

The Radiative Transfer Code *STOKES*  
Version 1.0

User's manual

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# Contents

<b>Preface</b>	<b>5</b>
<b>1 A brief introduction to <i>STOKES</i></b>	<b>7</b>
1.1 Overview	7
1.2 Structure of the program	9
1.3 A photon's life	10
1.3.1 The source routine	10
1.3.2 The proceed routine	12
1.3.3 The inside-cloud routine	13
1.3.4 The scattering routines	13
1.3.5 The shift routine	16
1.3.6 The register routine	16
1.4 Computation of dust properties	16
<b>2 How to run <i>STOKES</i></b>	<b>19</b>
2.1 The input file <i>input.par</i>	19
2.1.1 Setting general parameters	20
2.1.2 Defining emission regions	21
2.1.3 Defining scattering regions	22
2.1.4 Defining a dust model	23
2.2 Evaluating a simulation with <i>ANALYZE</i>	24
2.3 Running <i>STOKES</i> on multiple CPUs	25
<b>3 Exemplary input files and dust models</b>	<b>29</b>
3.1 Example 1: electron disk and dusty torus	29
3.2 Example 2: electron disk and polar cones	30
3.3 Example 3: electron shell and dust clouds	31
<b>Bibliography</b>	<b>33</b>



# Preface

The computer program *STOKES* was designed to perform three-dimensional radiative transfer simulations for astronomical applications. A crucial requirement was that the code should also consider the polarization properties of the radiation. The program is based on the Monte-Carlo method and treats optical and ultraviolet polarization induced by scattering off free electrons or dust grains. Emission and scattering regions can be arranged in various geometries within the model space, the computed continuum and line spectra can be evaluated at different inclinations and azimuthal viewing angles.

The idea of *STOKES* was given by the observed polarization of Active Galactic Nuclei. Martin Gaskell at the University of Nebraska in Lincoln (USA) suggested to me the project to write a Monte-Carlo radiative transfer code in order to model quasar polarization in the optical and ultraviolet range. Developing the program, we considered existing radiative transfer codes described in the literature. The Monte-Carlo code written by Kartje (1995), the *DIRTY* code (Gordon et al., 2001; Misselt et al., 2001), and the work of Fischer et al. (1994) and Wolf & Henning (1999) were very inspiring. We also would like to mention that Watanabe et al. (2003) present a radiative transfer code being of a similar design as *STOKES*.

We want to make *STOKES* publicly available and therefore publish the first release, e.g. the version 1.0, on the web page

`www.stokes-program.info`

On this website you can also find further support for the program including examples for the input file, precomputed dust models, and the *C++* source files. The program is available pre-compiled for Linux and Windows systems. We intend to further develop the code and to release follow-up versions.

If you are an astronomer or a physicist doing research on polarization and radiative transfer you might have use for *STOKES*. The program is 100% share ware, so you are invited to use it for your modeling purposes, adjust the source code to your personal needs, and forward the program to interested colleagues.

This manual gives a brief introduction to the concept of *STOKES* and the methods included (chapter 1). We explain the application of the code and the processing of its results (chapter 2) and provide some examples for illustration (chapter 3). As for any computer program, the flexibility and reliability of *STOKES* will rise with the feedback of its users. If you make use of the code and you would like to send feedback, suggestions for improvements, or point out bugs you may send email to:

`admin@stokes-program.info`

If *STOKES* is helpful for your research we kindly ask you to give reference to the article Goosmann & Gaskell (2007) in which we present the program.

*Meudon (France) in November 2004,  
René Goosmann*

# Chapter 1

## A brief introduction to *STOKES*

In this chapter we introduce the basic methods of the code (section 1.1) and present its main routines (section 1.2). These are then explained in more detail (section 1.3) by following the “life” of a model photon. The theoretical foundation of the dust scattering routines is given by Mie theory (section 1.4) from which cross-sections and matrix elements can be computed.

### 1.1 Overview

The *STOKES* program is based on the Monte-Carlo method (see e.g. Cashwell & Everett, 1959) and follows single photons from their generation inside the emission regions through various scattering processes until they become absorbed or manage to escape from the model region (see Fig. 1.1). The emission regions can be realized in cylindrical or double-conical geometries. The flux spectrum of the continuum radiation is defined by a power law  $F(\nu) \propto \nu^{-\alpha}$  with spectral index  $\alpha$ . For the line photons Lorentzian flux spectra are assumed. The relative line intensity with respect to the continuum flux can be defined by the user. Intrinsically, line and continuum photons are assumed to be unpolarized.

Around the source regions various geometries of scattering mirrors can be arranged. At its current state, the program offers toroidal, cylindrical, spherical, or conical shapes. These regions can be filled with free electrons or with dust consisting of silicate and graphite. Radial bulk motions of the scattering regions can be included, they result in a wavelength shift of the scattered photons. A photon works its way through the model region and generally undergoes several scattering processes. The path length between two scattering events is sampled by the Monte-Carlo method. We use accurate algorithms for Thomson and dust scattering (see section 1.3.4) in which the scattering angle is sampled depending on the polarization state of the incident photon.

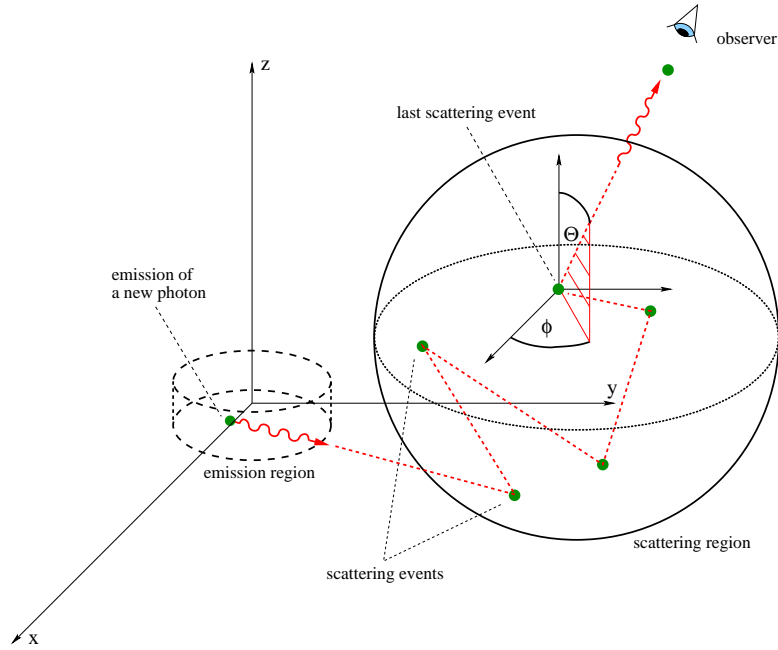


Figure 1.1: A photon working its way through the model space

In case of dust extinction, a large fraction of the photons will be absorbed and never reaches the virtual observer. If a photon escapes from the model region it is registered by a web of virtual detectors arranged in a spherical geometry. The flux and polarization information for each detector is obtained by adding up the Stokes parameters of all detected photons. The object can be evaluated for total and polarized flux, percentage of polarization, and for the polarization position angle at each viewing direction.

The seed for the random number generator is taken from the computers internal clock, hence two runs of the same model setup but started at different points in time do not give exactly the same results. They differ within the Poisson statistics of Monte-Carlo results. Considering the fact that the Stokes parameters are additive allows to conduct simulations with very large photon numbers by running the program on different computers simultaneously and with different seeds for the random number generator. The results can later be combined to one set using the auxiliary program *ANALYZE* (see chapter 2).

