

# OpTool User Guide

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## 1. Introduction

This tool produces complex dust particle opacities right from the command line. It is derived from Michiel Min's DHS OpacityTool and also implements Ryo Tazaki's MMF theory for highly porous aggregates.

### 1.1. Capabilities

- stand-alone tool, fully command line driven, no input files need to be edited
- full scattering matrix output in several formats, including for RADMC-3D
- combining materials through mixing into a complex grain with porosity
- *built-in*: a curated collection of materials for applications in astronomy
- external refractive index data can be used just as easily
- two computational methods: (i) **DHS (Distribution of Hollow Spheres)** for *irregular grains* and *low-porosity* aggregates. Standard Mie theory for *perfect spheres* is available as a limiting case. (ii) **MMF (Modified Mean Field)** theory for *high-porosity/fractal aggregates*
- **Python** interface module for plotting and post-processing

### 1.2. Terms of use

`optool` is distributed under the MIT license and can be used, changed and redistributed freely. The relevant references for this tool are listed below. Depending on which parts of `optool` you are using, please reference the corresponding papers.

- `optool`: <https://github.com/cdominik/optool.git>
- DHS model for irregular grains: Min et al. 2005, A&A, 432, 909
- MMF model for aggregates: Tazaki & Tanaka 2018, ApJ 860, 79
- DIANA standard Opacities: Woitke, Min et al. 2016, A&A 586, 103
- Third party software: Toon et al. 1981, Applied Optics 20, 3657
- References to refractive index data used in your particular application.

## 2. Examples

A simple grain made only of the default pyroxene, for the default grain size distribution ( $a^{-3.5}$  powerlaw from 0.05 to 3000 $\mu\text{m}$ ), on the default wavelength grid (0.05 $\mu\text{m}$  to 1cm).

```
optool pyr
```

Include the scattering matrix in the produced output

```
optool pyr -s
```

Reproduce the DIANA standard dust model, using a specific pyroxene (70% Mg) and carbon, in a mass ratio 0.87/0.13, and with a porosity of 25%.

```
optool pyr-mg70 0.87 c 0.13 -p 0.25
```

List the built-in materials

```
optool -c
```

Add a water ice mantle (built-in data from Warren+08) that is 20% of the core mass

```
optool pyr-mg70 0.87 c 0.13 -m h2o-w 0.2 -p 0.25
```

Like the previous example, but use ice refractive index data from a separate file.

```
optool pyr-mg70 0.87 c 0.13 -p 0.25 -m data/ice_hudgins.dat 0.2
```

Pure water ice grains in a narrow size distribution from 1 to 3 microns, with 15 sample sizes following an  $f(a) \propto a^{-2.5}$  powerlaw size distribution. Also, restrict the wavelength range to 10-100 $\mu\text{m}$ , and turn off DHS to get perfect spheres.

```
optool h2o -a 1 3 2.5 15 -l 10 100 -fmax 0
```

For silicon carbide, compute the opacity of a single grains size (2.5 $\mu\text{m}$ ) at  $\lambda=8.9\mu\text{m}$ .

```
optool -a 2.5 -l 8.9 sic
```

Represent the default dust model (DIANA, you also get this when you do not give any materials at all) in 42 grain sizes, and produce input files for RADMC-3D, one for each grain size, with full scattering matrix, chopping 3 degrees from the scattering peak.

```
optool -na 42 -d -s -radmc -chop 3
```

Use MMF to compute the opacities of dust aggregates made of pyroxene monomers. Use a monomer radius of 0.3  $\mu\text{m}$  to construct aggregates with compact-volume radii between 10 and 30  $\mu\text{m}$ , and a filling factor of 5%

```
optool pyr -a 10 30 -mmf 0.3 0.05
```

As before, but fix the fractal dimension  $D_f = 1.9$  instead of setting the filling factor

```
optool pyr -a 10 30 -mmf 0.3 1.9
```

### 3. Compiling optool

On most systems, you can download and compile `optool` with these simple steps, using the freely available GNU FORTRAN compiler `gfortran`.

```
git clone https://github.com/cdominik/optool.git
cd optool
make multi=true
```

The executable is called `optool`, and you should put it on your execution path. To use the Intel fortran compiler, to use multiple cores for speed (highly recommended if your system supports it), or to be able to write FITS files<sup>1</sup>, use one or more of the following parameters during compilation:

```
make ifort=true      # use the Intel fortran compiler iFort
make multi=true      # enable multicore support
make fits=true       # add support for writing FITS files[1]
```

You can also find binaries for Mac and Linux at my homepage.

