Parallel Computing In High Energy Astrophysics: Combining Microlensing and Black Hole Ray-Tracing

Bin Chen, Xinyu Dai, Eddie Baron, and Ronald Kantowski
Department of Physics & Astronomy, University of Oklahoma
440 W Brooks St Room 100, Norman, Oklahoma 73072
Email: bchen@ou.edu

Abstract—**Gravitational lensing is an important probe in cosmology and astrophysics. In particular, quasar microlensing strongly constrains the geometry of the high-energy X-ray emitting regions of active galactic nuclei (AGNs) which are very close to the central supermassive black hole powering the AGNs. The X-ray emission of a microlensed quasar is lensed by both the background supermassive black hole and the thousands (to millions) of random stars in the foreground lens galaxy. Parallel ray-tracing is an ideal tool to compute the image and light curve of a X-ray corona lensed by the black hole and foreground random stars. We present two parallel ray-tracing codes recently developed by our group to study strong lensing of AGN X-ray emission by Kerr black holes and microlensing by foreground lens galaxies, and a numerical scheme to combine microlensing with black hole lensing. We discuss the unique constraints on AGN X-ray emission sizes obtained by our computer programs.**

I. Microlensing and Kerr Black Hole Lensing

Gravitational microlensing was first discovered in QSO 2237+0305 [1] and has become an important astrophysical probe. In particular, recently developed Bayesian Monte-Carlo techniques [2] together with emerging high quality observational data [3] is making quasar microlensing a unique tool for probing the innermost structure of accretion disks. The ensemble of microlensing stars in foreground lens galaxies produces a magnification pattern in the source plane, and as the source moves across this pattern, the source magnification varies with time. The time varying microlensing magnification depends on the size of the emission source with larger emission regions smooth the magnification patterns more heavily and have less microlensing variability than smaller emission regions. The sizes of quasar X-ray emission regions were recently constrained to be $\sim 10\, r_g$ ($\equiv GM/c^2$; gravitational radii) of the central supermassive black hole [4], [5], [6].

The lensing effects of a Kerr black hole (a black hole with angular momentum) on accretion disks were predicted decades ago [7], and the relativistic distortion of the AGN Fe Kα line emission has been discovered [8]. It is much more difficult to detect the relativistic effect of the black hole on the observed X-ray continuum emission. The magnification to the observed X-ray flux is degenerate with the (unknown) intrinsic X-ray luminosity, whereas the modulation of the X-ray spectra by wavelength-dependent Kerr lensing is degenerate with other effects, in particular, absorption [9]. A new method to probe the effect of Kerr strong gravity is to study the inclination dependence of the AGN X-ray to optical flux ratio, given that the optical emission region is much larger than the X-ray emission and consequently the black hole lensing effect on optical emission is insignificant, and that Kerr lensing is strongly inclination dependent [10]. We propose another new method to probe the effect of the Kerr black hole on AGN X-ray emission by combining traditional quasar microlensing techniques with Kerr strong lensing analysis [11].

The traditional interpretation of quasar X-ray microlensing observations assumes a flat spacetime for the source plane. When the X-ray source is within a few r_g of the central supermassive black hole, both the flux profile and images of the X-ray emission are significantly altered. In other words, a quasars X-ray emission is gravitationally lensed by the central black hole at the very beginning of its trip to a distant observer, well before it is lensed by any foreground mass concentrations. Strong bending and redshift effects of Kerr lensing change the shape, size, and profile of the X-ray source, all of which are input parameters for foreground microlensing. The constraints obtained from current quasar X-ray microlensing should therefore be expanded by including Kerr gravity. Because Kerr lensing depends on important parameters such as inclination angle, black hole spin, and the velocity flow of the X-ray sources, quasar microlensing might become an even more powerful tool in probing the innermost region of AGNs.

