1 Radiative transfer codes

In order to solve the radiative transfer problem, the following optical properties of dust grains must be defined beforehand:

- extinction cross-sections (see Eq. (??)) for calculations of the optical distance inside a dusty object;
- particle albedo (Eq. (??)) and the scattering matrix (Eq. (??)) for description of the process of light scattering if the polarization is considered or phase function (Eq. (??)) if not (in some cases only the asymmetry parameter g (Eq. (??)) is used);
- absorption cross-sections which are used for calculations of dust temperature and emitted radiation.

Table 1 contains some characteristics of radiative transfer programs created during the last 25 years and their applications to the interpretation of observed data on dusty cosmic objects. As usual, many modern radiative transfer codes are modifications of earlier versions created at the same institute or university. We do not intend to search for the origin and roots of codes and just note that the author of the original code used to appear as the co-author of further publications. The major part of the papers mentioned in Table 1 are based on two methods: *a*) iterative scheme to solve the moment equations of radiative transfer equation (methods of moments, MoM) which was originally formulated by Hummer and Rybicki (1971) for spherical geometry with a central point source (1D geometry) and *b*) Monte Carlo (MC) simulation. In some cases, for simplification of calculations the phase function $\mathcal{F}$ (Eq. (??)) is taken in an approximate form suggested by Henyey and Greenstein (1941; HG function, see discussion in Part II, Sect. 6). The standard applications include: circumstellar (CS) shells and envelopes around early (pre-main-sequence; PMS) and late-type stars and young stellar objects (YSO), reflection nebulae (RN), interstellar clouds and globules, diffuse galactic light (DGL) and in recent years galaxies and active galactic nuclei (AGN).

Table 1: Papers presenting new approaches and schemes in radiative transfer in dusty media.

Author(s)	Method; particles; geometry; output; applications
Leung (1976)	MoM, quasi-diffusion approximation; homogeneous and coated spheres; 1D (sphere); intensity, SED; dust clouds with central source, CS shells
Witt (1977)	MC; spheres, HG phase function; plane-parallel layer; intensity; RN
White (1979)	Doubling method; MRN mixture; homogeneous layer (optically thick but geometrically thin); intensity, polarization; RN
Daniel (1980)	MC; single size spheres; homogeneous sphere; polarization; cool stars
Yorke (1980)	MoM; single size spheres; 1D (sphere), isotropic scattering; SED; cocoon stars
Rowan-Robinson (1980)	Ray tracing method; single size homogeneous and coated spheres; 1D (inhomogeneous sphere), isotropic scattering; SED, intensity profiles; hot-centred interstellar clouds; M giants and supergiants
Lefèvre *et al.* (1982)	MC; graphite and silicate spheres; inhomogeneous sphere, anisotropic scattering; SED; late-type stars
Lefèvre *et al.* (1983)	MC; graphite and silicate spheres; homogeneous ellipsoid, anisotropic scattering; SED, images; young and late-type stars
Warren-Smith (1983)	MC; spheres of different sizes; plane layers; surface brightness, polarization; RN
Spagna and Leung (1983)	Newton–Raphson iterative scheme; spheres (up to 5 constituents); 1D (homogeneous sphere); SED; CS shells, interstellar clouds
Rogers and Martin (1986)	Half-range MoM; spheres; 1D (sphere) with power density distribution; SED; CS shells (IRC +10 216)
Chini *et al.* (1986)	MoM; MRN mixture; 1D (sphere) with power density distribution; SED; CS shells
Wolfire and Cassinelli (1986)	Modified MoM; MRN mixture; 1D (sphere) with power density distribution; SED; protostars
Spagna and Leung (1987)	MoM, quasi-diffusion approximation; homogeneous and coated spheres; 2D (disks); intensity, SED; disk dust clouds; CS disks; disk galaxies
Bastien and Ménard (1988)	MC; spheres; 3D, arbitrary geometry, inhomogeneous density distribution; images, polarization maps; YSO, CS shells

Table 1: (Continued.)