### 4. Command line arguments

**-h** Show a compact help message about command line options.

#### 4.1. Grain composition

If no composition is specified, the default is **-c pyr 0.87 -c c 0.13 -p 0.25**.

**-c** List available built-in materials (the keys for the **-c** and **-m** options).

**[-c] KEY-or-FILE [MFRAC]**

Specify a material to include in the grain. **KEYorFILE** can be the key for a builtin material, or the path to an `lnk` file. **MFRAC** is the *mass* fraction (default 1.0) of the material. You can give up to 10 materials to build up the grain. Mass fractions do not have to add up to one, they will be renormalized. All materials will be mixed together using the *Bruggeman* rule, and vacuum can be added through the porosity. A **-c** switch before each **KEY-or-FILE** is optional.

**-m KEY-or-FILE [MFRAC]**

Like **-c**, but place this material into the grain mantle. Multiple mantle materials will be mixed using the Bruggeman rule, and then that mix will be added to the core using the *Maxwell-Garnett* rule. The **-m** is *not* optional, it must be present.

**-p POROSITY [P\_MANTLE]**

Porosity, the *volume* fraction of vacuum, a number smaller than 1. The default is 0. A single value will apply to both core and mantle, but a second value will be specific for the mantle (and may be 0).

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<sup>1</sup>This requires the `cfitsio` library to be installed on your system.

## 4.2. Grain geometry and computational method

If no method is explicitly specified, the default is **-dhs 0.8**, i.e. DHS with  $f_{\max}=0.8$ .

**-dhs [FMAX]**

Use the *Distribution of Hollow Spheres* (DHS, Min+ 2005) approach to model deviations from perfect spherical symmetry and low-porosity aggregates. Spheres with inner holes with volume fractions between 0 and  $f_{\max}$  (default 0.8) are averaged to mimic irregularities.  $f_{\max}=0$  means to use solid spheres (Mie theory), i.e. perfectly regular grains. For backward compatibility, **-fmax** can be used instead of **-dhs**.

**-mie**

Do a standard *Mie* calculation for perfect spheres. This is short for **-dhs 0**.

**-mmf [AO [DFRAC-OR-FILL]]**

Use *Modified Mean Field* theory (MMF, Tazaki & Tanaka 2018) to compute opacities of highly porous or fractal aggregates. **-c**, **-m**, and **-p** now determine the composition of monomers. **AO** is the monomer radius (default  $0.1\mu\text{m}$ ). Particles will be aggregates with a *compact size* given by the **-a** switch, giving rise to  $N = a^3/a_0^3$  monomers. When **DFRAC-OR-FILL** is greater than 1, it specifies the *fractal dimension*. When it is less than 1, it is interpreted as the *volume filling factor* of the aggregates instead. The default is 0.2, corresponding to a 20% filling factor.

## 4.3. Grain size distribution

**-a AMIN [AMAX [APOW [NA]]]**

Specify (minimum) grain radius, and optionally maximum grain radius, the size distribution powerlaw and the number of size bins. You may also use options to set individual values with **-amin**, **-amax**, **-apow**, **-na**. The defaults are  $0.05\mu\text{m}$ ,  $3000\mu\text{m}$ , 3.5, and 10 per size decade with a fixed minimum of 5, respectively. If only a single size is specified with **-a**, then  $a_{\max}=a_{\min}$  and  $n_a=1$  are implied.

If the APOW element looks like **AP:SIG**, the size distribution will be log normal, centered around  $a_p$ :  $dn/da = \exp\{-0.5[\ln(a/a_p)/\sigma]^2\}$

## 4.4. Wavelength grid

**-l LMIN [LMAX [NLAM]]**

Specify the (minimum) wavelength, and optionally the maximum wavelength and the number of wavelengths points for the construction of the wavelength grid. The default values are  $0.05\mu\text{m}$ ,  $10000\mu\text{m}$ , and 300, respectively. You may also use the options **-lmin**, **-lmax**, and **-nlam** (or **-nl**) to set individual values. If only one wavelength is specified with **-l**, then  $\lambda_{\max}=\lambda_{\min}$  and  $n_\lambda=1$  are implied.

