RADIATIVE TRANSFER PROBLEM IN DUSTY GALAXIES:
A PROGRAM SUITE

Dmitrij Semionov and Vladas Vansevičius
Institute of Physics, Savanorių 231, Vilnius LT-02300, Lithuania
dima@astro.lt

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Abstract. We present a program suite for the radiative transfer problem solution in axisymmetrical dusty galaxy disks, intended primarily for spectrophotometric analysis of stellar populations by means of integrated and differential photometry. The solution is obtained using a 2-D ray-tracing algorithm at a discrete wavelength set, emphasizing careful treatment of the effects of light scattering by interstellar dust grains. The program has been thoroughly tested and shows the performance and accuracy comparable to or better than other codes currently in use for astrophysical radiative transfer. The program’s source code and example model files are available at http://www.astro.lt/~dima/gfe/

Key words: radiative transfer – galaxies: dust, extinction.

1. INTRODUCTION

In order to correctly interpret the observed spectrophotometric properties of galaxies and thus understand their evolution it is necessary to investigate the interrelations between star formation histories and galaxy color/spectral evolution. However, it is impossible to establish these relations solely by modeling the colors of stellar populations. Interstellar extinction – especially, the scattering of stellar light by interstellar grains – plays an important role in redistributing the radiative energy and determining the radial color gradients in galactic disks. The only way to account for the effects of the galaxy internal extinction is a thorough and rigorous solution of the radiative transfer problem in dusty environments.

For efficient analysis of star formation history in galaxies it is important to obtain self-consistent solutions of the radiative transfer problem, i.e., the resulting derived spectral properties of the model galaxies must depend only on the input spectra of stellar populations, their spatial distribution and assumed properties of the interstellar dust. The code for the radiative transfer problem solution has to be as efficient as possible since, for an investigation of a single object or an analysis of a galaxy survey, we must account for a large number of free parameters: stellar population and dust distribution scale-lengths and scale-heights, the amount of dust, extinction laws, as well as various evolutionary parameters of stellar populations.

Most of the currently used astrophysical radiative transfer codes employ either the Monte-Carlo (e.g., Ciardi et al. 2001) or the ray-tracing (e.g., Razoumov & Scott 1999) methods. Some of these codes were compared and their differences discussed by Ivezic et al. (1997) and Baes & Dejonghe (2001) for 1-D and by
Dullemond & Turolla (2000) and Pascucci et al. (2004) for 2-D cases.

The Galactic Fog Engine (hereafter GFE), a program for a self-consistent solution of the radiative transfer problem in axisymmetrical models of dusty galaxy discs, presented in this paper, was developed considering all the requirements of careful treatment of the radiative transfer problem, mentioned above. The details of the ray-tracing scheme, implemented in GFE, were described by Semionov & Vansevičius (2005c). Here we describe the GFE from the point of view of the prospective user, outlining the steps required to construct galaxy models for evaluation of spectrophotometric effects of internal extinction by diffuse interstellar dust.

2. THE GALACTIC FOG ENGINE

In order to correctly recover histories of star formation in galaxies a wide range of spectral and detailed spatial energy distribution parameters are required. A far-infrared flux of the galaxy is particularly important to estimate its dust content. However, this information is not always available from observations and, furthermore, to interpret it correctly a detailed knowledge of the dust composition and its emissivity properties is required. Therefore, we restricted consideration of the galaxy models into UV, visual and NIR spectral ranges, which are dominated by stellar light – either directly observed or scattered by interstellar dust grains. The deterministic nature and a possibility of effective optimization, inherent in the ray-tracing approach, were the reasons to employ this algorithm for computation of the scattered light distribution using an iterative scheme (Henyey 1937).

The model galaxy is represented by a cylinder, subdivided into a set of layers of concentric internally homogeneous rings of varying vertical and radial extent. The amount and distribution of the absorbed and scattered light is obtained by sampling light and dust distributions within a cylinder, using a set of rays along which 1-D radiative transfer problems are solved. This ray-tracing iteration is repeated for a desired number of times by substituting the scattered light for the radiative field distribution. The GFE source code, helpful model data managing utilities, a user’s manual and model examples are available at the project’s web page, http://www.astro.lt/~dima/gfe/.

