Monte Carlo Modelling of Comptonised X-ray Radiation from Accretion Flows onto Neutron Stars and Black Holes

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Abstract

Accretion flows onto Galactic compact objects such as neutron stars and black holes have been best studied in the X-ray band. Recent progress in observational instruments allows us to investigate detailed temporal and spectral behaviour of the flows which should contain important information on accretion physics. However, precise comparison between the high-quality data and theoretical models requires careful treatment of X-ray generation in the accreted plasma which can have complicated structure. For this purpose, we have developed a general-purpose calculation framework of radiative transfer based on Monte Carlo methods, and applied it to Comptonisation. Multiple Compton scatterings, which play a key role in the radiative processes, are accurately traced by the simulation in complicated geometry. Using this framework, we build a radiation model of a columnar flow onto a magnetised neutron star where thermal and bulk Comptonisation are responsible for generating the X-ray spectrum, and extract physical properties of the accretion column by analysing broadband data of Vela X-1 obtained with Suzaku. The same framework is applied to the low/hard state of black hole binaries, and we simulate quasi-periodic oscillation and X-ray polarisation.

Radiative Transfer by Monte Carlo Simulation

Modern X-ray observations with XMM-Newton, Chandra, and Suzaku have brought high-quality data that include detailed information about physical conditions of matter where high-energy phenomena are taking place. However, improvement of data quality simultaneously require accurate and precise astrophysical models for interpretation of the data. In the era of Astro-H, this requirement will become more essential. →We have to solve a problem of radiative transfer precisely.

Approaches to radiative transfer problems

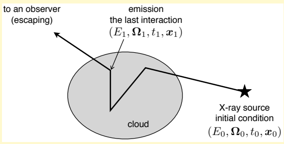
$\tau \ll 1$	$\tau \sim 1$	$\tau \gg 1$
optically thin	**reprocessing of photons**	optically thick
easy	We must treat • discrete process • competing processes • multiple interactions moreover, it depends on geometry	statistical approach continuous approximation diffusion approximation → partial differential equation (e.g. Kompaneets equation) blackbody if very thick e.g. standard dick

optical thickness

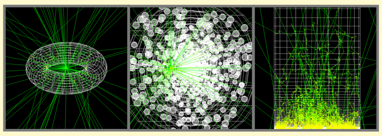
Monte Carlo approach

The MONACO framework

MONACO (Monte Carlo simulation for astrophysics and cosmology) is a multi-purpose framework to calculate X-ray radiation from astrophysical objects based on Monte Carlo simulation (Odaka et al. 2011, ApJ, 740, 103). In a single simulation trial, a photon starts at the X-ray source and is tracked until it escapes from the system. The last interaction is regarded as an emission seen by the observer.



Schematic drawing of a single simulation trial.



Visualization examples of MONACO simulations: AGN torus, clumpy stellar wind, & accretion column.

Comptonisation

Inverse Compton scattering by hot electrons or nonthermal electrons plays an important role in generating X-ray radiation in accretion flows. This process can be considered as photon reprocessing in a plasma. Although it is well known that the Kompaneets Equation or its extension gives the solution of Comptonisation, Monte Carlo simulations become a suitable approach if the system has complicated geometry or is not thick enough for modelling by the differential equation.

The target electrons can have not only thermal motions but also bulk motions in an accretion flow. We therefore developed an algorithm to calculate Compton scattering by a target electron that has both thermal and bulk motions. This algorithm uses two-step Lorentz transformations from the observer's frame to the electron's rest frame (see below). This method is nicely fitted to the Monte Carlo tracking.

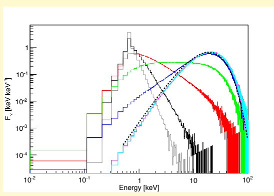
Calculation of Compton scatting using Lorentz transformation

Lab frame	Bulk motion's frame	Target electron's frame
• determine the next interaction point • see the bulk motion	• select the target electron • see the thermal motion	• calculate scattering by a rest electron

$$p^{\mu} \xrightarrow{\text{Lorentz transformation}} p'^{\mu} \xrightarrow{\text{Lorentz transformation}} p''^{\mu}$$

$$p_1^{\mu} \longleftarrow p_1'^{\mu} \longleftarrow p_1''^{\mu}$$

Magnetic field effects can be included.

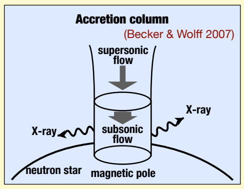


Comptonisation spectra with different Thomson depths of spherical plasmas calculated by MONACO. The thickest case agrees with a theoretical curve of a saturated Comptonization, which is given by the Wien spectrum (dashed).