**-l FILE**

Read the wavelength grid from **FILE**. The file may start with comment lines, and the first non-comment line needs to contain the number of wavelength values in the data block below it. In the data block, the first column is expected to hold the wavelength values, in  $\mu\text{m}$ . In particular, an **lnk** file could be used here.

## 4.5. Controlling the output

The standard output is the file `dustkappa.dat`, with the opacities and the asymmetry parameter  $g$ . The following options control and extend the output.

`-o [DIR]`

Put the output files in directory `DIR` instead of the current working directory. `./output` will be used if `-o` is present but `DIR` is not specified.

`-s [NANG]`

Include the full scattering matrix in the output. `NANG` can optionally specify the number of equally-spaced angular grid points to cover the range of angles between 0 and 180 degrees. The default for `NANG` is 180 and should normally be just fine.

`-chop [NDEG]`

Cut out the first `NDEG` (2 if unspecified) degrees of the forward scattering peak and compensate by a reduction in the scattering cross section.

`-d [NSUB]`

Divide the computation up into `NA` parts to produce a file for each grain size. Each size will actually be an average over a small range of `NSUB` grains around the real size, to smear out resonances. The default for `NSUB` is 5.

`-fits`

Write `dustkappa.fits` with the absorption cross sections and scattering matrix elements, instead of ASCII output. With the `-d` switch, `NA` files will be written.

`-radmc [LABEL]`

RADMC-3D uses a different angular grid and normalization for the scattering matrix, so the output has to be adapted for it. The extension of the files will be changed to `.inp`, and if you specify `LABEL`, it will be used in the file name(s).

## 5. Material properties

`optool` needs refractive index data to work. For your convenience, a useful list of materials is compiled into `optool`. You can also find and use other data. No matter where the data is from, you should *always* cite the original laboratory papers.

### 5.1. Built-in materials

To access one of the built-in materials, specify the corresponding key string like `pyr-mg70`. In each material class we have selected a useful default, accessible with an even simpler generic key (for example, `pyr` is an alias for `pyr-mg70`). Most of the built-in refractive index datasets have a wide wavelength coverage - the few exceptions are highlighted by bold-face numbers. If a material is being used outside of the measured region, `optool` will still function, using extrapolated optical properties.

Even the limited number of materials we have selected to include with `optool` can be daunting. To get started with some kind of standard opacity, we recommend to work with pyroxene `[pyr]`, carbon `[c]`, and (at low temperatures) water ice `[h2o]`.

-c Key generic	-c Key full key	Material	State	$\rho$ g/cm <sup>3</sup>	$\lambda_{\min}$ $\mu\text{m}$	$\lambda_{\max}$ $\mu\text{m}$	Reference
pyr	pyr-mg100	MgSiO <sub>3</sub>	amorph	2.71	0.2	500	Dorschner+95
	pyr-mg95	Mg <sub>0.95</sub> Fe <sub>0.05</sub> SiO <sub>3</sub>	amorph	2.74	0.2	500	Dorschner+95
	pyr-mg80	Mg <sub>0.8</sub> Fe <sub>0.2</sub> SiO <sub>3</sub>	amorph	2.9	0.2	500	Dorschner+95
	pyr-mg70	Mg <sub>0.7</sub> Fe <sub>0.3</sub> SiO <sub>3</sub>	amorph	3.01	0.2	500	Dorschner+95
	pyr-mg60	Mg <sub>0.6</sub> Fe <sub>0.4</sub> SiO <sub>3</sub>	amorph	3.1	0.2	500	Dorschner+95
	pyr-mg50	Mg <sub>0.5</sub> Fe <sub>0.5</sub> SiO <sub>3</sub>	amorph	3.2	0.2	500	Dorschner+95
	pyr-mg40	Mg <sub>0.4</sub> Fe <sub>0.6</sub> SiO <sub>3</sub>	amorph	3.3	0.2	500	Dorschner+95
ens	pyr-c-mg96	Mg <sub>0.96</sub> Fe <sub>0.04</sub> SiO <sub>3</sub>	cryst	2.8	<b>2.0</b>	<b>99</b>	Jäger+98
ol	ol-mg50	MgFeSiO <sub>4</sub>	amorph	3.71	0.2	500	Dorschner+95
	ol-mg40	Mg <sub>0.8</sub> Fe <sub>1.2</sub> SiO <sub>4</sub>	amorph	3.71	0.2	500	Dorschner+95
for	ol-c-mg100	Mg <sub>2</sub> SiO <sub>4</sub>	cryst	3.33	<b>3.0</b>	250	Steyer+74
	astrosil	MgFeSiO <sub>4</sub>	mixed	3.3	6e-5	1e5	Draine+03
c	c-z	C	amorph?	1.8	0.05	1e4	Zubko+96
	c-p	C	amorph	1.8	0.11	800	Preibisch+93
gra	c-gra	C graphite	cryst	2.16?	0.001	1000	Draine+03
org	c-org	CHON organics	amorph	1.4	0.1	1e5	Henning+96
	c-nano	C nano-diamond	cryst	2.3	0.02	<b>110</b>	Mutschke+04
iron	fe-c	Fe	metal	7.87	0.1	1e5	Henning+96
	fes	FeS	metal	4.83	0.1	1e5	Henning+96
	sic	SiC	cryst	3.22	0.001	1000	Laor93
qua	sio2	SiO <sub>2</sub>	amorph	2.65	0.0006	500	Kitamura+07
cor	cor-c	Al <sub>2</sub> O <sub>3</sub>	cryst	4.0	0.5	<b>40</b>	Koike+95
h2o	h2o-w	Water ice	cryst	0.92	0.04	2e6	Warren+08
co2	co2-w	CO <sub>2</sub> ice	cryst	1.6	0.05	2e5	Warren+86
nh3	nh3-m	NH <sub>3</sub> ice	cryst	0.75	0.14	200	Martonchik+83
co	co-a	CO ice	amorph	0.81	<b>3.8</b>	<b>5.8</b>	Palumbo+06
	co2-a/c	CO <sub>2</sub> ice	am/cr	1.2	<b>2.5</b>	<b>20</b>	Gerakines+20
	ch4-a/c	CH <sub>4</sub> ice	am/cr	0.47	<b>2.0</b>	<b>20</b>	Gerakines+20
	ch3oh-a/c	CH <sub>3</sub> OH ice	am/cr	0.78/1.02	<b>2.0</b>	<b>24</b>	Gerakines+20

