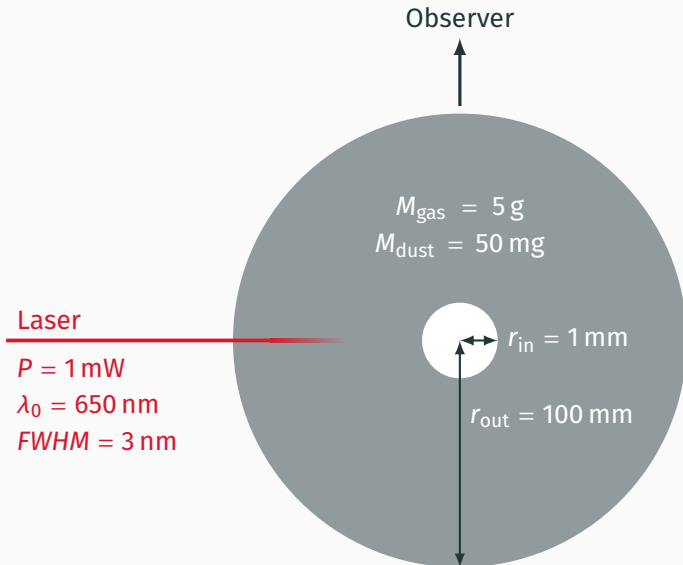
Observer

$M_{gas} = 5\,g$
$M_{dust} = 50\,mg$

Laser

$P = 1\,mW$
$\lambda_0 = 650\,nm$
$FWHM = 3\,nm$

$r_{in} = 1\,mm$

$r_{out} = 100\,mm$

Exercise I: Laser directed at a sphere

Create the grid

- `polaris-gen sphere grid1.dat`
  - `↪ --inner_radius 1mm --outer_radius 100mm`
  - `↪ --gas_mass 5g`

Simulate the scattered light (dust_mc → Monte-Carlo)

- `polaris-run sphere exercise_1 dust_mc`
  - `↪ --grid grid1.dat --wavelength 650nm`
  - `↪ --distance 1m --source laser`
  - `↪ --source_position ' -100mm' 0 0`
  - `↪ --source_direction 1 0 0 --source_power 1mW`
  - `↪ --source_center_wl 650nm --source_fwhm 3nm`
  - `↪ --rot_1 0 --rot_axis_1 1 0 0`

Exercise I: Laser directed at a sphere

Plot the emission map

- `polaris-plot sphere exercise_1 dust_mc map 1`
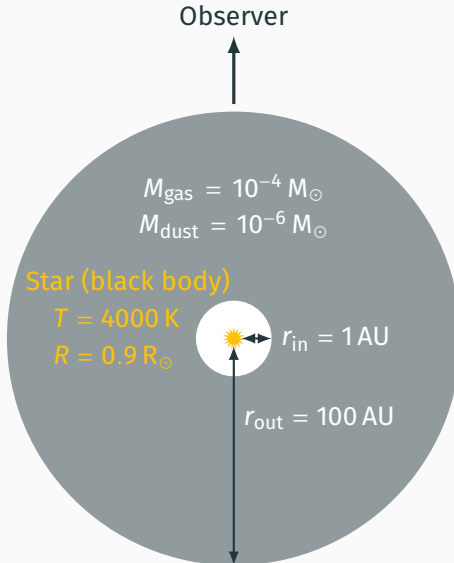 - ↪ `--cmap_unit nuF --cmap_scaling power 0.3 -v`
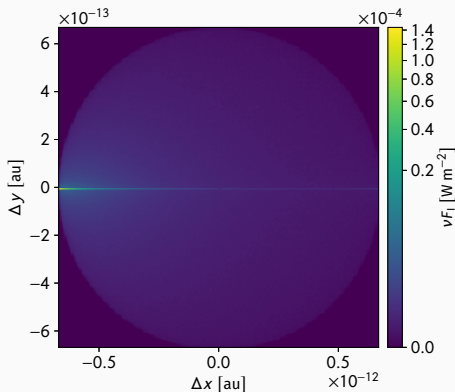
Continuum emission.

Exercise I: Questions

What will happen if the...

- Total mass is lower or higher?
- Wavelength is shorter or longer?
- Observer looks at a different angle or distance?
- Laser has more power?
- Laser has a broader beam (spectrum)?
+ *Own ideas*

Exercise II: Star with envelope

Create the grid

- `polaris-gen sphere grid2.dat`
   - ↪ `--inner_radius 1au --outer_radius 100au`
    - ↪ `--gas_mass 1e-4M_sun`

Simulate the scattered light (dust_mc → Monte-Carlo)

- `polaris-run sphere exercise_2 dust_mc`
    - ↪ `--grid grid2.dat --wavelength 1microns`
    - ↪ `--source ttauri --source_position 0 0 0`
    - ↪ `--source_temperature 4000`
    - ↪ `--source_radius 0.9R_sun --distance 140pc`
    - ↪ `--dust_size 5nm 250nm --photons 1e6`

