STOKES
A Monte Carlo radiative transfer code for polarization modeling

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(Sir George) Stokes

Born: 13 August 1819
Died: 1 February 1903

Irish mathematician, physicist, politician and theologian

Secretary, then president, of the Royal Society

Contributions to science:
- Fluid dynamics
- Chemical analysis
- Light
- Fluorescence
- Polarization

Monte Carlo code designed to perform three-dimensional radiative transfer

Written in C/C++ (imaging routine in IDL) – Stokes formalism

Created in 2004 to study the polarimetric signatures of Active Galactic Nuclei (AGN) in the optical / UV regime. Extended in the X-ray band (circa 2009)

Data cube of intensity+polarization as a function of 1- wavelength (spectroscopy), 2- sky position (imagery) and 3- time (variability)

Basic version publicaly available
(http://www.stokes-program.info/)

Can be adapted to a large panel of objects / sources :
- Red super-giant stars
- X-ray binaries
- Galactic Center
- AGN
Publications

Main papers:

Various utilisations of STOKES so far:
- Exploring the Unified Model of AGN
- Off-axis irradiation and broad emission lines polarization in AGN
- Probing the origin of the iron Kα line around stellar and supermassive black holes
- Spectropolarimetric signatures from disk-born outflows
- Modelling the complex geometry of « changing look » AGN
- Constraining the layout of circumnuclear clouds in the Galactic center

Total (May 2014):
- 25 articles (refereed papers and proceedings)
- 96 citations
A photon journey
Emission regions

SED:
- Power-law
- (multiple) black-body emission

Morphology:
- point-like
- cylinder
- slab
- double-cone
- torus
- segments

Waveband/energy band:
- optical/UV: 1400 – 10 000 Å
- X-rays: 0.8 – 300 keV

Parallel computing
Impact of statistics

Importance of Random Number Generation (RNG) in radiative transfer codes

Usual RNG: Linear Congruential Generators (LCG)
  → fast and efficient only for short series ($< 10^7$ photons)
  → loop back on series of values it has sampled before

RNG implemented in STOKES: Mersenne Twister Generator (MTG)
  → generates pseudo-random numbers using a so-called twisted generalized feedback shift register
  → very high period of $2^{19937} - 1$
  → provides a 623-dimensional equidistribution up to an accuracy of 32 bits
  → passes the “Diehard” tests Marsaglia (1985)

\[ x_0 = 585, \quad x_{n+1} \rightarrow (29 \times n - 108) \mod 574 \]
Reprocessing regions

Composition:
- Dust (user-defined mixture)
- Electrons
- Atoms (from H to Ni)

Morphology:
- cylinder
- slab
- double-cone
- torus
- clouds
- disk-born winds

Processes:
- Thomson/Compton/Mie scattering
- Radiative recombination
- Photoionization / Fluorescence
- Dust / atomic absorption

3D velocity is implemented
Multiple-scattering (crucial for circular polarization)
Results

Photons stored in terms of Stoke's vector \((I,Q,U,V) + t\)

Results processed with the module called ANALYZE

→ Total flux
→ Percentage of total polarization (linear + circular)
→ Polarized flux
→ Polarization angle
→ Percentage of circular polarization
→ Ellipticity
→ Polarization map
→ Time-lag

Example:
- Phenomenologically-based structure (Elvis 2000)
- Radiation-driven wind
- Bi-phased (WHIM / dust)
- Emission region off-axis

Marin & Goosmann (2013)
Results

Graphs showing:
- Total flux
- Polarized flux
- Total polarization
- Polarization angle
- Circular polarization
- Ellipticity

Axes:
- X-axis: 2000 to 8000
- Y-axis: 1e-07 to 1e-05 for total flux, 0 to 10 for total polarization, 0 to 0.2 for circular polarization, and 0 to 0.03 for ellipticity
Results

(Mie scattering removed)
Principal hypothesis: the polar outflows sustain the same half-opening angle as the dusty torus

Raban et al. (2009) → polar winds (represented as a bi-conical structure) are inclined with respect to the obscuring torus axis
Probing (unusual) AGN with polarimetry

Constraining the 3D geometry of the tilted outflows with polarimetry

Marin et al, (in prep.)

Polarization degree and polarization angle as 2 independent and complementary informations
Multi-wavelength polarimetry

To probe the geometry and kinematics of emission and scattering regions, it is important to provide consistent and simultaneous polarization models in the optical/UV and the X-ray band.
Promoting X-ray polarimetry

The actual context of the Galactic Center
- 3D location of Sgr A*, Sgr B2, Sgr C … ?
- Are Sgr B2 and Sgr C reflecting past Sgr A* emission?

JAXA – Suzaky X-ray map of the GC
Promoting X-ray polarimetry

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X-ray polarimetry can bring answers

Churazov & Sunyaev (2002)
Marin et al. (2014)
Synergy with other codes

Potential coupling with:

**MoCa** – F. Tamborra, G. Matt, S. Bianchi
IDL code (interactive and vectorized), modular and fully special relativistic (Klein-Nishina cross-section, Juttner distribution …) → to include special relativity

**SKIRT** – M. Stalevski, M. Baes
3D Monte Carlo radiative transfer code (photon packages)
Temperature, kinematic, adaptative grid, variety of reprocessing geometry → to include infrared mechanisms

Polarization to be implemented