## 5.2. External refractory index files (lnk files)

optool can use external refractive index data in files with the following format:

- The file may start with several comment lines (lines starting with !, #, or \*).
- The next line contains two numbers, the number of wavelengths  $n_\lambda$  and the specific density  $\rho$  of the material in g/cm<sup>3</sup>.
- The remaining lines should form three columns of data:  $\lambda[\mu\text{m}]$  (sorted either up or down), and the real and imaginary parts of the refractive index,  $n$  and  $k$ .

You can find additional refractive index data here, in databases like the Jena database, and associated with original papers in the literature. Don't forget to add the line with  $n_\lambda$  and  $\rho$ ! If that is not possible, optool will count the lines and you can specify the density after the mass fraction, like this: `optool -c path/to/file.lnk 0.7 3.42`.

## 6. Output files

### **dustkappa.dat**

This is an ASCII file containing the basic opacity results. It starts with a comment section describing the dust model, followed by the format number (3, currently), followed by the number of wavelengths in the grid, both on lines by themselves. Then follows a block with these columns:

1. wavelength  $\lambda$  [micron]
2. mass absorption cross section  $\kappa_{\text{abs}}$  [ $\text{cm}^2/\text{g}$ ]
3. mass scattering cross section  $\kappa_{\text{sca}}$  [ $\text{cm}^2/\text{g}$ ]
4. asymmetry parameter  $g$

### **dustkapscatmat.dat**

ASCII file with cross sections and full scattering matrix. It is an extended version of the **dustkappa.dat** file. This file has a format number (0), the number of wavelengths and then the number of angular points after the comment section. After an empty line, this is followed by the same block of wavelengths and opacities as described above for the **dustkappa.dat** file. Another empty line is followed by a list of the grid angles, yet another empty line, and then the scattering matrix elements for all wavelengths and all angles. The comment section at the start of the file shows the structure in a formal way. See the appendix for information about the normalization of the scattering matrix and about the angular grid that is used for it. Also, see the **-radmc** switch which will modify<sup>2</sup> the output to make sure it can be used as an input file for RADMC-3D.