Exercise II: Star with envelope

Plot the emission map

- `polaris-plot sphere exercise_2 dust_mc map 1`
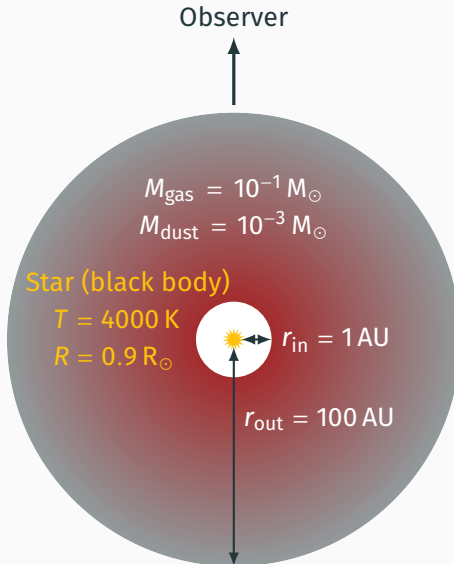 - ↪ `--cmap_scaling log -v`
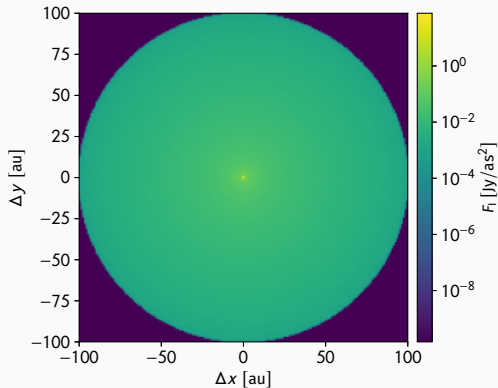
Continuum emission.

Exercise II: Questions

What will happen if the...

- Star is smaller or larger?
- Star is colder or hotter?
- Dust grains are smaller or larger?
- Sphere has a smaller or larger inner radius?
- Number of photons is lower or higher?
+ *Previous questions and own ideas*

Observer

$M_{gas} = 10^{-1}\,M_\odot$
$M_{dust} = 10^{-3}\,M_\odot$

Star (black body)
$T = 4000\,K$
$R = 0.9\,R_\odot$

$r_{in} = 1\,AU$

$r_{out} = 100\,AU$

Simulate the heating of dust grains (Monte-Carlo)

- ```
  polaris-run sphere exercise_3 temp
      ↪ --grid grid2.dat --conv_dens 1e3
      ↪ --dust_size 5nm 1mm
      ↪ --source ttauri --source_position 0 0 0
      ↪ --source_temperature 4000
      ↪ --source_radius 0.9R_sun
      ↪ --photons 1e6
  ```

Exercise III: Thermal emission of an envelope

Plot the temperature distribution

- `polaris-plot sphere exercise_3 temp midplane`
  - ↪ `output dust_temperature xy -v`
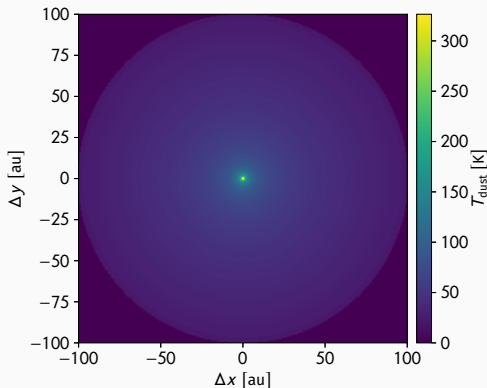
Temperature distribution in a horizontal cut through the model.

Simulate the thermal emission (Raytracing)

- `polaris-run sphere exercise_3 dust`
    - ↪ `--wavelength 1mm --dust_size 5nm 1mm`
    - ↪ `--source ttauri --source_position 0 0 0`
    - ↪ `--source_temperature 4000`
    - ↪ `--source_radius 0.9R_sun`
    - ↪ `--pixel 201`

Exercise III: Thermal emission of an envelope

Plot the emission map

- ```
  polaris-plot sphere exercise_3 dust map 1
  ```
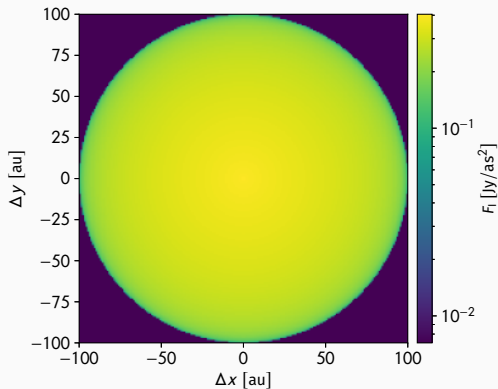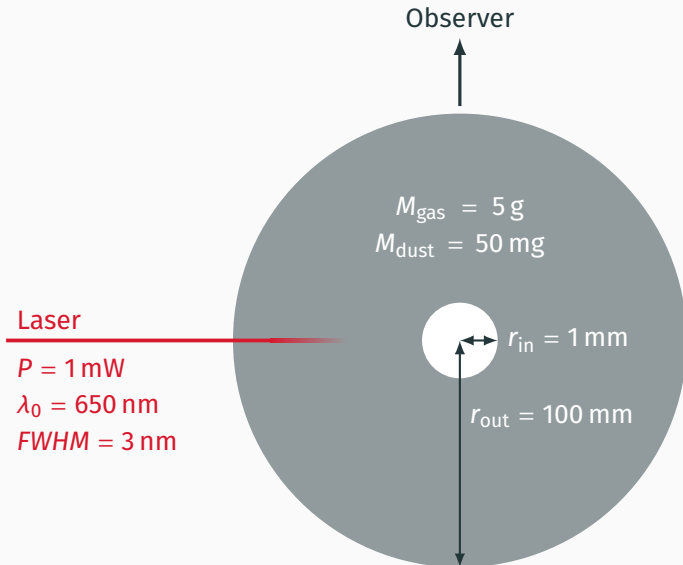   ↪ ```
      --cmap_scaling log -v
      ```



Continuum emission.