## 1.2 Structure of the program

The *STOKES* program is written in the computer language  $C^{++}$ . The object-oriented capabilities of  $C^{++}$  allow to divide a complex program into organic parts containing all their properties (declarations) and capabilities (routines) by themselves. For the *STOKES* program these organic parts were designed according to the physical aspects of the model space, of the radiative transfer, and of the virtual detectors.

We use a Cartesian coordinate system to define the geometrical features of the model region: source areas and scattering regions. The geometry of these elements is described by mathematical equations and stored by the object *model*. This object initializes all relevant model parameters and then works as a database for the other objects.

In order to handle dust scattering, an additional object called *mie* supports *model*. This object contains routines to calculate Mie parameters consisting of cross-sections and scattering matrix elements. Their calculation is time consuming and it would slow down the program significantly if the Mie data were calculated during the actual simulation. Instead, if dust scattering is part of the run, *mie* does all the necessary calculations at the beginning of the program or simply reads in precomputed Mie data from a file. It stores all the relevant parameters in a look-up table.

The radiative transfer is realized by the object *photon*. This object defines all properties and capabilities of a photon being relevant for the modeling. It stores the photon's wavelength, Stokes vector, position inside the model region, and direction of flight. Routines to move a photon inside the model region and to make it interact with matter are also defined in *photon*. The routines of *photon* will be described in more detail in the next section 1.3.

The object *monitor* rules the observational part of the system. It manages a web of detectors summing up and storing the Stokes parameters of all detected photons. Viewing directions are given by the two angles  $\theta$  and  $\phi$  defined with respect to the coordinate system of the model space. We measure  $\theta$  between the line of sight and the  $z$ -axis and  $\phi$  between the projected line of sight onto the  $xy$ -plane and the  $x$ -axis. Each detector is defined as a (sub-)object at a given viewing angle and stores spectra of Stokes parameters. During execution *monitor* regularly saves the data on a disk. It creates four files containing information about the four Stokes parameters  $I$ ,  $Q$ -,  $U$ - and  $V$ .

### 1.3 A photon's life

We describe the major routines of the *STOKES* program and how they work together by following a model photon's life from its generation to its absorption or detection.

The photon is generated by the *source-routine*. If it is generated inside a scattering region, the *proceed-routine* shifts the photon by a path-length that is sampled using the Monte-Carlo method. If the photon does not leave the cloud, which is checked by the *inside-cloud-routine*, a scattering event is simulated by the *dust-scattering-routine* or by the *electron-scattering-routine*. In case of dust scattering the routine might set up the absorption flag, hence destroy it, and make the cycle start over by creating a new photon inside the source region.

If the photon leaves the scattering cloud or if it was not generated within one, the *shift-routine* detects any other scattering region along its flight direction. If there is another scattering cloud, the photon moves to the cloud's border, and the *proceed-routine* takes over again. If there is no further scattering cloud on the way, the photon escapes from the model region and is detected by the *register-routine*. Its Stokes parameters are saved according to its wavelength and flight direction.

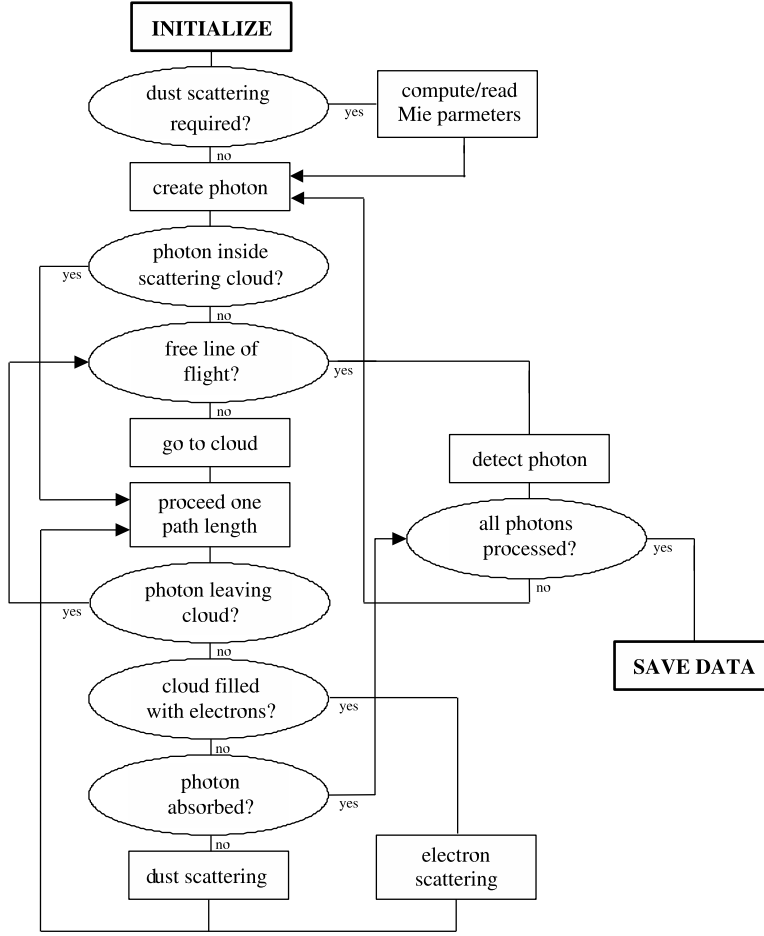
The execution of the program is visualized in the flowchart in Fig. 1.2. The routines ruling a photon's life are described in more detail in the following sections.

#### 1.3.1 The source routine

To generate a model photon its initial parameters position, flight direction, wavelength, and polarization have to be set. Some of these values are sampled using the Monte-Carlo method and hence involve random numbers. In the following we denote such random numbers in the range between 0 and 1 by  $r_i$ .

The sampling of the initial position depends on the nature of the photon. If it is a continuum or a broad line photon it is emitted in a cylindrical region while a narrow line photon originates in a double-conical region. Assuming a constant density of the emitting material a random starting position for the photon is sampled inside the source region declared.

At each position of the source elements we assume isotropic emission. The initial flight direction of the photon is determined by two angles, a polar angle  $\theta$  and an azimuthal angle  $\phi$ , which are defined with respect to a standard spherical coordinate system. From this, we obtain the following sampling equations for the angles:

Figure 1.2: Flowchart showing the execution of *STOKES*

$$\theta = \arccos(1 - 2r_1), \quad (1.1)$$

$$\phi = 2\pi r_2. \quad (1.2)$$

In order to determine the wavelength  $\lambda$  of a continuum photon we assume a power law  $F(\nu) \propto \nu^{-\alpha}$  for the intrinsic flux spectrum. Herein,  $\nu$  denotes the photon frequency and  $\alpha$  is the spectral index. The wavelength is sampled over a range  $[\lambda_{min}, \lambda_{max}]$ . This leads to the sampling equations:

$$\lambda = \begin{cases} [\lambda_{min}^\alpha + r_3 (\lambda_{max}^\alpha - \lambda_{min}^\alpha)]^{\frac{1}{\alpha}}, & \alpha \neq 1, \\ \lambda_{min}^\alpha \left( \frac{\lambda_{max}^\alpha}{\lambda_{min}^\alpha} \right)^{r_3}, & \alpha = 1. \end{cases} \quad (1.3)$$

For line photons we presume a Lorentzian profile with centroid  $\lambda_0$ , and line width  $\Gamma$ . The sampling equation is more complicated and can not be explicitly solved in analytical form. If we define the auxiliary function  $\bar{F}(\lambda')$  as

$$\bar{F}(\lambda') = \frac{1}{2} \log [(\lambda' - \lambda_0)^2 + \Gamma^2] + \frac{\lambda_0}{\Gamma} \arctan \frac{\lambda' - \lambda_0}{\Gamma}, \quad (1.4)$$

the wavelength  $\lambda$  of the photon is numerically computed from the equation

$$\bar{F}(\lambda) - (1 - r_3)\bar{F}(\lambda_{min}) - r_3\bar{F}(\lambda_{max}) = 0, \quad (1.5)$$

Note that the above sampling equations include the wavelength-dependence of the photon energy.