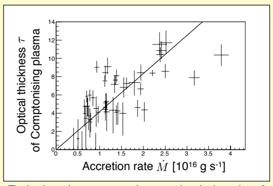
Accretion Flow onto a Neutron Star

(Odaka et al. 2013, ApJ, 767, 70; Odaka el al. 2014, ApJ, 780, 38)

Accreting neutron stars in high mass X-ray binaries provide us with ideal laboratories for studying accretion mechanism in a strong magnetic field. However, it is still difficult to obtain physical information on the accretion flow since the X-ray radiation mechanism and physical relations between the accreted plasma and the radiation are poorly understood. We therefore attempt to build a physical radiation model of a columnar accretion flow onto a magnetised neutron star in the framework of thermal and bulk Comptonisation.

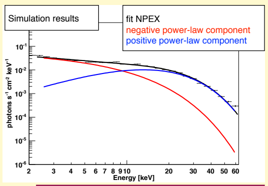


Before modelling in detail, we first applied pure thermal Comptonisation model to broadband X-ray data of Vela X-1 obtained with *Suzaku*. The time variability of the spectral parameters extracted from the data shows nice agreement with the Comptonisation model. Moreover, based on the model, we found positive correlation between the optical thickness of the plasma and the mass accretion rate. This natural physical relation supports that thermal Comptonisation plays an important role in generating the X-ray emission.



Relation between the optical depth of the accreted plasma and the mass accretion rate extracted from the *Suzaku* data of Vela X-1. Each data point corresponds to a short 2 ks exposure spectrum sliced from the whole observation (140 ks).

Then, we performed detailed calculation of the accretion column model that includes effects of the magnetic field. The simulation with realistic model parameters nicely reproduced an observational feature of X-ray pulsars with a photon index of about 1.0 and quasi-exponential cutoff. We successfully extracted physical parameters of the accretion flow; particularly we found the column radius to be a few hundred metres (see table below).



Conditions (assuming Vela X-1)
Electron temperature: 6 keV
Seed photon: thermal bremsstrahlung
Column radius: 200 m
Magnetic field: 2×10^{12} G
Luminosity: 4.5×10^{36} erg s^{-1}

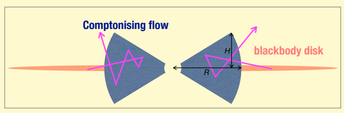
Table 5
The Self-consistent Solutions of the Accretion Column Spectrum

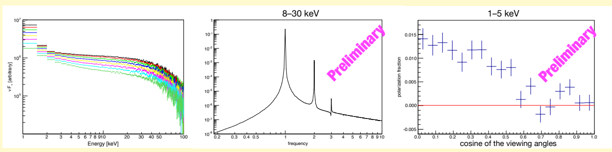
$L_{\rm obs}$ (erg s^{-1})	r_0 (m)	L_0 (erg s^{-1})	A_1 (ph s^{-1} cm^{-2} keV^{-1})	Γ	A_2 (ph s^{-1} cm^{-2} keV^{-1})	E_f (keV)	L_X (erg s^{-1})	A_2/A_1
1.5×10^{36}	150	9.19×10^{35}	3.4×10^{-2}	0.58	0.0	17	1.2×10^{36}	0
3.0×10^{36}	150	1.68×10^{36}	5.3×10^{-1}	0.34	2.9×10^{-4}	6.6	3.0×10^{36}	5.5×10^{-4}
4.5×10^{36}	200	2.37×10^{36}	5.5×10^{-1}	0.17	4.4×10^{-4}	6.6	4.4×10^{36}	8.0×10^{-4}
6.0×10^{36}	300	3.51×10^{36}	6.7×10^{-1}	0.03	4.4×10^{-4}	6.9	6.2×10^{36}	6.6×10^{-4}

Accretion Flow onto a Black Hole

(Odaka, Done et al. in preparation)

The same framework of the Comptonisation calculation is applicable to a black hole accretion flow. Thermal Comptonisation is the main radiative process in the low/hard state of a black hole binary, but the physical properties and geometry of the accretion flow are still unclear. We investigate X-ray properties of black holes using Monte Carlo simulations, assuming the truncated disc-hot inner flow geometry (Narayan & Yi 1995; Done, Gierlinski & Kubota 2007).





Left: Comptonisation spectra observed from different viewing angles.
Middle: simulated power spectrum showing quasi-periodic oscillation (QPO) on the assumption of the Lense-Thirring precession (Ingram, Done & Fragile 2009) of the accretion flow.
Right: polarisation fraction as a function of (cosine of) the viewing angle. Photon polarisation can also be calculated at scatterings in the Monte Carlo simulation.
Conditions: *H*/*R* = 0.3, electron temperature = 14.8 keV, radial Thomson depth = 8.0