Author(s)	Method; particles; geometry; output; applications
Egan *et al.* (1988)	Updated and comprehensive versions of codes of Leung (1976) and Spagna and Leung (1983) for one-dimensional geometries (sphere, plane-parallel, cylindrical)
Efstathiou and Rowan-Robinson (1990)	Ray tracing method; single and multi-compo- nent mixtures of spheres; 2D axisymmetric inhomogeneous configurations (disks, ellipsoids, tori); SED; late type stars, AGN
Höfflich (1991)	MC; Thomson scattering; axisymmetric photospheres; polarization; SN 1987A
Collison and Fix (1991)	Iterative scheme; single size silicate spheres; 2D axisymmetric inhomogeneous shells, isotropic scattering; SED, images; CS shells
Whitney and Hartmann (1992)	MC; spheres, HG phase function; 3D (disks); images, polarization maps; PMS objects
Pier and Krolik (1992)	Multi-dimensional Newton–Raphson technique; MRN mixture; 2D (homogeneous torus); SED; AGN, Seyfert galaxies
Bosma (1993a, 1993b)	New iterative scheme in MoM; anisotropic scattering, randomly oriented particles; 1D (sphere); intensity and polarization;
Fischer (1993)	MC; MRN mixture; 3D, arbitrary geometry, inhomogeneous density distribution; images, polarization maps; protostellar sources
Groenewegen (1993)	Iterative scheme; spheres; 1D (sphere) with power density distribution, isotropic scattering, determination of inner radius as dust condensation boundary; SED; shells around AGB stars
Voshchinnikov and Karjukin (1994)	MC, method of symmetrized trajectories; spheres (Rayleigh, MRN mixture); 2D (inhomogeneous spheroid); intensity, polarization; CS shells around young stars
Code and Whitney (1995)	MC; electrons, spherical particles; 3D (illuminated spherical blobs); intensity, polarization; supergiants, RCB stars, DGL, RN
Sonnhalter *et al.* (1995)	Frequency dependent flux-limited diffusion approximation; mixture of carbon, silicate and silicate-ice spheres; 2D axially-symmetric dusty disks with different density distribution; intensities, images at different wavelengths
Lopez *et al.* (1996)	MC; carbon spheres; inhomogeneous axisymmetric shell, anisotropic scattering; SED, images; AGB stars, Red Rectangle
Steinacker and Henning (1996)*	Direct solution to discretized radiative transfer equation; spheres; 3D arbitrary configuration; SED, images; CS shells, YSO
Men'shchikov and Henning (1997)	MoM; spheres of different sizes and materials; 2D axially-symmetric CS disks with arbitrary density distribution; SED, images; CS shells, YSO
Ivezić and Elitzur (1997)	Numerical integration; spheres (6 types of materials and 2 size distributions); 1D (sphere and plane-parallel slab); SED; CS shells, interstellar clouds, YSO
Városi and Dwek (1999)	Analytical approximation and MC; spheres; spherically-symmetric two-phase clumpy medium; fluxes; star-forming regions, starburst galaxies
Wolf and Henning (2000)	MC including calculations of dust temperature; spheres of different sizes and materials; 3D, arbitrary number, shape and geometrical configuration of illuminating sources and dust density distribution; SED, images, polarization maps; CS shells, YSO, AGN
Gordon *et al.* (2001) and Misselt *et al.* (2001)	MC; mixture of carbonaceous and silicate grains, polycyclic aromatic hydrocarbons (PAHs); 3D, arbitrary distribution of stars and dust; SED, images, polarization maps; RN, clusters of stars, galaxies
Wolf *et al.* (2002)*	Dissemination of MC code of Wolf and Henning (2000) on non-spherical particles

* First results only

A short description of recent progress in continuum radiative transfer modelling is given in the review of Henning (2000).

The old and still troublesome problem is verification of numerical codes. It was seriously analyzed by Ivezić *et al.* (1997) who compared three different radiative transfer codes and obtained the benchmark results for temperature and emerging spectra in the case of spherical geometry.

Note that astronomers can use results and experience gained in other fields of science. For example, 3D radiative transfer codes are widely used in the terrestrial atmosphere applications as described, for example, by

Cahalan (2000).

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