The polarization properties of a photon are stored in its Stokes vector consisting of the four Stokes parameters  $I$ ,  $Q$ ,  $U$ , and  $V$ . If we imagine an electromagnetic wave being associated to the photon, then the Stokes parameters can be derived from the position of the electric field vector  $\vec{E}$  inside the so-called polarization plane. The polarization plane is oriented perpendicularly to the flight direction of the photon. We assume that newly generated photons are unpolarized. In this case, the Stokes vector has the simple form:

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}. \quad (1.6)$$

### 1.3.2 The proceed routine

If we ignore scattering back into the beam, the intensity of a photon beam traversing a slab of scattering material with particle number density  $n$  and extinction cross-section  $\sigma$  will drop by a factor  $e^{-n\sigma l}$ , with  $l$  being the distance traveled inside the scattering region. The same factor therefore determines the probability density of a photon-particle interaction at the distance  $l$ . This leads to the sampling function:

$$l = \frac{1}{n\sigma} \ln(1 - r_4). \quad (1.7)$$

The factor  $\frac{1}{n\sigma}$  is the mean free path length. Depending on the scattering material, the program will use either a dust extinction cross-section  $\sigma_{ext}$  computed from Mie theory or, in case of electron scattering, the Thomson cross section  $\sigma_{Th}$ .

### 1.3.3 The inside-cloud routine

After the photon was shifted by a path length and before conducting the next scattering event, it is necessary to check if the photon is still inside the scattering cloud. Each scattering region is mathematically described by a polynomial in-equation, or by a set of coupled polynomial in-equations. For instants, in the case of a spherical cloud with central position  $\vec{p}_0 = (x_0, y_0, z_0)^T$  and radius  $r$  such an in-equation is given by:

$$(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 < r^2, \quad (1.8)$$

with  $x$ ,  $y$ , and  $z$  being the photon coordinates. In order to decide if the photon is inside or outside the region, the program evaluates the associated in-equation(s) for the current photon position.

### 1.3.4 The scattering routines

Consider a photon being scattered off a spherical particle (see Fig. 1.3). The outgoing electromagnetic wave associated with the photon can be resolved into two components (see e.g. Bohren & Huffman, 1983). These components refer to directions of the electric field vector parallel and perpendicular to the scattering plane. We name the two components  $E_{\parallel}$  and  $E_{\perp}$ . For scattering off a spherical particle the following relation between the incoming and scattered electric fields holds:

$$\begin{pmatrix} E_{\parallel,s} \\ E_{\perp,s} \end{pmatrix} = \begin{pmatrix} S_2(\theta) & 0 \\ 0 & S_1(\theta) \end{pmatrix} \begin{pmatrix} E_{\parallel,i} \\ E_{\perp,i} \end{pmatrix}. \quad (1.9)$$

The values  $S_1(\theta)$  and  $S_2(\theta)$  are the so-called scattering matrix elements. They are independent of the azimuthal angle  $\phi$ . In case of Thomson scattering they are given by simple analytic expressions:

$$S_1(\theta) = \cos^2 \theta, \quad (1.10)$$

$$S_2(\theta) = 1. \quad (1.11)$$

For dust scattering the albedo and the matrix elements of a standard dust grain are calculated from Mie theory (see section 1.4). The albedo at the photon wavelength is compared to a random number  $r_5$  in order to decide whether the photon is absorbed or scattered. In case of absorption, the photon is lost, and the cycle starts over with the generation of a new photon by the *source routine*.

If the photon is scattered the angle-dependent classical intensity distribution of a scattered electromagnetic wave measures the probability of finding it at a certain direction. Such probability density distributions are derived from equation (1.9).

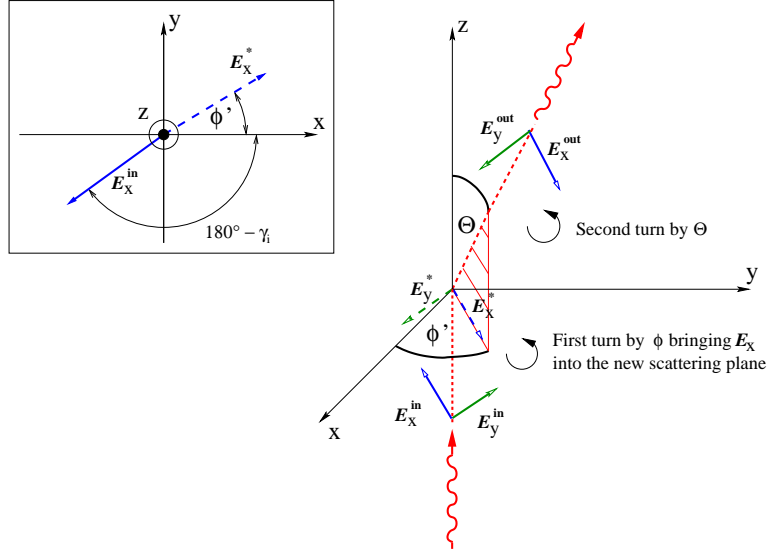


Figure 1.3: Geometry and denotations for a single scattering event. The inset shows the first rotation of the  $\vec{E}$ -vector by the angle  $\phi$ , the view on the polarization plane is along the negative  $z$ -axis.

In order to also consider the impact of the incident polarization on the scattering angle, we split up the incident intensity  $I_i$  into a completely polarized and a completely unpolarized part:

$$I_i = I_{i,\text{pol}} + I_{i,\text{unpol}} = P_i I_i + (1 - P_i) I_i. \quad (1.12)$$

The incident polarization is denoted by  $P_i$ , its position angle by  $\gamma_i$ . Both are calculated from the incident Stokes parameters of the photon. We now rotate the polarization plane around the incident flight direction by the angle  $180^\circ - \gamma_i$  in order to reach a position where the incident electric field vector of the completely polarized component is aligned with the reference axis (position angle =  $0^\circ$  from the  $x$ -axis, see the inset of Fig. 1.3). We then compute the angle-dependent intensity  $I_s$  behind the scattering center from equation 1.9 together with equation 1.12:

$$I_s(\theta, \phi') = \frac{I_i}{k^2 d^2} \left[ \frac{1}{2} (|S_1(\theta)|^2 + |S_2(\theta)|^2) (1 - P_i) + (|S_1(\theta)|^2 \sin^2 \phi' + |S_2(\theta)|^2 \cos^2 \phi') P_i \right], \quad (1.13)$$

with  $d$  being the distance between the scattered photon and the scattering center, and  $k$  denoting the wave-number. Considering this intensity as a probability density  $p$ , we obtain the probability distribution for the scattering angles  $\theta$  and  $\phi'$ :

$$P(\theta) = C \int_0^\pi (|S_1(\theta)|^2 + |S_2(\theta)|^2) \sin(\theta') d\theta', \quad (1.14)$$

$$P_\theta(\phi') = \frac{1}{2\pi} \left( \phi' - \frac{|S_1(\theta)|^2 - |S_2(\theta)|^2}{|S_1(\theta)|^2 + |S_2(\theta)|^2} P \frac{\sin 2\phi'}{2} \right). \quad (1.15)$$

The number  $C$  is a normalization constant in order to make (1.14) range from 0 to 1 for scattering angles between  $0^\circ$  and  $180^\circ$ . To sample  $\phi'$  and  $\theta$ , the right hand-sides of these equations have to be set equal to random numbers  $r_6, r_7$ . Then, they are solved for the angles. Note that the sampling of the scattering angle  $\theta$  is independent of the incident polarization. Since at the beginning we performed a coordinate transformation to make the electric field vector oscillate along the reference axis, the sampling of  $\phi'$  has to be followed by the back-transformation

$$\phi = 180^\circ - \gamma_i + \phi'. \quad (1.16)$$

This procedure of finding the sampling equations for the scattering angles is analogous to the one followed by Fischer et al. (1994).

