Astro2020 Science White Paper

QUASAR MICROLENSING: REVOLUTIONIZING OUR UNDERSTANDING OF QUASAR STRUCTURE AND DYNAMICS

Thematic Area: ☒ Galaxy Evolution

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Abstract: Microlensing by stars within distant galaxies acting as strong gravitational lenses of multiply-imaged quasars, provides a unique and direct measurement of the internal structure of the lensed quasar on nano-arcsecond scales. The measurement relies on the temporal variation of high-magnification caustic crossings which vary on timescales of days to years. Multiwavelength observations provide information from distinct emission regions in the quasar. Through monitoring of these strong gravitational lenses, a full tomographic view can emerge with Astronomical-Unit scale resolution. Work to date has demonstrated the potential of this technique in about a dozen systems. In the 2020s there will be orders of magnitude more systems to work with. Monitoring of lens systems for caustic-crossing events to enable triggering of multi-platform, multi-wavelength observations in the 2020s will fulfill the potential of quasar microlensing as a unique and comprehensive probe of active black hole structure and dynamics.

Quasars are powered by the accretion of matter onto a supermassive black hole (SMBH; black holes with mass exceeding ~$10^6 M_\odot$). Their central engines radiate via a range of mechanisms that span several orders of magnitude in physical size, from the inner thermal accretion disk and X-ray corona to the broad emission line region (BELR) and relativistic jets, as shown in **Figure 1**. At their cosmological distances, we observe this complex structure on sub-microarcsecond scales, making direct resolution an extraordinary challenge. Nevertheless, a detailed understanding of quasar physics has profound scientific benefit: their emission processes can serve as (often unique) laboratories for extreme physics; they have are one of our most powerful probes of the early universe; and they are an important driver of galaxy evolution and enrichment, cosmic star formation, and perhaps even reionization.

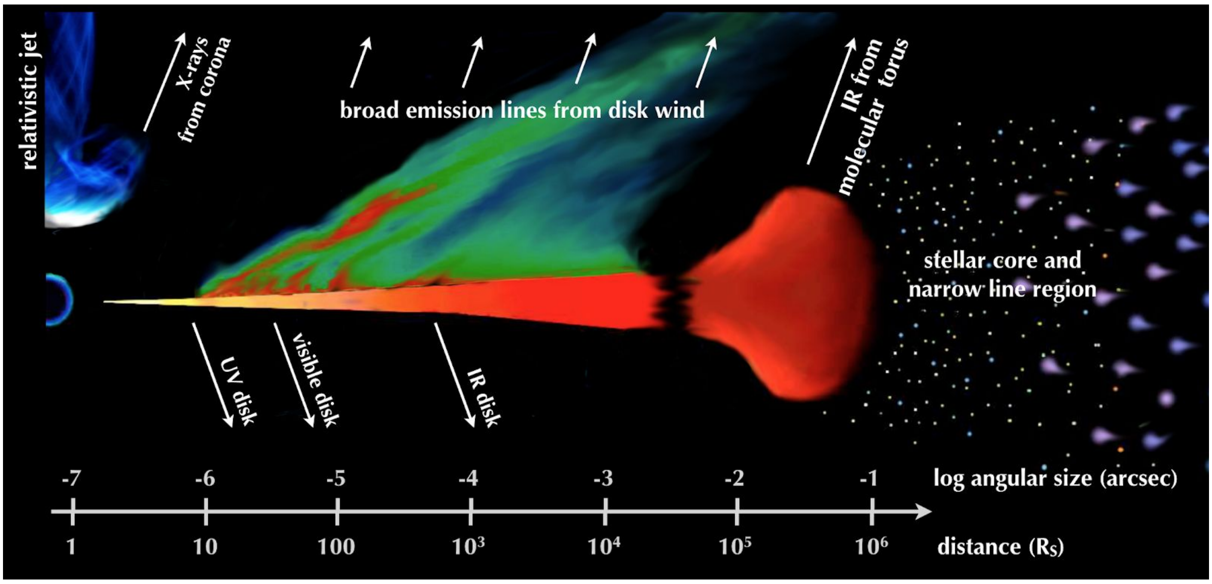

Figure 1. Quasar cross-section in log scale, with distance given in gravitational radii of central SMBH and log angular size for a typical luminous quasar at z=1 with black hole mass $10^8 M_\odot$. (Adapted from images by Martin Elvis and Daniel Proga).