### **dustkappa.fits**

The FITS-file (ending in '.fits') is written instead of the ASCII output when using the **-fits** switch. It has two HDU blocks. The first block contains the cross sections per unit mass. This is an  $n_\lambda \times 4$  matrix with these columns:

1. wavelength in [ $\mu\text{m}$ ]
2. mass extinction cross section  $\kappa_{\text{ext}}$  in [ $\text{cm}^2/\text{g}$ ]
3. mass absorption cross section  $\kappa_{\text{abs}}$  in [ $\text{cm}^2/\text{g}$ ]
4. mass scattering cross section  $\kappa_{\text{sca}}$  in [ $\text{cm}^2/\text{g}$ ]

The second HDU block contains the scattering matrix elements. It is a  $n_\lambda \times 6 \times n_{\text{ang}}$  matrix, containing the 6 elements of the scattering matrix for  $n_{\text{ang}}$  equidistant scattering angles from forward scattering (element 0) to backward scattering (element  $n_{\text{ang}}-1$ ), for each wavelength value. The stored matrix elements are  $F_{11}$ ,  $F_{12}$ ,  $F_{22}$ ,  $F_{33}$ ,  $F_{34}$ , and  $F_{44}$ .

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<sup>2</sup>This includes a change of the angular grid and a change in the normalization of the scattering matrix.

## 7. Python interface

`optool` comes with a python module `optool.py` that runs `optool` in the background<sup>3</sup> and puts all computed quantities as `numpy` arrays into a python object. This makes it straight forward to inspect and further process the output, for example to produce custom opacity files for use in a radiative transfer tool. Here is how to use the module:

```
import optool
p = optool.particle('~bin/optool pyr 0.8 -m ice 0.2 -na 24 -d')
```

The argument to `optool.particle()` must be a valid shell command<sup>4</sup> to run `optool`, if necessary with the full path to the `optool` binary. Depending on the presence of the `optool`'s `-d` switch, the command will produce opacities either for  $n_p = 1$  particle, or for  $n_p = n_a$  particles. Most of the attributes (with the exception of the global wavelength and angular grids) will therefore be arrays with the first dimension equal to  $n_p$ , even if  $n_p = 1$ . The resulting object will have the following attributes:

Attribute	Type/Shape	Quantity
<code>cmd</code>	string	The full command given in the <code>particle()</code> call
<code>radmc</code>	boolean	Output follows RADMC conventions
<code>scat</code>	boolean	Scattering matrix is available
<code>nlam</code>	int	Number of wavelength points
<code>lam</code>	float[nlam]	The wavelength grid
<code>nang</code>	int	Number of scattering angles
<code>scatang</code>	float[nang]	The angular grid
<code>materials</code>	[[[...]]... ]	Lists with [location, $m_{\text{frac}}$ , $\rho$ , material]
<code>np</code>	int	Number of particles, either 1 or (with -d) $n_a$
<code>fmax</code>	float[np]	Maximum volume fraction of vacuum for DHS
<code>pcore, pmantle</code>	float[np]	Porosity of the core/mantle material
<code>amin, amax</code>	float[np]	min/max grain size used for each particle
<code>nsub</code>	int[np]	Number of sizes averaged for each particle.
<code>apow</code>	float[np]	Negative size distribution power law (e.g. 3.5)
<code>a1, a2, a3</code>	float[np]	Mean $\langle a \rangle$ , $\langle a^2 \rangle$ , and $\langle a^3 \rangle$ of the particle
<code>rho</code>	float[np]	Specific density of grains
<code>kabs, ksca, kext</code>	float[np, nlam]	Absorption, scattering, extinction cross section
<code>gsca</code>	float[np, nlam]	Asymmetry parameter
<code>f11, ..., f44</code>	float[np, nlam, nang]	Scattering matrix element $F_{11}, \dots, F_{44}$
<code>chop</code>	float[np]	Degrees chopped off forward scattering
<code>plot()</code>	method	Plot the cross sections and matrix elements
<code>computemean()</code>	method	Compute Planck/Rosseland mean opacities
<code>tmin, tmax, ntemp</code>	float, float, int	Temperature grid for mean opacities
<code>temp</code>	float[ntemp]	Temperatures used for mean opacities
<code>kplanck, kross</code>	float[np, ntemp]	Mean opacities, after calling <code>computemean()</code>
<code>norm</code>	string	Current scattering matrix normalization
<code>scatnorm()</code>	method	Check/change scat. matrix normalization

<sup>3</sup>The module runs the command as a subprocess, with output to a temporary subdirectory.

<sup>4</sup>As a string, or as a list like `['path/to my/command', 'arg1', 'arg2', ...]`.





Figure 1: Screenshot of plots created by running `p.plot()` on an optool particle.