With each scattering event, the co-moving coordinate system undergoes a double rotation: the first rotation, by the azimuthal angle  $\phi$ , happens around the current flight direction of the photon. It rotates the  $\mathbf{E}$ -vector inside the polarization plane to the position of the new scattering plane (see Fig. 1.3). Physically, it does not affect the polarization state, but the Stokes vector undergoes the following coordinate transformation (see Bohren & Huffman, 1983):

$$\begin{pmatrix} I^* \\ Q^* \\ U^* \\ V^* \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ & \cos 2\phi & \sin 2\phi & 0 \\ 0 & -\sin 2\phi & \cos 2\phi & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} I^{in} \\ Q^{in} \\ U^{in} \\ V^{in} \end{pmatrix}. \quad (1.17)$$

The second rotation happens inside the scattering plane and by the scattering angle  $\theta$ . The change of the Stokes vector is determined by the so-called Mueller matrix. For scattering off a spherical particle, the matrix is of the following form:

$$\begin{pmatrix} I^{out} \\ Q^{out} \\ U^{out} \\ V^{out} \end{pmatrix} = \frac{1}{k^2 d^2} \begin{pmatrix} S_{11} & S_{12} & 0 & 0 \\ S_{12} & S_{22} & 0 & 0 \\ 0 & 0 & S_{33} & S_{34} \\ 0 & 0 & -S_{34} & S_{44} \end{pmatrix} \begin{pmatrix} I^* \\ Q^* \\ U^* \\ V^* \end{pmatrix}. \quad (1.18)$$

The entries of the Mueller matrix are closely related to the elements of the scattering matrix  $S_1(\theta)$  and  $S_2(\theta)$  as is explained in section 1.4

### 1.3.5 The shift routine

When a photon escapes from a scattering cloud, the code will check if there is any other scattering region along its flight direction. The photon trajectory is defined by the current photon position  $\vec{x}_p$  and by the velocity vector  $\vec{v}_p$ :

$$\vec{x} = \vec{x}_p + t\vec{v}_p, \quad (1.19)$$

with  $t$  denoting the time. The borders of the scattering clouds are described by polynomial equations. In order to find possible clouds along the photon's flight direction, it is hence necessary to combine these polynomial equations with equation 1.19 and to solve for  $t$ . For instants, in the case of a spherical scattering cloud with central position  $\vec{p}_0 = (x_0, y_0, z_0)^T$  and radius  $r$  the border is described by the equation:

$$(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 = r^2, \quad (1.20)$$

which leads to the following equation for the time parameter  $t$ :

$$t^2 - 2t(\vec{x}_p - \vec{p}_0)\vec{v}_p + (\vec{x}_p - \vec{p}_0)^2 - r^2 = 0. \quad (1.21)$$

If a real, non-negative solution  $t_s$  for  $t$  exists, the photon will be set to the border of the new scattering cloud by the transformation  $\vec{x} \rightarrow \vec{x} + t_s\vec{v}_p$ . Otherwise the photon is considered to escape from the model space.

### 1.3.6 The register routine

When a photon is recorded by one of the virtual detectors, it is necessary to rotate the polarization plane around the flight direction until it matches with the reference axis of the detector. Then, the Stokes vectors of all incoming photons can be added up to the values  $\hat{I}$ ,  $\hat{Q}$ ,  $\hat{U}$  and  $\hat{V}$ . Finally, the net polarization properties are derived from:

$$P = \frac{\sqrt{\hat{Q}^2 + \hat{U}^2 + \hat{V}^2}}{\hat{I}}, \quad (1.22)$$

$$\gamma = \frac{1}{2} \arctan \frac{\hat{U}}{\hat{Q}}. \quad (1.23)$$

## 1.4 Computation of dust properties

Mathis, Rumpl, & Nordsiek (1977) suggested dust compositions to reproduce extinction curves observed in our Galaxy. They assumed spherical dust grains having a size distribution proportional to  $a^s$ , with  $a$  being the grain radius and  $s$  a given index. Weingartner & Draine (2001) further developed the model by

using carbonaceous and siliceous dust compositions to verify interstellar extinction in the Milky Way and in the Magellanic clouds. The dust compositions that can be modeled with *STOKES* are based on this work. The user can choose the minimum and maximum radii of the grain size distribution, its index  $s$ , and the abundances of graphite and silicate.

The Mie data, i.e. scattering and extinction cross sections, albedo, and entries of the scattering matrix, are computed using the code given by Bohren & Huffman (1983). We imported complex dielectric functions for graphite and silicate measured by Draine & Lee (1984). For graphite, two dielectric functions have to be considered since the optical properties for light polarized parallel and perpendicular to the crystals axis differ from each other. The program therefore works with two different kinds of graphite having abundances in a ratio of 1:2.

The code computes a weighted average of the dust composition and grain size distribution defined. The properties of the resulting “standard dust grain” are used by the *proceed* and the *scattering* routines of *STOKES*. In the following, we briefly summarize the specific equations and describe the routines used to compute the Mie data for user-defined dust compositions and grain size distributions.

Mie theory is based on the solution of the Maxwell equations for electromagnetic scattering off spheres having a homogeneous refractive index and dimensions in the range of the incoming wavelength. A fairly good description of the mathematical procedure was given by Bohren & Huffman (1983).

We show the results connected to the computation of the extinction cross section  $\sigma_{ext}$ , the scattering cross section  $\sigma_{sca}$ , and the scattering matrix elements  $S_1(\theta)$  and  $S_2(\theta)$  for a given substance, photon wavelength, and grain size radius.

$$\sigma_{sca} = \frac{2\pi}{k^2} \sum_{n=1}^{\infty} (2n+1) [|a_n(m, x)|^2 + |b_n(m, x)|^2], \quad (1.24)$$

$$\sigma_{ext} = \frac{2\pi}{k^2} \sum_{n=1}^{\infty} (2n+1) \Re[a_n(m, x) + b_n(m, x)], \quad (1.25)$$

$$S_1(\cos \Theta) = \frac{2\pi}{k^2} \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} [a_n(m, x)\pi_n + b_n(m, x)\tau_n], \quad (1.26)$$

$$S_2(\cos \Theta) = \frac{2\pi}{k^2} \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} [a_n(m, x)\tau_n + b_n(m, x)\pi_n]. \quad (1.27)$$

The complex functions  $\pi_n$  and  $\tau_n$  are defined by a recursion that is based on the Legendre polynomials. The functions  $a_n$ ,  $b_n$  take two arguments. The first argument is the relative refractive index  $m$  as defined by  $m = \frac{N_1}{N}$ , where  $N_1$  and  $N$  are the complex refractive indexes inside and outside the particle respectively.