**What will happen if the...**

- Dust is colder or hotter?
- Emission map has less or more pixel?
- Temperature midplane cut has less or more pixel?
+ *Previous questions and own ideas*

# Polarized continuum RT

## Exercise I: Laser directed at a sphere

Observer

$M_{gas} = 5\,g$
$M_{dust} = 50\,mg$

$r_{in} = 1\,mm$

$r_{out} = 100\,mm$

Laser

$P = 1\,mW$
$\lambda_0 = 650\,nm$
$FWHM = 3\,nm$

## Exercise I: Laser directed at a sphere

**Create the grid**

- ```
  polaris-gen sphere grid1.dat
  ```
  ↪ `--inner_radius 1mm --outer_radius 100mm`
  ↪ `--gas_mass 5g`

Simulate the scattered light (dust_mc → Monte-Carlo)

- ```
  polaris-run sphere exercise_1 dust_mc
  ```
  ↪ `--grid grid1.dat --wavelength 650nm`
  ↪ `--distance 1m --source laser`
  ↪ `--source_position ' -100mm' 0 0`
  ↪ `--source_direction 1 0 0 --source_power 1mW`
  ↪ `--source_center_wl 650nm --source_fwhm 3nm`
  ↪ `--rot_1 0 --rot_axis_1 1 0 0`

Exercise I: Laser directed at a sphere

Plot the polarized emission maps

- `polaris-plot sphere exercise_1 dust_mc map 1`
  - ↪ `--cmap_unit nuF --cmap_scaling log -v`

Left: Polarized emission. *Right:* Degree of polarization.

What will happen if the...

- Total mass is lower or higher?
- Wavelength is shorter or longer?
- Observer looks at a different angle or distance?
- Dust grains are smaller or larger?
- *Previous questions and own ideas*

Exercise II: Star with envelope

Observer

$M_{gas} = 10^{-4} \, M_\odot$
$M_{dust} = 10^{-6} \, M_\odot$

Star (black body)
$T = 4000 \, K$
$R = 0.9 \, R_\odot$

$r_{in} = 1 \, AU$

$r_{out} = 100 \, AU$

Exercise II: Star with envelope

Create the grid

- `polaris-gen sphere grid2.dat`
    - `↪ --inner_radius 1au --outer_radius 100au`
    - `↪ --gas_mass 1e-4M_sun`

Simulate the scattered light (dust_mc → Monte-Carlo)

- `polaris-run sphere exercise_2 dust_mc`
    - `↪ --grid grid2.dat --wavelength 1microns`
    - `↪ --source ttauri --source_position 0 0 0`
    - `↪ --source_temperature 4000`
    - `↪ --source_radius 0.9R_sun --distance 140pc`
    - `↪ --dust_size 5nm 250nm --photons 1e6`

Plot the polarized emission maps

- `polaris-plot sphere exercise_2 dust_mc map 1`
  - ↪ `--cmap_scaling log -v`

Left: Polarized emission. *Right:* Degree of polarization.

Exercise II: Questions

What will happen if the...

- Total mass is lower or higher?
- Wavelength is shorter or longer?
- Observer looks at a different angle or distance?
- Dust grains are smaller or larger?
+ *Previous questions and own ideas*

Exercise III: Thermal emission of an envelope

Plot the magnetic field

- `polaris-plot sphere exercise_3 temp midplane`
    - ↪ `input mag_field xy -v`

Magnetic field in a horizontal cut through the model.