Microlensing of strongly-lensed quasars (**Figures 2 & 3**) provides us with a technique capable of characterizing the internal structure of black hole environments over orders of magnitude ranges of scale. In this paper we outline the motivation and observational needs to fully exploit this technique. There are similarities in strategy to what will be required for gravitational-wave multi-messenger follow-up observations, and there may be an opportunity for coordinating the communities.

Cosmological microlensing: Although the central engines of quasars are unresolveable by foreseeable telescopes, these structures may be tomographically mapped when they are strongly-lensed into multiple images by a massive foreground galaxy. The effect of individual stars within the lensing galaxy and along the line of sight of each distinct lensed image of the quasar, results in a grainy but dramatic substructure that varies on nano-arcsecond scales in the plane of the quasar and that can lead to order unity or greater differential magnifications. This results in size-dependent differential microlensing of the central engine. Furthermore, this is not a static screen. Due to the relative transverse velocities of the quasar and lensing galaxy from our point of view, as well as the general motion of the stars within the lensing galaxy, these patterns constantly shift, resulting in secular magnification changes in each lensed quasar image (**Figure 3**).

Figure 2. Hubble Space Telescope images of three representative four-image strongly-lensed quasars, illustrating the types of objects that produce cosmological microlensing. A 1-arcsecond angular scale bar is shown in each panel. The intrinsic variability of the lensed quasar will appear in each of the four images with a time-delay that is set primarily by the gravitational profile of the lensing galaxy, and the relative distances. Each lensed image will feature additional magnification changes through microlensing by the screen of stars within the lensing galaxy, along each image's line of sight. This is the signal discussed here.

Using multi-wavelength observations of multiple caustic-crossing events, it is possible in principle to reconstruct the two-dimensional structure of the emitting regions corresponding to each wavelength. Due to the magnifications involved (**Figure 3)**, the angular sizes resolved correspond to physical scales of a few Astronomical Units (**Figure 1)**. With observations at corresponding wavelengths, it becomes possible to measure the inner radius of the accretion disk, as well as its overall structure and environment. These are related directly to the black hole mass and spin. By identifying and tracking multiple such events in a large sample of lensed quasars, it will be possible to address a series of fundamental questions about the nature of accreting supermassive black holes, including:

- The mass and spin distribution of SMBHs.
- The relationship between SMBH mass and growth rate.
- Quasar accretion efficiency through the accretion disk temperature gradient.
- Whether re accretion disks are uniform, or exhibit structural complexity.
- Whether General Relativity is an accurate description of SMBHs.

In addition to the quasar physics, there is speculation that features in such systems may be calibratable to known physical sizes or luminosities, in particular from the dust-sublimation distance, which may become a new standard rod or standard candle. There is already tantalizing work in this direction (e.g. Lusso+Risaliti 2017).