The value  $N_1$  contains the dielectric function of the grain substance considered. The second argument is the size parameter  $x = \frac{2\pi Na}{\lambda}$  with the grain radius  $a$  and the wavelength  $\lambda$ . The functions are computed iteratively according to the method described in Wiscombe (1979, 1980).

The set of constants needed for *STOKES* contains the albedo and the entries of the Mueller matrix at each  $\lambda$  and  $a$ . They are derived from the data given above:

$$albedo = \frac{\sigma_{sca}}{\sigma_{ext}}, \quad (1.28)$$

$$S_{11} = S_{22} = \frac{1}{2} [ |S_2(\theta)|^2 + |S_1(\theta)|^2 ], \quad (1.29)$$

$$S_{12} = \frac{1}{2} [ |S_2(\theta)|^2 - |S_1(\theta)|^2 ], \quad (1.30)$$

$$S_{33} = S_{44} = \frac{1}{2} [ S_2^*(\theta)S_1(\theta) + S_2(\theta)S_1^*(\theta) ], \quad (1.31)$$

$$S_{34} = \frac{1}{2} [ S_2^*(\theta)S_1(\theta) - S_2(\theta)S_1^*(\theta) ]. \quad (1.32)$$

We denote the abundances of the various dust components by a row of constants  $g_l$ , with  $l = 1, 2, 3, \dots$  and  $\sum g_l = 1$ . Knowing the extinction cross-section, albedo, and Mueller matrix elements for all components and grain radii, the integrated absorption and scattering properties of the “standard dust grain” are obtained:

$$\overline{\sigma_{ext}} = \frac{1}{K} \sum_l \int_{a_{min}}^{a_{max}} g_l \sigma_{ext} a^s da, \quad (1.33)$$

$$\overline{albedo} = \frac{1}{K} \sum_l \int_{a_{min}}^{a_{max}} g_l albedo a^s da, \quad (1.34)$$

$$\overline{S_{11}} = \overline{S_{22}} = \frac{1}{K} \sum_l \int_{a_{min}}^{a_{max}} g_l S_{11} a^s da, \quad (1.35)$$

$$\overline{S_{12}} = \frac{1}{K} \sum_l \int_{a_{min}}^{a_{max}} g_l S_{12} a^s da, \quad (1.36)$$

$$\overline{S_{33}} = \overline{S_{44}} = \frac{1}{K} \sum_l \int_{a_{min}}^{a_{max}} g_l S_{33} a^s da, \quad (1.37)$$

$$\overline{S_{34}} = \frac{1}{K} \sum_l \int_{a_{min}}^{a_{max}} g_l S_{34} a^s da, \quad (1.38)$$

with  $a_{min}$ ,  $a_{max}$  being the limits and  $s$  being the index of the grain size distribution. The normalization constant  $K$  is calculated from:

$$K = \int_{a_{min}}^{a_{max}} a^s da. \quad (1.39)$$

## Chapter 2

# How to run *STOKES*

The *STOKES* code requires a main input file called *input.par*. This file defines all parameters for a model run. If the model includes dust-filled scattering regions, *STOKES* either computes the dust properties or reads them from a file. Files containing dust models have the suffix *dst*, they must be stored in the same directory as the *STOKES* executable file, and the file *input.par*.

Having your directory prepared with all necessary files, you launch the program. On a Linux system this naturally happens in a command line environment, while for Windows users it is more common to launch programs by clicking on the icon in a window. However, we would like to encourage Windows users to also execute *STOKES* from the command line, as it may print important messages. You make sure that these messages are visible if you run the program from the command line.

When the execution is finished, the program produces four different files with the suffix *sto*. These files contain the “raw” Stokes data of all virtual detectors. To obtain more convenient results, such as the percentage  $P$  of polarization and the position angle  $\gamma$ , you should launch the program *ANALYZE* in the same directory (see section 2.2).

In the following section 2.1 we explain in more detail how to construct the input file *input.par*. Then, in section 2.2, we will discuss the output files of *STOKES* and their transformation by the auxiliary program *ANALYZE*. In the final section 2.3 we describe how to run *STOKES* simultaneously on several CPUs and how to collect and process the results.

### 2.1 The input file *input.par*

Construction of an input file for *STOKES* is rather simple. All entries in the file are based on keywords declared by the following pattern:

**keyword** *parameter1 parameter2 ...*

The keyword and the parameters are separated by blanks. Each keyword takes a well-defined number of parameters determining the specific model feature. All model parameters have a default setting that will be modified when the associated keyword appears in the input file. You can find a list of all keywords for *input.par* and their default settings in the tables 2.1 and 2.2 at the end of this chapter.

If you want to have comments in the input file you have to put a `#` at their beginning. The rest of the line will then be ignored. If you put the keyword `end` somewhere, *STOKES* finishes reading the input file at that position and all following entries are ignored. Note that the scanning of keywords in *input.par* is case-sensitive.

### 2.1.1 Setting general parameters

Before constructing the model space by defining emission and scattering regions, the general model parameters should be defined. It is recommended to change the default file name for the output files:

**OutputFile** *output-file-name CPU-number*

Setting *CPU number* different from 1 only makes sense if you want to perform calculations for the same model on several processors. Then, the input files on the various processors must have successive CPU numbers (see section 2.3). The numbers are later attached to the output file names.

It is further necessary to define how many viewing directions should be considered and which is the wavelength range and resolution of the virtual detectors. If we assume a rectangular coordinate system with *x*-, *y*-, and *z*-axis, a viewing direction is given by its angle  $\theta$  with the *z*-axis and by the azimuthal angle  $\phi$  with the *xz*-plane. The number of viewing directions considered by *STOKES* is declared by the two commands:

**ThetaViewAng** *number-theta*  
**PhiViewAng** *number-phi*

The viewing directions in  $\theta$  are spaced in equal steps of  $\cos\theta$ , which, for an isotropic source at the origin of the model space, corresponds to equal fluxes at all viewing angles. Having a higher parameter *number-phi* is useful when the model space is asymmetric with respect to the *z*-axis. If *number-phi* equals 1 the photon flux will be summed over all azimuthal directions.

By default, the model setup is assumed to be symmetric with respect to the *xy*-plane, and the results of the upper and lower half-space are summed up to enable better statistics. If the model arrangement does not show this

symmetry *STOKES* can take into account all viewing directions in  $\theta$  by setting the *symmetry-flag*, which is a character string, to “no” (meaning *false*):

PlaneSym *symmetry-flag*

At each viewing direction *STOKES* will produce spectra over a range of wavelengths and with a spectral resolution declared by:

LambdaMin *min-wavelength*  
 LambdaMax *max-wavelength*  
 SpectRes *number-channels*

The total number of photons to be sampled is determined by the parameter *photon-number* and declared by the command:

PhotonNum *photon-number*

### 2.1.2 Defining emission regions

At its current state, *STOKES* offers three types of emission regions: a cylindrically shaped continuum source, a cylindrical broad emission line source, and a double-conical narrow emission line source. The difference between broad and narrow line region is rather formal and due to the fact that *STOKES* first was designed for radiative transfer in the unified scheme of Active Galactic Nuclei. In fact, the line width for both emission line regions can be defined in the same way, the difference between them is given by the geometry.