GFE results were compared in detail with other radiative transfer problem solving code outputs by reproducing several previously published 1-D and 2-D models of dusty environments (Semionov & Vansevičius 2002; an update to this article is available at the project’s web page). The results, obtained using the GFE, provide a very close match (within 1%) to the results, obtained using Monte-Carlo method (Semionov & Vansevičius 2002, 2005a,b).

The program is written in Fortran 77 and has been thoroughly tested on various desktop and workstation configurations using GNU g77 and other free and proprietary compilers with consistent results and performance. The code is free for science and academic use, however, publications, using the data computed by GFE, must acknowledge the code’s use by including a reference to the present article. Also, at the first mention of the Galaxy Fog Engine or the GFE abbreviation a footnote with the web address of the project’s home page must be provided.

3. THE MODELS

The spectrophotometric characteristics of the galaxy model are defined by the
geometry of stellar and dust mass distribution and their spectral properties. Stars and interstellar dust can be distributed in the model volume according to a wide range of different 2-D laws: single and double exponential, spheroidal, de Vaucouleurs, etc. Due to a limitation, imposed by the used algorithm, all interstellar dust distributed within the galaxy models has the same optical characteristics: albedo, scattering phase function and absorptivity (Laor & Draine 1993), while each stellar population, included in the galaxy model, can possess its unique spectral energy distributions.

The model galaxy description is passed into the GFE program through the input file galaxy, which must contain one mandatory and any number of optional blocks, see Figure 1. The mandatory block defines a general model geometry, parameters and execution control flags, which determine computation steps to be performed. This block must be located at the beginning of the galaxy file. Optional blocks start with the line containing a single integer denoting its type: mass distribution of stellar population and its spectrum (block type 1), interstellar dust mass distribution (2) and dust grain optical parameters (3). Optional blocks may appear in the input file in arbitrary orders and in unlimited numbers. However, if the block 3 is present in the input file more than once, the optical properties of dust grains will be computed using the latest occurrence of this block, i.e., will override any previous definitions.

The file galaxy can also contain “include” and “substitute” directives and “comments”, making it possible to combine an input file from several files, each describing a particular stellar population or dust distribution, etc. Included files may in turn contain further comments and directives. It is also possible to sequentially compute several models in a single GFE run by using “substitute” directives and a substitute file, substab. If during parsing of the main input file galaxy the program encounters symbol ‘#’ followed by a single digit, it attempts to substitute this pair of symbols with a value from the substab file. Each of the nine possible substitute parameters (variables) from #1 to #9 corresponds to the first nine columns in the substab file, each line of this file thus defining a set of variables for a single model. After finishing the computations the program returns to the start of the input file and repeats all steps, however, this time using the next line in the substab file and proceeding until the end of that file.

At the output the program produces image files, aperture photometry data and image cross-section (light-scans, integrated within one pixel-wide image strips) data at each specified wavelength, as well as an execution log file, containing information on the performed computation steps, and model radiative energy balance after each iteration. The resulting aperture photometry is presented in magnitudes by integrating output images within either circular or elliptical (inclination dependent – the aperture axis ratio is determined by the stellar population scale-length to scale-height ratio) apertures of specified sizes and as a photometric profile.

4. SUMMARY

The GFE program suite, presented in this paper, was successfully applied to model a variety of dusty disk galaxies (Semionov & Vansevičius 2002, 2003), even reproducing the effects of dusty spiral arms (Semionov et al. 2006). By applying the GFE code it has been proved, that the ray-tracing algorithm is a viable way to solve the radiative transfer problem in astrophysics, which is an accurate enough, easily modifiable and flexible tool for spectrophotometric modeling of galaxies.
Fig. 1. The structure of the main model description file, galaxy, used in the GFE (left) and the internal structure of each parameter block (right).

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