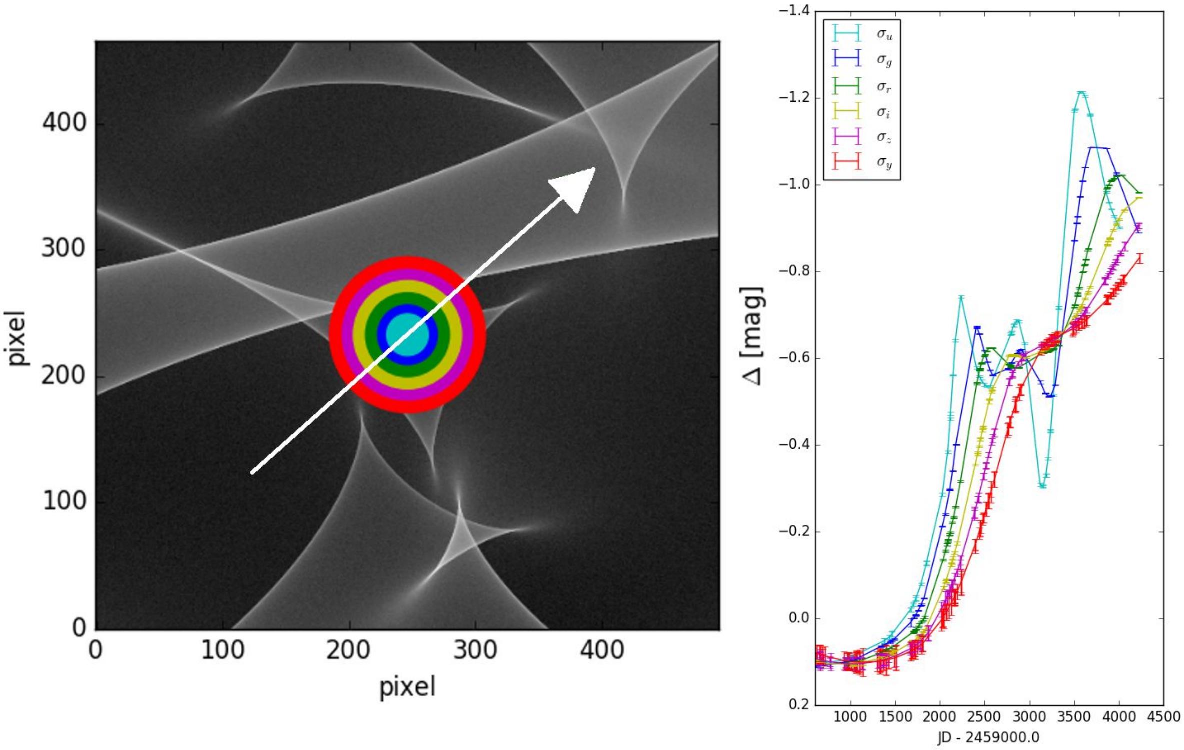

Figure 3. Adapted from Marshall+2017. Ten year long simulated light curve for image A of RXJ1131-1231. The left panel shows the concentric Gaussian emission regions observed by on the 6 LSST filters projected on top of the magnification pattern. The right panel shows the extracted light curves interpolated at epochs observed by LSST according to one (baseline) simulated observing strategy.

Insights to date: Since the discovery of the first gravitational lens in 1979 (Walsh+1979) of the two-image lensed quasar Q0957+561, there have been numerous concerted efforts to monitor such systems. Microlensing by the lens-galaxy stars is routinely detected (Irwin+1989, Anguita+2008, Morgan+2010), and indeed is a systematic that must be accounted for when the primary goal of monitoring is to measure time delays between images towards Hubble constant measurements (Eigenbrod+2005, Suyu+2017). To date, the following main breakthroughs in quasar physics measurements that have been accomplished:

- Constraints on some accretion disk sizes and temperature gradients revealing possible tension with the standard Shakura-Sunyaev profile (e.g. Blackburne+2011, Bate+2018);
- Constraints on the geometry and kinematics of a broad-emission line region (e.g. O'Dowd+2015, Sluse+2012);
- Measurements of X-ray corona geometry (e.g. Morgan+2008, Dai+2010).

Our community recognizes that the cadence, photometric precision, spectroscopic information and wavelength range of the observations possible to date are not up to the challenge of disentangling the full complexity of microlensing signals, but that these are all areas that can be tackled this coming decade, with great promise.