Simulate the polarized thermal emission
(Raytracing, dust_pa → perfect alignment)

- ```
  polaris-run sphere exercise_3 dust_pa
  ```
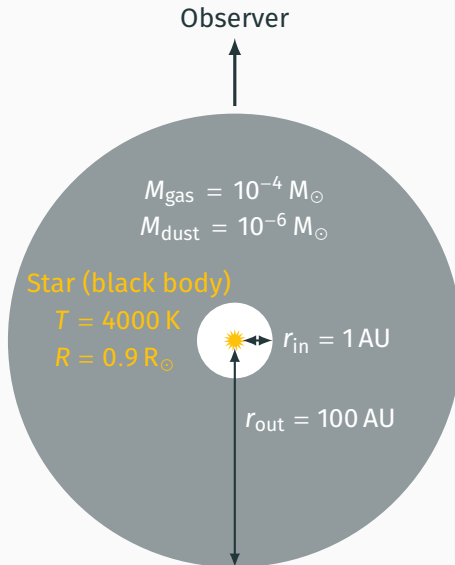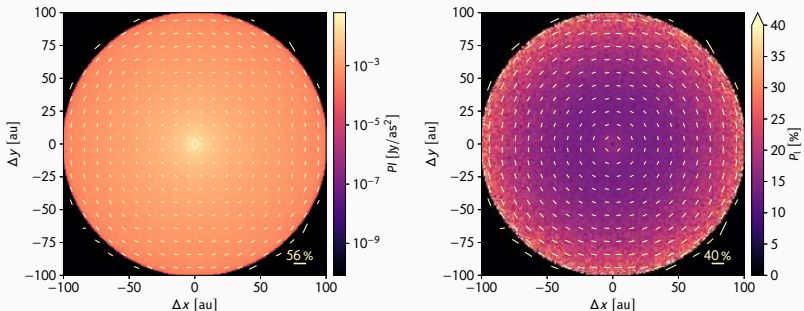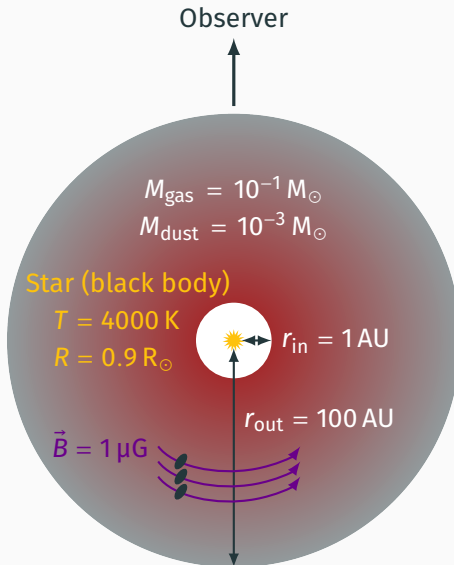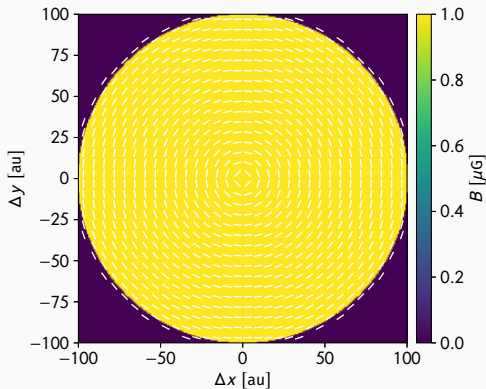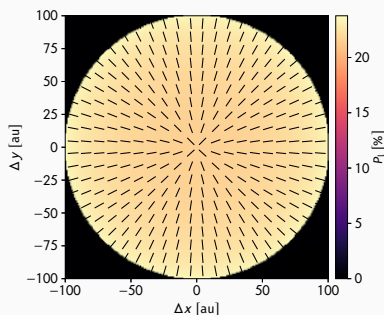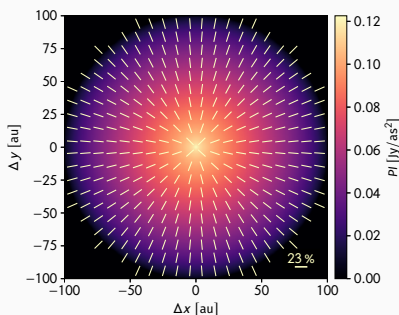 ```
  ↪ --wavelength 1mm --dust mrn_oblate
  ```
  ```
  ↪ --source ttauri --source_position 0 0 0
  ```
  ```
  ↪ --source_temperature 4000
  ```
  ```
  ↪ --source_radius 0.9R_sun
  ```
  ```
  ↪ --dust_size 5nm 250nm
  ```

## Exercise III: Thermal emission of an envelope

**Plot the polarized emission maps**

- `polaris-plot sphere exercise_3 dust_pa map 1 -v`



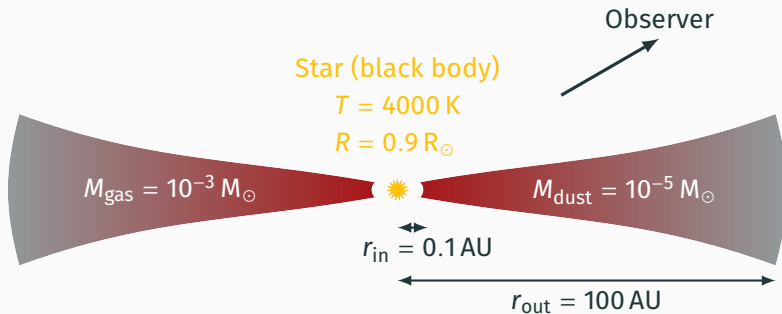*Left:* Polarized emission. *Right:* Degree of polarization.

**What will happen if the...**

- Total mass is lower or higher?
- Wavelength is shorter or longer?
- Observer looks at a different angle or distance?
- Dust grains are smaller or larger?
+ *Previous questions and own ideas*

# Circumstellar disks

Observer

Star (black body)
$T = 4000\,\text{K}$
$R = 0.9\,\text{R}_\odot$

$M_{\text{gas}} = 10^{-3}\,\text{M}_\odot$

$M_{\text{dust}} = 10^{-5}\,\text{M}_\odot$

$r_{\text{in}} = 0.1\,\text{AU}$

$r_{\text{out}} = 100\,\text{AU}$

## Exercise IV: Circumstellar disk continuum emission

**Create the grid**

- `polaris-gen disk grid.dat`
    ↪ `--inner_radius 0.1au --outer_radius 100au`
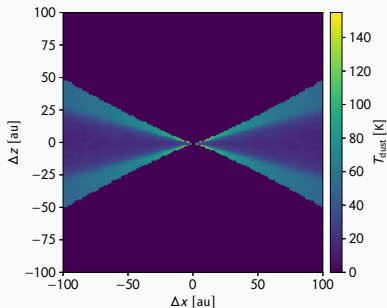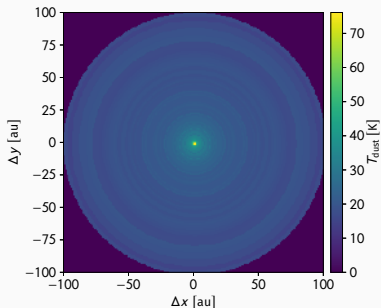    ↪ `--gas_mass 1e-3M_sun`

**Simulate the heating of dust grains (Monte-Carlo)**

- `polaris-run disk exercise_4 temp`
    ↪ `--grid grid.dat`
    ↪ `--source ttauri --source_position 0 0 0`
    ↪ `--source_temperature 4000`
    ↪ `--source_radius 0.9R_sun`
    ↪ `--dust_size 5nm 250nm --photons 1e6`

**Plot the temperature distributions**

- `polaris-plot disk exercise_4 temp midplane`
  - ↪ `output dust_temperature xy -v`



Temperature distribution in a horizontal (*left*) or vertical (*right*) cut through the model.

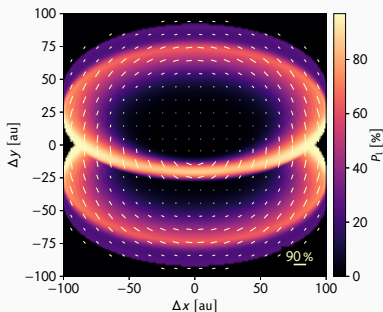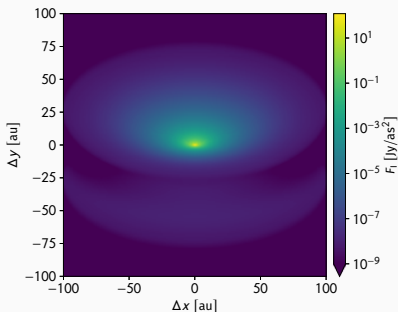## Exercise IV: Circumstellar disk continuum emission