II. Combining Microlensing Ray-Tracing with Kerr Black Hole Ray-Tracing

In [11] we have shown that for normal quasar gravitational lensing systems at cosmological redshifts an "effectively flat" source plane between the background quasar and the foreground lens plane can be conveniently defined as the interface between Kerr ray-tracing and microlensing ray-tracing, i.e., as the ending point of the backward microlensing ray-tracing and the starting point of the backward Kerr ray-tracing. We also showed that the parallel light approximation is adequate for Kerr ray-tracing. This makes it possible to generate the image of Kerr lensing and the microlensing magnification pattern independently in this source plane, and significantly reduces the computing time. To combine Kerr lensing with microlensing all we need is a fast ray-tracing code for both Kerr black hole lensing and microlensing.

In standard linearized lensing theory photons travel along straight lines, except at the lens plane where bending happens instantaneously. The time consuming part in generating microlensing magnification patterns in the source plane is adding bending angles caused by all the random stars (from a few tens to tens of thousands). Algorithms based on a hierarchical tree code [12] or Fourier transforms [2] have been developed to improve the speed of this process. For example, gains in CPU-time of factors of $\sim$1000 can be reached for $\sim 10^6$ microlenses using the tree code compared with a direct summation the deflection angles. A modern way to speed up microlensing ray-tracing is parallel computing, or using parallel hardware such as GPU [13]. The ability for astronomers to acquire a large number of simulated microlensing magnification patterns spanning a high dimensional parameter space is critical for using microlensing techniques to probe either quasar accretion disks or cosmological parameters, given that thousands of new lenses are expected to be discovered by next generation all-sky surveys such as LSST. Consequently, parallel computing and GPU ray-tracing will play an important role in high energy astrophysics in the next two decades.

In contrast to microlensing ray-tracing where the bending angle needs to be computed only once for each ray, in Kerr lensing it can take a few hundred steps to trace a ray from a distant point (e.g., $r_{\rm obs} = 10^6 r_g$) to a point on the accretion disk near the black hole with desired accuracy. We used a $5^{\rm th}$ order Runge-Kutta algorithm with adaptive step-size control in our backward ray-tracing code. It takes $\sim 1800\,{\rm sec}$ to generate a single image of a Kerr-lensed accretion disk of radii $r \sim 20 r_g$ with resolution 2000×2000 using an *Intel* i7 processor. The parallel speed up is summarized in Table I. The lensed image of an accretion disk depends on the inclination angle of the observer, the spin a of the black hole, and the velocity and intensity profiles of the accretion flows. Consequently, to measure these parameters via Kerr+Micro lensing analysis, a large number of Kerr-lensed images need to be generated. For example, even assuming a fixed geometry, velocity, and intensity profile for the accretion disk, to constrain the disk size (from a few to hundreds of r_g), inclination angle θ, and black hole spin a simultaneously through microlensing, $n_r \times n_\theta \times n_{\rm a}$ images need to be generated through Kerr ray-tracing. Parallel computing is clearly needed for such simulations.

The good news is that microlensing and black hole ray tracing can be done independently and combined seamlessly [11], and both ray-tracing problems are *embarrassingly parallel*. Furthermore, GPU ray-tracing is practical and highly desired for both cases [14], [15]. We have developed a parallel Kerr black hole ray-tracing code in [10] and a parallel microlensing ray-tracing code in [11] using the hybrid OpenMP+MPI algorithm. We expect a speed up by a factor of at least 10 using GPU ray-tracing.

III. CONCLUSIONS

As an application of our Kerr+Micro lensing ray-tracing code, we first compare the theoretical microlensing light curves with/without Kerr strong lensing. We find that X-ray microlensed light curves incorporating Kerr strong gravity can differ significantly from standard curves. The amplitude of the fluctuations in the light curves can increase or decrease by $\sim$0.65–0.75 mag by including Kerr strong gravity. Consequently, current X-ray microlensing observations can under or overestimate the sizes of the X-ray emission regions. We estimated this bias and found that the size of the X-ray emission region can be underestimated by up to $\sim$50% or overestimated by up to $\sim$20% depending on the spin of the black hole, the disk inclination angle, and the emission profile. We conclude that more accurate microlensing size constraints should be obtainable by including Kerr lensing, and that it should be possible to constrain important parameters such as inclination angles and black hole spins from combined Kerr and microlensing effects. We plan to combine our Kerr lensing code with the Bayesian Monte Carlo simulation code, apply it to observed light curves of lensed quasars, and constrain important parameters such as black hole spin and disk inclination angles in the future. High performance parallel computing will be further implemented in this future project.