The cylindrical emission region for the continuum source is assumed to be centered on the origin of the coordinate system. The syntax for defining a continuum region is as follows:

ContSource *R a b  $\alpha$   $v_r$*

For the geometrical denotations *R*, *a*, and *b* see Fig. 2.1a. The parameter  $\alpha$  determines the spectral index of the continuum radiation following a power law  $F(\nu) \propto \nu^{-\alpha}$ . The continuum will be sampled between the borders *min-wavelength* and *max-wavelength*. You can define a radial velocity  $v_r$  of the emitting material, which results in a wavelength shift of the photons sampled.

The cylindrical broad emission line region is declared by:

BLRSource *R a b  $\lambda_0$   $\Gamma$   $v_r$  strength*

The geometrical parameters *R*, *a*, and *b* are again explained in Fig. 2.1a. The line centroid is determined by  $\lambda_0$ , and  $\Gamma$  denotes the line width at the half-maximum. The parameter *strength* measures the percentage of all photons sampled (*=photon-number*) to be reserved for the line. This is a purely phenomenological definition of the line strength and does not involve any physics

of the production of the emission lines. With regard to the continuum, *strength* should be adjusted by the user until the required relation between line and continuum is achieved. If you define a radial velocity  $v_r$  of the emitting material, the photon wavelength will be shifted according to this motion.

The declaration of a double-conically shaped narrow emission line region is rather similar:

`NLRSource r1 r2 θ0 αe λ0 Γ vr strength`

The line characteristics are defined as for the broad line region, only the geometrical parameters are different (see Fig. 2.1b). The parameter  $\alpha_e$  denotes a radial density dependence if it is set different from 0. The emission rate then changes as  $\left[\frac{r}{r_1}\right]^{-\alpha_e}$ . The radial velocity  $v_r$  of the emitting material produces a wavelength shift of the photon.

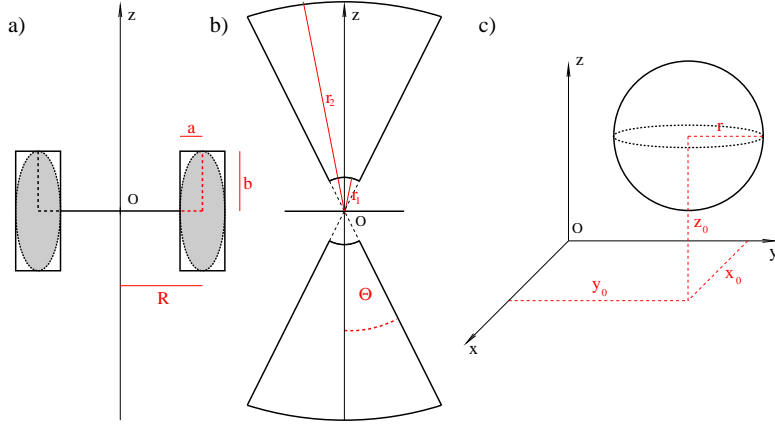


Figure 2.1: Geometries of emission and scattering regions in *STOKES*

### 2.1.3 Defining scattering regions

So far, *STOKES* supports four types of scattering regions: cylindrical regions, toroidal regions, double-conical regions, and single spheres. The cylinders, tori, and double-cones are centered on the origin of the coordinate system, while a sphere can be located anywhere in the model space. The double-cones have to be defined along the  $z$ -axis. All scattering regions can be declared to contain either dust or electrons. The material is denoted by the parameter *dust-flag*, which is a string of characters. If it is equal to the word “dust” the scattering region will be filled with dust, in any other case (like “electrons”) it is filled with electrons. The density of the material is given by the parameter  $\rho$ . Hereby,  $\rho$  is a particle number density. The central-symmetric regions - cylinders, tori,

and double-cones - can be attributed with a radial velocity  $v_r$  of the material simulating an in- or outflow. The scattering events within these regions will consider the radial velocity of the scattering particles by a Doppler-shift of the wavelength. The maximum number of scattering regions allowed is 30.

For a cylindrical region the syntax is (geometrical parameters see Fig. 2.1a):

`Cylinder R a b dust-flag  $\rho$   $v_r$`

For a toroidal region the syntax is (geometrical parameters see Fig. 2.1a):

`Torus R a b dust-flag  $\rho$   $v_r$`

For a double-cone region the syntax is (geometrical parameters see Fig. 2.1b):

`Double-cone  $r_1$   $r_2$   $\theta$  dust-flag  $\rho$   $v_r$`

For a spherical region the syntax is (geometrical parameters see Fig. 2.1c):

`Sphere  $x_0$   $y_0$   $z_0$  dust-flag  $\rho$`

While conducting the radiative transfer, *STOKES* moves photons within the model space. At the borders of scattering regions the program has to decide if a photon is inside the cloud, in which case it possibly undergoes interaction with the scattering material. It turns out that this decision can cause numerical difficulties when the photon happens to be very close to the border of the scattering region. It is therefore necessary to clarify if the photon is inside or outside the scattering region, which is done by shifting it by an additional distance  $dx$  when the photon enters or leaves a scattering cloud. The parameter *gap* should be small compared to the expansion of the scattering regions and also small compared to their minimum mean free path length. If one obtains inconsistent results, especially if photons seem to penetrate through optically thick dust regions, it is worth trying to increase  $dx$ . To define the parameter *gap* use the following command:

`Gap  $dx$`

#### 2.1.4 Defining a dust model

For the scattering regions filled with dust, a dust model has to be declared. The default dust model is based on a composition reproducing a standard Galactic extinction curve. A new dust model can be defined by changing the default parameters, the new dust properties are then calculated at the beginning of the program. For later use the dust model will be saved in a file on the disk. The declaration of a dust model is as follows:

```

GrainRadMin  $r_{min}$ 
GrainRadMax  $r_{max}$ 
GrainSizeInd  $\alpha_s$ 
DustComp graph-orth graph-para silicate
GrainRadNum  $N_{rad}$ 
GrainLambdaNum  $N_\lambda$ 
DustModel dust-file-name

```

The program calculates the extinction properties of dust grains with a number distribution of grain radii  $r_s$  following a power law  $n(r_s) \propto r_s^{\alpha_s}$ . The limits of the grain radii and the grain size index are given by  $r_{min}$ ,  $r_{max}$ , and  $\alpha_s$ . The fraction of each dust component, is given by the percentages *graph-orth*, *graph-para*, and *silicate*. Since *graph-orth* and *graph-para* both refer to graphite but denote different polarization planes with respect to the crystal symmetry, *graph-para* must be twice the value of *graph-orth*. The sum of all three percentages must equal 100, of course. The dust composition and grain size distribution are integrated to produce an average dust grain used for the radiative transfer. The parameters  $N_{rad}$  and  $N_\lambda$  determine how many grain radii and wavelengths are considered for the integrations.

When *STOKES* is launched, it will first check if the dust model declared by *dust-file-name* already exists in the current work directory. If it does exist, the program reads in the dust data from the file. If no dust model is found, the Mie data is computed and then saved into the file *dust-file-name.dst* to be used again for other model runs.

The structure of a dust file starts out with the date and time of computation and with a list of the dust parameters as given in the declarations above. After a first delimiter, the wavelength dependence of the extinction, scattering, and absorption cross-section of an integrated dust grain are given in  $\text{cm}^2$ , followed by the albedo. Then, after a second delimiter, the wavelength dependence of the four Mueller matrix entries  $S_{11}$ ,  $S_{12}$ ,  $S_{33}$ , and  $S_{34}$  for each scattering angle are listed.