**Simulate the full emission (Raytracing)**

- `polaris-run disk exercise_4 dust`
    - `↪ --wavelength 10microns --rot_1 60`
    - `↪ --source ttauri --source_position 0 0 0`
    - `↪ --source_temperature 4000`
    - `↪ --source_radius 0.9R_sun --distance 140pc`
    - `↪ --dust_size 5nm 250nm`

# Exercise IV: Circumstellar disk continuum emission

**Plot the polarized emission maps**

- `polaris-plot disk exercise_4 dust map 1`
  `↪ --cmap_scaling log --vmin 1e-9 -v`



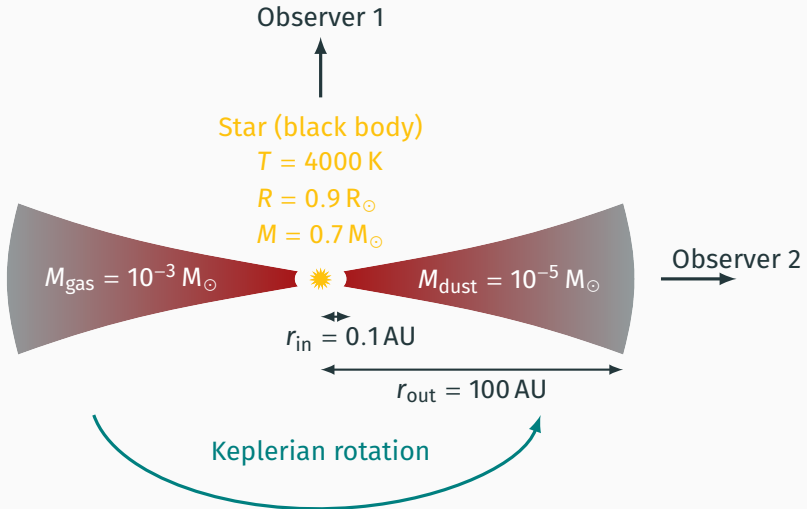*Left:* Continuum emission. *Right:* Degree of polarization.

**What will happen if the...**

- Star is at a different position?
- Total mass is lower or higher?
- Wavelength is shorter or longer?
- Observer looks at a different angle or distance?
- Dust grains are smaller or larger?
+ *Previous questions and own ideas*

# Spectral line RT

Observer 1

Star (black body)
$T = 4000\,\mathrm{K}$
$R = 0.9\,\mathrm{R_\odot}$
$M = 0.7\,\mathrm{M_\odot}$

$M_{\mathrm{gas}} = 10^{-3}\,\mathrm{M_\odot}$

$M_{\mathrm{dust}} = 10^{-5}\,\mathrm{M_\odot}$

Observer 2

$r_{\mathrm{in}} = 0.1\,\mathrm{AU}$

$r_{\mathrm{out}} = 100\,\mathrm{AU}$
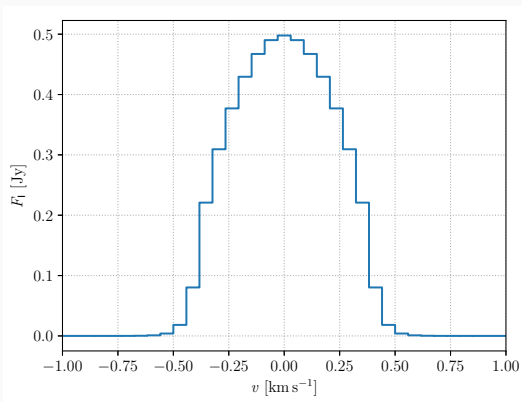
Keplerian rotation

**Simulate the spectral line emission (Raytracing)**

- `polaris-run disk exercise_4 line`
  - ↪ `--max_vel 1km/s`
  - ↪ `--gas c18o --transition 1 --channels 35`
  - ↪ `--abundance 2e-7 --lvl_pop LTE`
  - ↪ `--turbulence 100`

**Plot the spectrum**

- `polaris-plot disk exercise_4 line spectrum 1 -v`
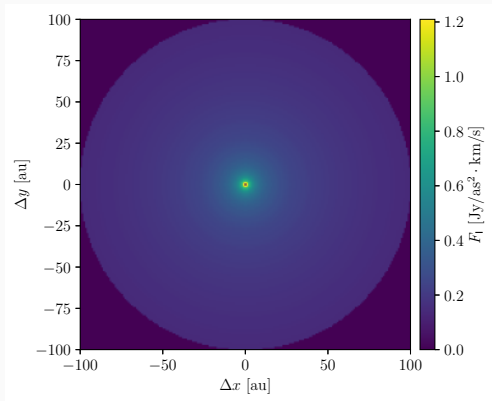


Spectral line profile

# Exercise V: Circumstellar disk line emission

**Plot the integrated velocity channel map**

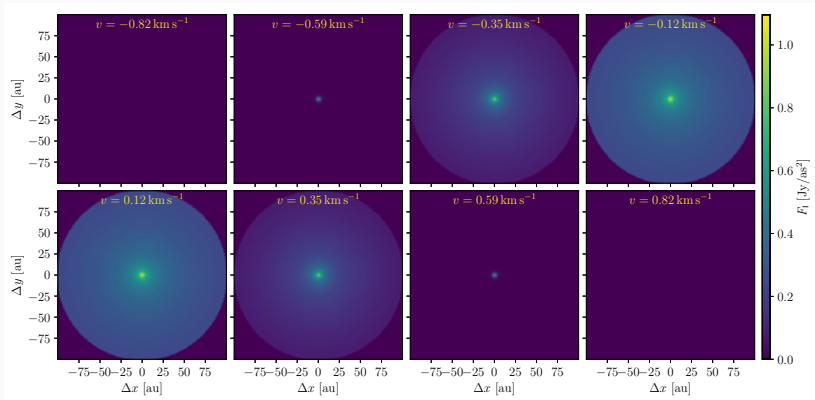- `polaris-plot disk exercise_4 line int_map 1 -v`



Integrated velocity channel map

# Exercise V: Circumstellar disk line emission

## Plot the velocity channels maps

- `polaris-plot disk exercise_4 line vel_map 1 -v`
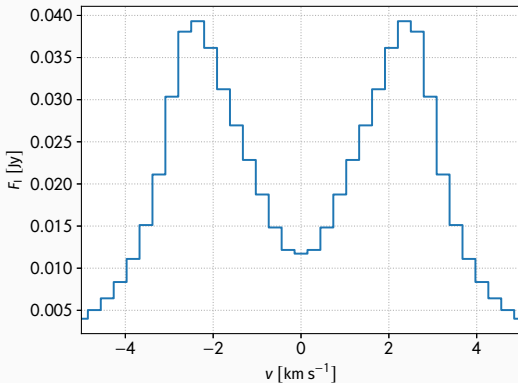


Velocity channels maps

**Simulate the spectral line emission (Raytracing)**

- `polaris-run disk exercise_4 line`
    - ↪ `--rot_1 90 --kepler --max_vel 5km/s`
    - ↪ `--gas c18o --transition 1 --channels 35`
    - ↪ `--abundance 2e-7 --lvl_pop LTE`
    - ↪ `--turbulence 100 --source_mass 0.7M_sun`