The `plot()` method is used like this:

`p.plot()`

It will produce the following plots:

- a plot showing the opacities  $\kappa_{\text{abs}}$ ,  $\kappa_{\text{sca}}$ , and  $\kappa_{\text{ext}}$  as a function of wavelength, along with the asymmetry parameter  $g$  (on a linear y-scale). Note that the blue  $g$  curve does not have its own axis, imagine the full  $y$  axis going from 0 to 1 for  $g$ .
- a plot showing the scattering matrix elements as a function of scattering angle, with sliders to go through grain sizes and wavelengths. When interpreting the  $y$  axis, note that we plot the positive/negative  $\log_{10}$  of positive/negative matrix elements, compressing the range from  $10^{-2}$  to  $10^2$  into a line (use the grey lines as a guide, ignore the  $y$ -axis labels).
- If the `computemean` method has been called first, the mean opacities  $\kappa_{\text{Planck}}$  and  $\kappa_{\text{Ross}}$  are shown in a separate plot. The mean opacities are per unit of grain mass, so please apply a dust-to-gas mass ratio to obtain opacities for a gas-dust mixture.

You can also use *particle arithmetic* (multiplying `particle` objects with factors and adding them - this is implemented in a way that it works correctly also for the scattering matrix), for example to produce opacities for a mixture of different grains or scale opacities using a dust-to-gas ratio:

```
p1 = optool.particle('optool -a 0.01 0.3 pyr-mg70')      # silicate grains
p2 = optool.particle('optool -a 0.03 0.1 c-z')           # carbon grains
p  = 0.75*p1 + 0.25*p2    # add with mass fractions
p  = p * 0.01             # apply dust-to-gas ratio -> opacity per gas mass
```

## A. Units

Due to conventions in our field, the input and output of `optool` uses the following units

- **microns** for grain sizes and wavelengths
- **g/cm<sup>3</sup>** for mass densities of materials
- **cm<sup>2</sup> g<sup>-1</sup>** for opacities  $\kappa_{\text{abs}}$ ,  $\kappa_{\text{sca}}$ , and  $\kappa_{\text{ext}}$
- **sr<sup>-1</sup>** or **cm<sup>2</sup> g<sup>-1</sup> sr<sup>-1</sup>** for the scattering matrix elements, see below.

## B. Scattering Matrix: The fine print

### B.1. Phase function normalization

A number of different normalizations for the scattering matrix are being used in the literature and in computational tools. The differences are significant, and it is important to be aware of the choice. For `optool` we are using a convention (Hovenier (2004)) in which the average over all directions of the 1-1 element of the scattering matrix equals unity, i.e.

$$\oint_{(4\pi)} F_{11}(\lambda, \Theta) d\Omega = 2\pi \int_{-1}^1 F_{11}(\lambda, \mu) d\mu = 4\pi \quad , \quad (1)$$

with  $\mu = \cos \Theta$ . `optool` can also produce output for RADMC-3D which uses instead

$$\oint_{(4\pi)} Z_{11}(\lambda, \Theta) d\Omega = 2\pi \int_{-1}^1 Z_{11}(\lambda, \mu) d\mu = \kappa_{\text{sca}}(\lambda) \quad . \quad (2)$$

The books by Bohren & Huffman and by Mishchenko use different normalizations again. You can change the normalization of the scattering matrix in the python interface with the `scatnorm()` method. By default, it checks the current normalization. Using an argument `'r'`, `'b'`, `'m'`, or `'h'` will modify the normalization.

### B.2. Forward-scattering peak

Particles that are much larger than the wavelength of the considered radiation can show extreme forward scattering, where much of the *scattered* radiation is sent into just a few degrees around the forward direction. This can be difficult to handle for radiative transfer codes which have limited angular resolution or limited sampling. MCMMax3D has the `nspike` keyword to deal with this issue. Other tools (e.g. RADMC-3D) require this to be taken care of by the process that creates the opacity files. The `-chop` switch specifies a number of degrees around the forward scattering direction. Inside that cone, the scattering matrix gets limited to the value at the edge of the cone. To compensate and ensure energy conservation, the scattering cross section will be reduced accordingly. As a result, the radiation that would be *scattered* into this narrow range of angles will be treated as if it did have *no interaction at all* with the grain.