TABLE I. SCALABILITY OF THE KERR BLACK HOLE RAY-TRACING CODE FOR AN DISK OF RADIUS $20\,r_g$ WITH RESOLUTION 2000×2000. THE SCALING IS NOT PERFECTLY LINEAR MAINLY BECAUSE OF THE COST OF SAVING A LARGE ARRAY OF DATA NEEDED FOR OUR ANALYSIS, IN PARTICULAR, DIAGNOSING DATA FOR THOSE RAYS FALLING INTO THE BLACK HOLE.

No. Processors	1	2	4	8	16	32
Speed ($\times$3200 rays/s)	1	1.8	3.5	7.0	13.6	27

ACKNOWLEDGMENT

The authors would like to thank the Univ. of Oklahoma supercomputing center for allocation of computing time.

REFERENCES

[1] M. J. Irwin, et al., "Photometric variations in the Q 2237+0305 system-First detection of a microlensing event," *Astron. J.*, Vol. 98, pp. 1989, 1989.

[2] C. S. Kochanek, "The Structure of the X-Ray and Optical Emitting Regions of the Lensed Quasar Q 2237+0305," *Astrophys. J.*, Vol. 605, pp. 58, 2004.

[3] B. Chen, et al., "X-ray Monitoring of Gravitational Lenses with Chandra," *Astrophys. J.*, Vol. 755, pp. 24, 2012.

[4] C. W. Morgan, et al., "Further Evidence that Quasar X-Ray Emitting Regions are Compact: X-Ray and Optical Microlensing in the Lensed Quasar QJ 0158-4325," *Astrophys. J.*, Vol. 756, pp. 52, 2012.

[5] A. M. Mosquera, et al. "The Structure of the X-Ray and Optical Emitting Regions of the Lensed Quasar Q 2237+0305," *Astrophys. J.* Vol. 769, pp. 53, 2013.

[6] J. A. Blackburne, et al., "The Structure of HE 1104-1805 from Infrared to X-Ray," *Astrophys. J.*, submitted, arXiv1304.1620, 2013.

[7] J. M. Bardeen, "Rotating Black Holes: Locally Nonrotating Frames, Energy Extraction, and Scalar Synchrotron Radiation," *Astrophys. J.* Vol. 178, pp. 347, 1972

[8] Y. Tanaka, et al. "Gravitationally redshifted emission implying an accretion disk and massive black hole in the active galaxy MCG-6-30-15," *Nature*, Vol. 375, pp. 659, 1995.

[9] L. Miller et al., "An absorption origin for the X-ray spectral variability of MCG-6-30-15," *A&A*, Vol. 483, pp. 437, 2008.

[10] B. Chen, et al., "Inclination-Dependent AGN Flux Profiles from Strong Lensing of the Kerr Spacetime," *Astrophys. J.*, Vol. 762, pp. 122, 2013.

[11] B. Chen, et al., "Effects of Kerr Strong Gravity on Quasar X-ray Microlensing," *Astrophys. J.*, Vol. 769, pp. 131, 2013.

[12] J. Wambsganss, "Gravitational lensing: numerical simulations with a hierarchical tree code," *J. Comput. Appl. Math*, Vol. 109, pp 353, 1999.

[13] N. F. Bate and C. J. Fluke, "A Graphics Processing Unit-enabled, High-resolution Cosmological Microlensing Parameter Survey," *Astrophys. J.*, Vol. 744, pp. 90, 2012.

[14] G. Vernardos and C. J. Fluke, "A new parameter space study of cosmological microlensing," *Mon. Not. R. Astron. Soc.*, Vol. 434, pp. 832, 2013.

[15] D. Kuchelmeister, et al., "GPU-based four-dimensional general-relativistic ray tracing," *Comput. Phys. Commun.*, Vol. 183, pp. 2282, 2012.