# Exercise V: Circumstellar disk line emission

**Plot the spectrum**

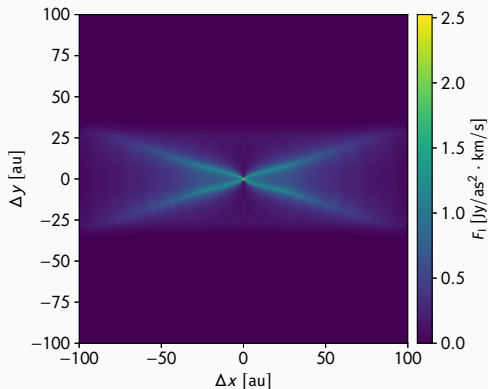- `polaris-plot disk exercise_4 line spectrum 1 -v`



Spectral line profile

# Exercise V: Circumstellar disk line emission

## Plot the integrated velocity channel map

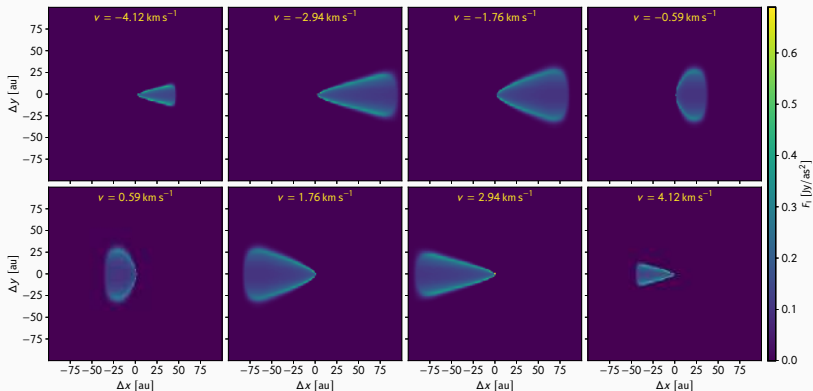- `polaris-plot disk exercise_4 line int_map 1 -v`



Integrated velocity channel map

# Exercise V: Circumstellar disk line emission

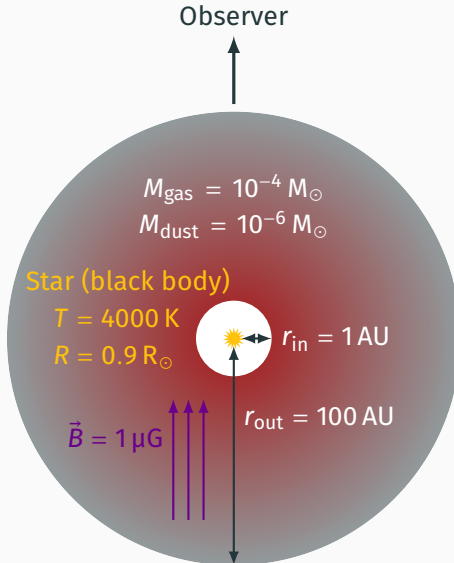## Plot the velocity channels maps

- `polaris-plot disk exercise_4 line vel_map 1 -v`



Velocity channels maps

**What will happen if the…**

- Line transition is different?
- Maximum velocity is lower or higher?
- Number of channels is lower or higher?
- Level population is calculated differently?
- Turbulence is weaker or stronger?
- Mass of the star is lower or higher?
+ *Previous questions and own ideas*

Observer

$M_{gas} = 10^{-4} \, M_\odot$
$M_{dust} = 10^{-6} \, M_\odot$

Star (black body)
$T = 4000 \, K$
$R = 0.9 \, R_\odot$

$r_{in} = 1 \, AU$

$r_{out} = 100 \, AU$

$\vec{B} = 1 \, \mu G$

## Exercise VI: Zeeman line emission of an envelope

**Create the grid**

- `polaris-gen sphere grid3.dat`
    - ↪ `--extra vertical_mag_field`
    - ↪ `--inner_radius 1au --outer_radius 100au`
    - ↪ `--gas_mass 1e-4M_sun`

**Simulate the heating of dust grains (Monte-Carlo)**

- `polaris-run sphere exercise_5 temp`
    - ↪ `--grid grid3.dat`
    - ↪ `--source ttauri --source_position 0 0 0`
    - ↪ `--source_temperature 4000`
    - ↪ `--source_radius 0.9R_sun`
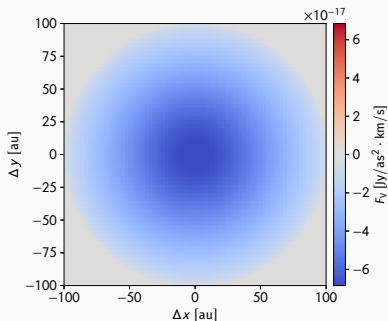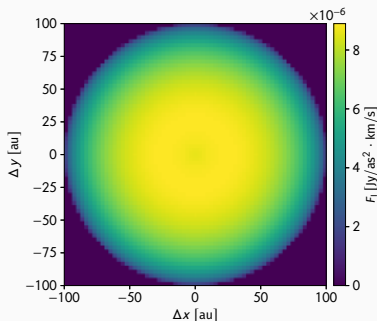    - ↪ `--photons 1e6`

**Simulate the polarized spectral line emission (Raytracing)**

- `polaris-run sphere exercise_5 zeeman --gas oh`
  - ↪ `--transition 2 --max_vel 1km/s --pixel 65`
  - ↪ `--channels 35 --abundance 1e-07`
  - ↪ `--lvl_pop LTE --turbulence 100`

# Exercise VI: Zeeman line emission of an envelope

**Plot the integrated velocity channel map**

- `polaris-plot sphere exercise_5 zeeman`
    `↪ int_map 1 -v`



Spectral line intensity (*left*) and circular polarization *(right)* integrated velocity channel map.

# Exercise VI: Zeeman line emission of an envelope

**Plot the velocity channel maps**

