

Development of general relativistic radiative transfer code based on ray-tracing: CARTOON

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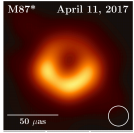
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Black Hole Astrophysics with VLBI: Multi-Wavelength and Multi-Messenger Era (2021/1/18~20 @ICRR)

Introduction & Aim of this work

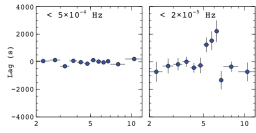
■ Phenomena caused by general relativistic effect

Black hole shadow



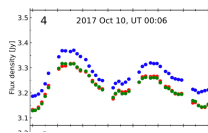
EHTC,2019

Reflection spectrum



Zoghbi+2012

Light curve



Iwata+2020

■ In order to understand such phenomena, it is needed to calculate

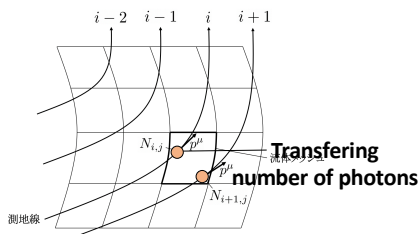
- a time variation on a **short time scale**.
- photon propagation **with high-resolution near event horizon**.
- radiation fields accurately **both in optically thick and thin regime**.

In this work, we develop new general relativistic radiative transfer code to solve the radiation field more accurately in curved spacetime by improving ARTIST code (Takahashi & Umemura, 2017)

Method

■ Algorithm of our new code (CARTOON)

: Calculation code of Authentic Radiative Transfer based On phOton Number conservation in curved spacetime



p^μ : four momentum of photon
 $N_{i,j}$: photon number of each points
 dV : volume of each fluid grid
 ※ "hat" (^) denotes values on ZAMO frame.

- Calculate geodesics in whole computational domain:

$$\frac{dx^\mu}{d\lambda} = p^\mu, \quad \frac{dp^\mu}{d\lambda} = -\Gamma^\mu_{\alpha\beta} p^\alpha p^\beta$$
- Solve the general relativistic radiative transfer equation along geodesics based on the photon conservation method which is newly developed.

Strong points of CARTOON

- CARTOON **guarantees the conservation of photon number**.
- CARTOON **treats general relativistic effects accurately**(light bending and gravitational redshift).
- CARTOON can calculate a radiation field **independently of the optical thickness of the medium**.

Summary

- We develop novel general relativistic radiative transfer code: CARTOON by improving ARTIST code and **some radiation propagation tests are accurately solved by CARTOON**.
- We will apply this code to calculate **reflection spectrum** by accretion disk to estimate a **BH spin and dynamics of accretion flow near event horizon**.

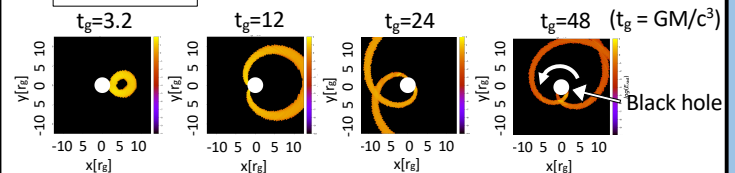
Test calculations

■ Set up

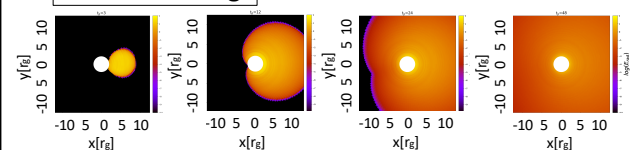
- Initially isotropic radiation field at $(x,y,z) = (6.0,0.0,0.0)$
- BH spin $a = 0.5$

■ 2D radiation propagation test

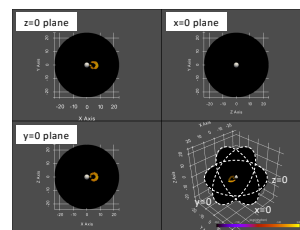
in vacuum (Color denotes radiation energy density.)



with scattering



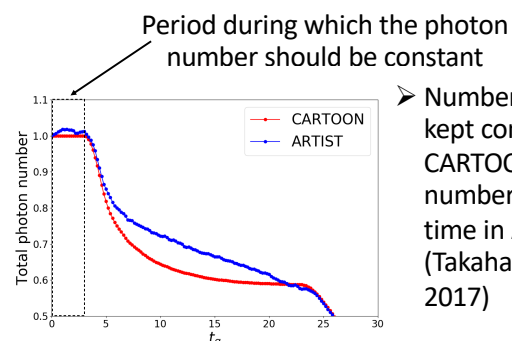
■ 3D radiation propagation test



- Radiation propagation is accurately solved in both 2D and 3D space by CARTOON. (cf. analytic solution of wavefront by Hanni(1977))

■ Accuracy of calculation

- Time variation of photons



- Number of photon is kept constant by CARTOON, but photon number changes with time in ARTIST (Takahashi & Umemura, 2017)