## 2.2 Evaluating a simulation with *ANALYZE*

Each run of *STOKES* creates a set of four output files with the suffix *sto*, one file for each Stokes parameter. The file name is given by the parameter *output-file-name* to which the parameter *CPU-number* is attached. The next character of the file name denotes the Stokes parameter  $I$ ,  $Q$ ,  $U$ , or  $V$  stored in the file. The construction of the output files is rather simple: the first line contains general information of the model run, like the name or the date and time of the simulation. The next line includes all model parameters. Then, following a delimiter, there is a series of data tables containing the Stokes parameters at all wavelengths and for the different viewing directions considered.

To be conveniently readable the output files of *STOKES* require to be processed with the auxiliary program *ANALYZE*. It extracts various information from the *STOKES* output files and produces four new files with names ending on *...TF.res*, *...PO.res*, *...PA.res*, and *...PF.res*. At the top, these files contain an identical section listing all model parameters and general information about the model run. Here you also find the number of photons sampled compared to the total number of photons defined for the run. This might be helpful if you check the intermediate results of a *STOKES* simulation that is still running. Below the general parameter part, the files contain the following spectral results for each viewing direction:

spectral result	file suffix
Total flux $F_\lambda$	<i>...TF.res</i>
Percentage of polarization $P$	<i>...PO.res</i>
Polarization position angle	<i>...PA.res</i>
Polarized flux $P \times F_\lambda$	<i>...PF.res</i>

The viewing direction is denoted at the beginning of each line by a code of the kind “cosT.../P...”. Herein “cosT” is followed by the cosine of  $\theta$  and “P” marks  $\phi$  given in degrees. If there is only one azimuthal viewing direction defined, the denotation of  $\phi$  is suppressed. For the file *...PA.res* the position angle of the polarization vector is measured from a zero axis perpendicular to the  $z$ -axis of the model space’s coordinate system.

The program *ANALYZE* also produces a new set of result files with the suffix *sto* but containing no CPU-number. The role of these files is related to a possible expansion of the model run and to running *STOKES* on multiple CPUs, which is explained in the next section 2.3.

## 2.3 Running *STOKES* on multiple CPUs

It is possible to perform simultaneous simulations with *STOKES* on several CPUs. Therefore, the program has to be copied to all machines in use, together with the input file *input.par* of the specified model. Then, the input files have to be attributed with successive CPU-numbers following the declaration of the output file name. As a result, the different copies of *STOKES* will produce output files with successive CPU-numbers that, after all runs are finished, have to be copied into one directory, together with the program *ANALYZE*. Running *ANALYZE* on the multiple output files will add up the Stokes parameters of the various runs and combine them into four new output files with the suffix *.sto*. These new output files do not contain any CPU-number. In case you want to extend your model for more photons by adding further runs, these combined result files can be used again by attributing a CPU-number to their file names. Note, the more photons you sample the smoother the spectral results become.

In addition to the combined result files *ANALYZE* produces the usual result files with the suffix *res* (see previous section 2.2). They contain the flux and polarization data extracted from the multiple run.

Table 2.1: Commands to use in *input.par*, their default parameters, and eventual limits (part 1)

command	parameters	default parameters / limits	function
<b>OutputFile</b>	<i>output-file-name CPU-number</i>	empty-space 1	set output file name and number of the processor
<b>ThetaViewAng</b>	<i>number-theta</i>	10 (max = 80)	set number of viewing angles in $i$
<b>PhiViewAng</b>	<i>number-phi</i>	1 (max = 40)	set number of azimuthal viewing angles
<b>PlaneSym</b>	<i>symmetry-flag</i>	“yes”	indicate symmetry with respect to the $xy$ -plane
<b>LambdaMin</b>	<i>min-wavelength</i>	1000 (min = 1000)	minimum continuum wavelength in Å
<b>LambdaMax</b>	<i>max-wavelength</i>	10000 (max = 10000)	maximum continuum wavelength in Å
<b>SpectRes</b>	<i>number-channels</i>	45 (max = 200)	number of channels for each detector
<b>PhotonNum</b>	<i>photon-number</i>	1000000	number of photons to sample
<b>ContSource</b>	$R a b \alpha v_r$	0 0 0 2 0	define continuum emission region (see Fig. 2.1a), set spectral index $\alpha$ and radial velocity $v_r$
<b>BLRSource</b>	$R a b \lambda_0 \Gamma$ strength $v_r$	0.007 0.005 0.005 6563 150 0 0	define broad line region (see Fig. 2.1b), set line centroid, width (both in Å), relative strength (percentage), and radial velocity $v_r$
<b>NLRSource</b>	$r_1 r_2 \theta_0 \alpha_e \lambda_0 \Gamma$ strength $v_r$	10 100 25 0 6563 25 0 0	define narrow line region (see Fig. 2.1c), set line centroid, width (both in Å), relative strength (percentage), and radial velocity $v_r$
<b>GrainRadMin</b>	$r_{min}$	0.005 microns	minimum grain radius of the dust model
<b>GrainRadMax</b>	$r_{min}$	0.250 microns	maximum grain radius of the dust model
<b>GrainSizeInd</b>	$\alpha_s$	-3.5	grain size index of the dust model
<b>DustComp</b>	<i>graph-orth graph-para silicate</i>	12.5 25.0 62.5	Abundances for the dust components (percentages); Note: <i>graph-para</i> = $2 \times$ <i>graph-orth</i> and sum = 100
<b>GrainRadNum</b>	$N_{rad}$	100	number of grain radii considered for the dust model
<b>GrainLambdaNum</b>	$N_\lambda$	100	number of grain radii considered for the dust model
<b>DustModel</b>	<i>dust-file-name</i>	default	file name of the dust model

Table 2.2: Commands to use in *input.par*, their default parameters, and eventual limits (part 2)

command	parameters	default parameters / limits	function
<b>Cylinder</b>	$R a b$ “dust”/“electrons” $\rho v_r$	not predefined	define cylindrical scattering region (see Fig. 2.1a), with dust/electron density $\rho$ , and radial velocity $v_r$
<b>Torus</b>	$R a b$ “dust”/“electrons” $\rho v_r$	not predefined	define toroidal scattering region (see Fig. 2.1a), with dust/electron density $\rho$ , and radial velocity $v_r$
<b>Double-cone</b>	$r_1 r_2 \theta$ “dust”/“electrons” $\rho v_r$	not predefined	define double-conical scattering region (see Fig. 2.1b), with dust/electron density $\rho$ , and radial velocity $v_r$
<b>Sphere</b>	$x_0 y_0 z_0$ “dust”/“electrons” $\rho$	not predefined	define spherical scattering region (see Fig. 2.1c), with dust/electron density $\rho$
<b>Gap</b>	$dx$	$10^{-6}$ pc	computational parameter: photon displacement, must be small compared to dimensions and mean free path lengths of scattering regions

## Chapter 3

# Exemplary input files and dust models

If you want to familiarize yourself with the program and learn quickly how to run it, you might have a look at the following three examples we provide. These examples also show how to parametrize two dust models that are relevant for astronomical applications (see sections 3.1 and 3.2). You can download the input files and the precomputed dust models from the web page featuring *STOKES*.

So far, the program computes all dust models for a wavelength range of 1000Å to 10000Å, as the optical data we adopted from Draine & Lee (1984) is given for this range. The accuracy of the model can be changed by choosing the parameters  $N_{rad}$  and  $N_{\lambda}$  denoting the number of wavelengths and grain radii at which the Mie data is computed. It is our experience, that dust models computed for  $N_{rad} = 200$  and  $N_{\lambda} = 200$  are quite accurate, so we adopted these parameters for our precomputed models.