- ```
  polaris-plot sphere exercise_5 zeeman
      ↪ vel_map 1 -v
  ```


Spectral line intensity velocity channel maps.

Exercise VI: Zeeman line emission of an envelope

Plot the velocity channel maps

- `polaris-plot sphere exercise_5 zeeman`
  ↪ `vel_map 1 -v`
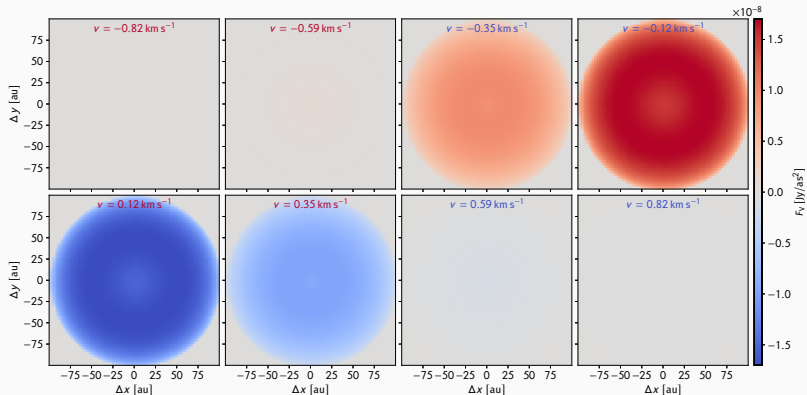
Spectral line circular polarization velocity channel maps.

Exercise VI: Zeeman line emission of an envelope

Plot the spectrum