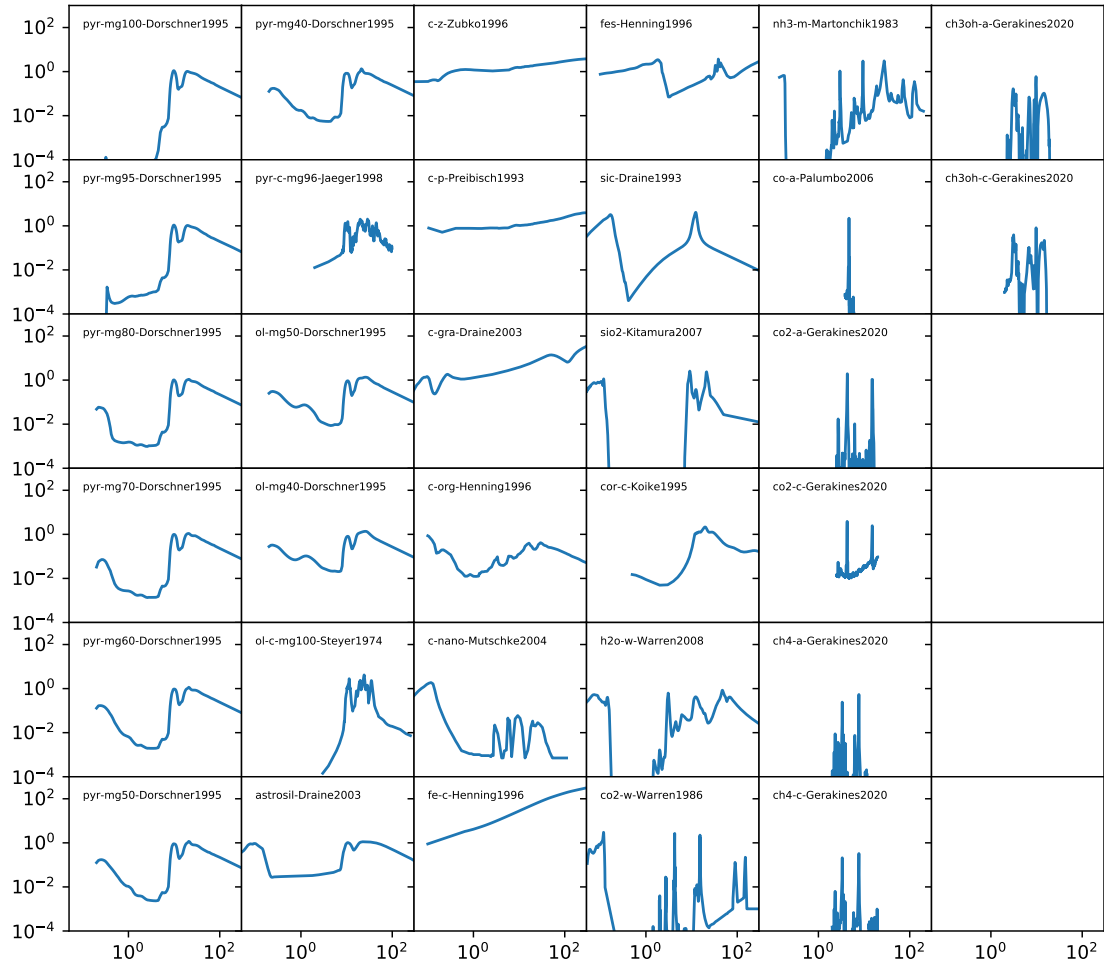
### B.3. Angular grid

`optool` uses an angular grid in one degree steps from 0 to 180 degrees. The full degrees are the cell *interfaces* of that grid. `optool` computes the scattering matrix at the cell *midpoints*, i.e. at  $0.5^\circ$ ,  $1.5^\circ$  etc to  $179.5^\circ$ , for a total of 180 values. The scattering matrix is normalized in this way, so that a numerical integral gives the correct result.

RADMC-3D requires the values of the scattering matrix on the cell *boundaries*, so at  $0^\circ$ ,  $1^\circ$  etc to  $180^\circ$ , for a total of 181 values. For the input files for RADMC-3D, we interpolate and extend the computed values to the cell boundaries.

## C. Overview of optical properties

This grid plot shows the imaginary parts of all built-in materials, in the wavelength range from 0.05 to  $300\ \mu\text{m}$ .