### 3.1 Example 1: electron disk and dusty torus

The first example is taken from an application of *STOKES* to modeling polarization in Active Galactic Nuclei. The input file sets up an emitting and scattering electron disk located within the funnel of an optically thick torus. The system is hence axis-symmetric and will only be evaluated at different polar viewing angles  $\theta$ . A flat continuum spectrum within a wavelength range of 2000Å to 8000Å is considered.

The torus is filled with dust of the model *AGN*. This dust composition is based on modeling extinction curves of quasars as described in Gaskell et al. (2004). It contains graphite and silicate. The abundance for graphite is set to 15% and silicate contributes 85%. The grain size distribution  $n(a)$  contains radii  $a$  between  $0.005\mu$  and  $0.200\mu$  and follows a power law with  $n(a) \propto a^{-2.05}$ .

In Fig. 3.1 we show the modeling results for the degree of polarization  $P$ . The diagram can be constructed from the output file *Disk+TorusPO.res*. The wavelength dependence of  $P$  varies with the inclination of the object. As one looks at the object from an edge-on direction, e.g. at higher inclinations, the spectra are dominated by radiation scattered off the inner surface of the torus, the polarization rises with wavelength. Observations at a low inclination give a direct view at the electron disk and the polarization is dominated by wavelength independent Thomson scattering.

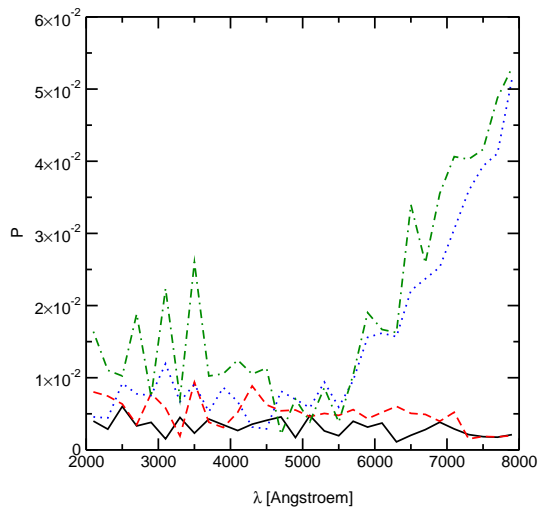


Figure 3.1: Polarization spectra at different inclinations for example 1. The curves denote the following inclinations  $i$ :  $\cos i = 0.95$  (solid),  $\cos i = 0.85$  (dashed),  $\cos i = 0.75$  (dotted), and  $\cos i = 0.65$  (dashed-dotted).

### 3.2 Example 2: electron disk and polar cones

In this example we model a system consisting of a disk with polar scattering cones and a surrounding broad line region. The emitting and scattering disk is supposed to be dominated by electrons. Along its symmetry axis we define a scattering double-cone filled with electrons and, further out, a dusty double-cone emitting a narrow  $H\alpha$  emission line at  $6563\text{\AA}$ . Both cones have a radial outflow velocity. A broad  $H\alpha$  emission line at  $6563\text{\AA}$  comes from a cylindrical region around the electron disk. The dusty part of the conical scattering region is filled with dust of the model *MilkyWay*. It describes an average dust composition as observed from extinction measurements in our Galaxy. The grain size

distribution  $n(a)$  follows a power law with  $n(a) \propto a^{-3.5}$  over a range of  $0.005\mu$  to  $0.250\mu$ . We assume an abundance for silicate of 62.5% and for graphite of 37.5%. This grain composition and size distribution represents the Galactic standard extinction curve fairly well. It was used in the modeling of Fischer et al. (1994).

We show the results for the polarized flux in Fig. 3.2. The diagram can be constructed from the result file *Disk+ConesPF.res*. As the inclination increases toward an edge-on view, the line centroid, seen in polarized flux, shifts toward greater wavelengths. This is due to the radial outflow of the ionization cones. The angle between the velocity vector of the scattering material and the viewing direction increases toward  $90^\circ$ , hence the degree of polarization rises and the Doppler-redshift of the polarized broad line becomes more prominent.

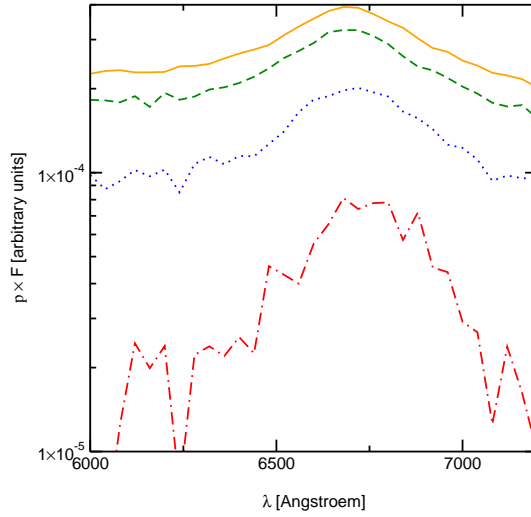


Figure 3.2: Polarized flux spectra at different inclinations for example 2. The curves denote the following inclinations  $i$ :  $\cos i = 0.9$  (solid),  $\cos i = 0.7$  (dashed),  $\cos i = 0.5$  (dotted), and  $\cos i = 0.3$  (dashed-dotted).

### 3.3 Example 3: electron shell and dust clouds

The last example features a setup that is not axis-symmetric. We assume a point-like narrow line region emitting an [OIII]-line at  $5007\text{\AA}$ . This source is shielded by a rapidly expanding, highly ionized shell. Some nearby dust-clouds are distributed without a clear pattern around the system. The dust composition is similar to dust in the Milky Way and read from the file *MilkyWay.dst*.

In order to conduct this simulation correctly the file *MilkyWay.dst* must first be computed from example 2 and then copied into the current working directory.

In Fig. 3.3 we show the results for the total flux seen at an edge-on inclination. The diagram can be constructed from the output file *Shell+CloudTF.res*. The asymmetry of the line profile is due to the surrounding dust clouds. They absorb a fraction of the light penetrating through the expanding shell or scatter it toward different directions.

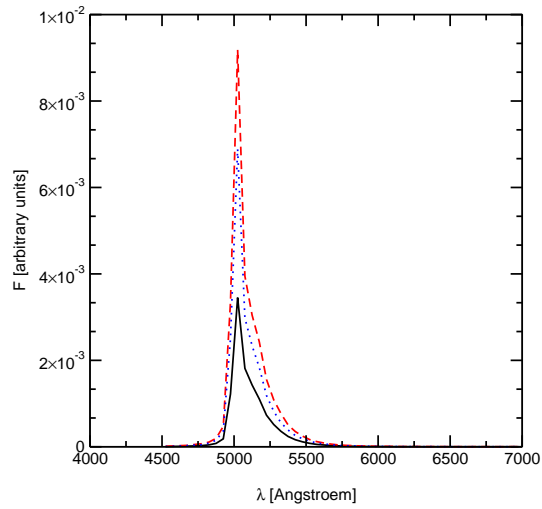


Figure 3.3: Total flux spectra for example 3 at three edge-on viewing directions. The curves denote the following azimuthal viewing angles:  $\phi = 135$  (solid),  $\phi = 225$  (dashed), and  $\phi = 315$  (dotted).

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