- ```
  polaris-plot sphere exercise_5 zeeman
      ↪ spectrum 1 -v
  ```
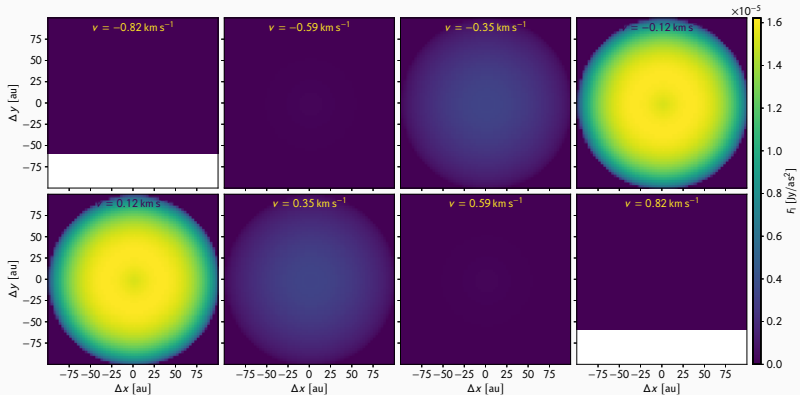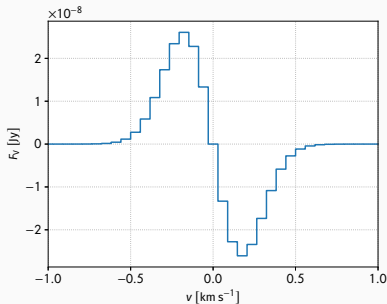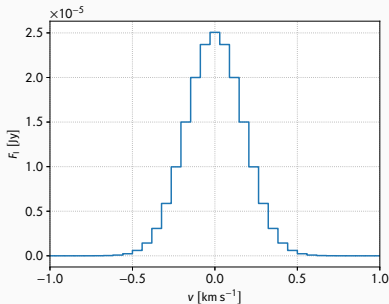

Spectral line intensity (*left*) and circular polarization *(right)* profiles.

Exercise VI: Zeeman line emission of an envelope

Plot the LOS magnetic field strength

- `polaris-plot sphere exercise_5 zeeman`
  `↪ mag_field 1 -v`
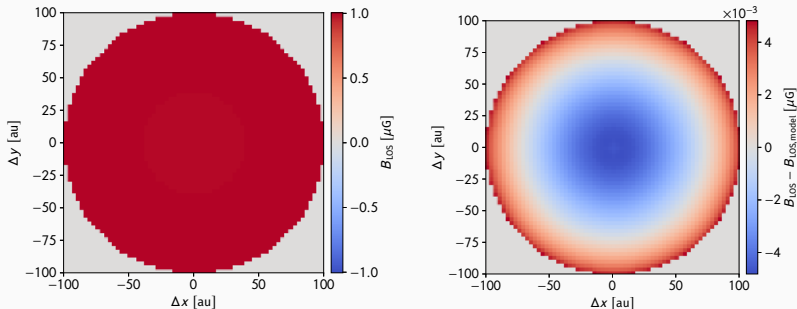
Derived LOS magnetic field strength (*left*) and difference to model value *(right)*.

Exercise VI: Questions

What will happen if the…

- Magnetic field if weaker or stronger?
- Line transition is different?
- Number of channels is lower or higher?
- Maximum velocity is lower or higher?
+ *Previous questions and own ideas*

Grid types
– Cartesian *(OcTree)*
– Spherical
– Cylindrical
– Voronoi

Grid quantities
– Densities *(gas, dust, electrons)*
– Temperatures *(gas, dust, electrons)*
– Velocity field
– Magnetic field strength
– Properties *(gas, dust, electrons)*

Additional data
– Emission sources *(stars, ISRF, ...)*
– Detector parameter *(direction, λ, ...)*
– Dust properties *(silicate, carbon, THEMIS, ...)*
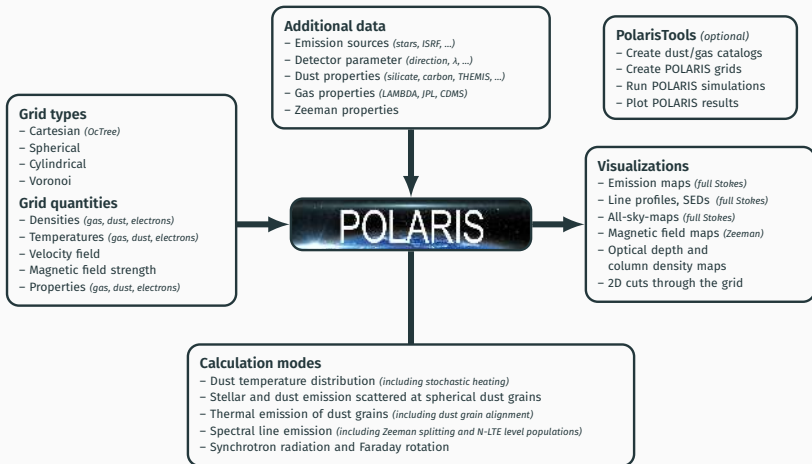– Gas properties *(LAMBDA, JPL, CDMS)*
– Zeeman properties

PolarisTools *(optional)*
– Create dust/gas catalogs
– Create POLARIS grids
– Run POLARIS simulations
– Plot POLARIS results

POLARIS

Visualizations
– Emission maps *(full Stokes)*
– Line profiles, SEDs *(full Stokes)*
– All-sky-maps *(full Stokes)*
– Magnetic field maps *(Zeeman)*
– Optical depth and
  column density maps
– 2D cuts through the grid

Calculation modes
– Dust temperature distribution *(including stochastic heating)*
– Stellar and dust emission scattered at spherical dust grains
– Thermal emission of dust grains *(including dust grain alignment)*
– Spectral line emission *(including Zeeman splitting and N-LTE level populations)*
– Synchrotron radiation and Faraday rotation

Thank you all for your participation!