The gold-standard microlensing experiment is an high-cadence, multi-wavelength observation of a quasar under a caustic-crossing event--the transit of an high-magnification caustic due to an individual star across the background source. The nano-arcsecond gradient of such a curve scans the central engine structure with resolution on the scale of the SMBH event horizon. Observation of several such events would produce a rich dataset for mapping quasar structure. In practice, quasars are variable objects, and the intrinsic variability itself depends on wavelength. By virtue of the multiple imaging in these systems, however, the same overall monitoring campaign required to trigger caustic-crossing event observations will provide the difference in arrival time for light between each lensed image, so that the intrinsic-variation behavior can be separated from the caustic-crossing microlensing magnification changes. Photometric and spectroscopic monitoring can also map emission line time delays which can be used for reverberation mapping -- a complimentary measurement. Interpretation of reverberation mapping time delays relies on a suitable physical model for the quasar (Peterson 1993).

The greatest challenge to the micro-lensing experiment is the timescales involved. The median Einstein crossing time (where ~1 caustic-crossing event is expected) within a single lensed quasar image is approximately once every 20 years (Mosquera & Kochanek 2011). Even the most dramatic overachiever known today, “Huchra’s Lens” Q2237+0305 with an unusually high caustic-crossing frequency (up to 6 per decade considering all four lensed images; Wyithe+2000) has eluded comprehensive follow-up due to the challenges of traditional monitoring. For this reason, efforts to date have relied on statistical inference based on single- or few-epoch observations during high-magnification events, and photometric light-curves of low-magnification fluctuations.

What the 2020s holds: Today, approximately a few dozen bright four-image lensed-quasar systems are known. By the mid-2020s, due to both ground- and space-based wide-field surveys including Dark Energy Survey, DESI, LSST and *Euclid*, at least *hundreds*, perhaps 1000s of bright and robustly modellable systems will be found (e.g. Oguri & Marshall 2010). LSST will monitor the entire southern observable sky with a cadence of about 80 times per annum (Ivezic+2018), giving us a decade of “free” monitoring of these lensed quasars (**Figure 2**). The rate of detected caustic-crossing events is expected to be in the hundreds per year, many for bright sources.

The quasar microlensing community is faced with a powerful set of challenges if we are to make optimal use of this upcoming flood of data. These challenges include:

1) Selection of a target sample of lensed quasars, to create a statistically significant set of sources that will represent a meaningful span of properties such as black hole mass, luminosity, orientation, and internal kinematic behavior. With a large enough sample, it would be desirable to represent multiple cosmic look-back times, as well.

2) Development of a practical set of target-of-opportunity (TOO) targets drawn from the full sample above, and follow-up programs, both imaging and spectroscopic, spanning the EM spectrum. We must also ensure that the necessary facilities, instruments, and observing configurations are in place. Such resources will likely be increasingly available to respond to gravitational wave multi-messenger events. The microlensing program can supplement and complement such infrastructure.

3) Computational facilities and analytic tools must be in place to deal with these data. Of particular importance is the development of real-time light-curve analysis techniques that give us absolute confidence in our TOO triggers for caustic crossing events, and which also to derive maximum information from the full 10-year light-curves.

4) Human resources must be in place to ensure that these opportunities are fully realized.

Conclusion: Gravitational microlensing of multiply-imaged quasars has proved its potential to resolve the nano-arcsecond structure of quasar central engines. The ultimate promise of the technique is full tomographic mapping of their structure. However, to achieve this goal, a statistically large number of quasars must be monitored through high-magnification caustic-crossing events. The next generation of wide-field survey is expected to bring this promise to fruition as they detect up to hundreds of such events per year. However, a number of challenges must be met in order to take full advantage of this opportunity. We must: understand which quasars and events are desirable candidates for follow-up; prepare proposals and instrumentation for multi-platform follow-up spanning the EM spectrum; develop computational techniques and facilities to analyze a huge and complex data set in real time; recruit and train the personnel needed for this challenging endeavour. If these challenges can be met, then by the end of the 2020s we expect a detailed geometric and kinematic model of quasar central engines spanning the full range of emission properties. With this depth of understanding, quasars will become powerful laboratories of extreme physics and even more powerful cosmological probes; moreover their important role in cosmic evolution will be greatly clarified.

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