## D. How to ingest refractive index data for another material

Using external refractive index data means that you have to keep track of where those files are. It can be convenient to compile your favorite materials into `optool`, so that accessing them will be as simple as using the built-in materials. Here is how to do that:

1. Give your `lnk` file a name exactly like `pyr-mg70-Dorschner1995.lnk`, where the start of the name (`pyr-mg70`) is the key to access the material and `Dorschner1995` (the text after the final `-`) is the reference.
2. Put this file into the `lnk_data` directory.
3. Optionally edit `lnk_data/lnk-help.txt`, so that `optool -c` will list the new material. Note that, in order to define *generic keys*, `optool` looks for pairs that look like `genkey -> fullkey` in this file.
4. Run `make ingest` to update `optool_refind.f90`, now with your new material.
5. Recompile and install the code.

## E. Internals

This appendix describes some key aspects of the internal workings of the code.

### Refractive Index Data

Measured refractive index data is obtained from data compiled into the code, or read-in from a file. That data is then interpolated and extrapolated onto the wavelength grid requested for the computation. Extrapolation toward short wavelengths is done keeping the refractive indices constant. Extrapolation toward long wavelengths assumes that the last two measured data points define a powerlaw. Interpolation in the measured grid is done using double-logarithmic interpolation.

### Mixing

Once the refractive index for all involved materials is available, the core and the mantle mixtures are created independently, using the Bruggeman rule. Mass fractions are converted into volume fractions, and porosity is implemented using vacuum as an additional material. The subroutine doing the mixing uses an iterative procedure that is very stable, also for a large number of components.

If there is a mantle, the Maxwell Garnett rule is applied with the core being treated as an inclusion inside a mantle matrix.

### DHS

In order to simulate irregularities in grains (irregular shapes, or the properties of low-porosity aggregates), `optool` averages the opacities of grains with an inner empty region, over a range of volume fractions of this inner region between 0 and  $f_{\max}$ . The subroutine used to compute the opacities and scattering matrix elements for these structures is `DMiLay` (Toon & Ackerman 1981). When the size parameter  $x = 2\pi a/\lambda$  exceeds a value of  $10^4$ , no DHS averaging is used. A standard Mie calculation is performed, using the routine `MeerhoffMie` (reference missing), for a fixed size parameter of 5000, with proper scaling to the actual size of the particle.

## MMF

To construct fluffy/fractal aggregates, `optool` needs the number of monomers  $N$ , the fractal dimension  $D_f$ , and a scaling factor  $k_f$  which are related to the radius of gyration  $R_g$  of the aggregate by

$$N = k_f \left( \frac{R_g}{a_0} \right)^{D_f} \quad (3)$$

The size  $a$  of the particles as specified by the `-a` switch is interpreted as the *compact* size of all material in the aggregate, so that  $N = a^3/a_0^3$ , where  $a_0$  is the monomer radius. The average volume filling factor  $f$  can be expressed by  $f = N \cdot \left( \sqrt{3/5} a_0 / R_g \right)^3$ . To determine the structure of the aggregates, the user can specify a structure parameter. If that parameter is larger than 1, it is interpreted as the *fractal dimension*  $D_f$ . Using a fixed fractal dimension means that the volume filling factor will decrease with aggregate size. As an alternative, the structure parameter can be less than 1. In that case, it is interpreted as a fixed *volume filling factor*  $f$  that applies to all aggregate sizes - with the implication that then the fractal dimension increases as a function of size. The fractal prefactor  $k_f$  is chosen automatically so that the asymptotic density of small aggregates is the monomer material density. To force another value for the prefactor, it can be given explicitly as the third value of the `-mmf` option. The following table summarizes the relevant equations.

	<code>-mmf AO DF</code>	<code>-mmf AO FILL</code>	<code>-mmf AO DF KF</code>
$f$	$N^{(D_f-3)/3}$	<b>given by user</b>	$\sqrt{27/125} k_f^{3/D_f} N^{3-1/D_f}$
$D_f$	<b>given by user</b>	$3 \ln N / \ln(N/f)$	<b>given by user</b>
$k_f$	$(5/3)^{D_f/2}$	$(5/3)^{D_f/2}$	<b>given by user</b>

With the structure defined, `optool` then applies the formalism from Tazaki & Tanaka (2018) to compute cross sections and the scattering matrix. For the determination of the geometrical cross section needed in the theory, we use the general expressions from Tazaki (2021). `optool` also computes the phase shift  $\Delta\phi$  caused by the aggregate to check the validity of the scattering matrix and the asymmetry parameter. If the condition  $\Delta\phi < 1$  for accurate scattering matrix results is violated, a warning will be issued. However, the opacities will remain applicable.

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