論文の内容の要旨

論文 題目 Subaru Telescope Adaptive Optics Observations of Gravitationally Lensed Quasars in the Sloan Digital Sky Survey
(すばる望遠鏡補償光学系によるSDSS 重力レンズクェーサーの観測的研究)

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This work presents the results of an imaging observation campaign conducted with the Subaru Telescope adaptive optics (AO) system (IRCS+AO188) on the gravitationally lensed quasars discovered through the SDSS Quasar Lens Search (SQLS) project in the Sloan Digital Sky Survey (SDSS) database. Eighteen confirmed gravitationally lensed quasars and 2 candidates were observed either with a natural or a laser guide star (LGS), effectively doubling the number of SQLS lensed quasars with available high-resolution images. Sixteen of the confirmed systems are two-image quasars, one is likely to be three-image, and one is a four-image lensed quasar. Two other back-up objects were observed without AO.

The purposes of the high resolution observations are to provide accurate astrometry and relative photometry in the near-infrared, which are used to obtain accurate lensing models and masses inside the Einstein radii, to derive robust morphology for the lensing galaxies, to study (if detected) the quasar host galaxies at high redshift ~ 2, and to check if high-resolution images reveal previously unseen features, as well as quantify the effects of these features.

For the majority of the systems, a suitable Point Spread Function (PSF) star did not enter the field of view of the camera, and therefore nearby bright stars observable with the same AO configuration (i.e. located at same distance from a tip-tilt star of similar brightness to the tip-tilt star of the target) were observed separately. Due to rapid temporal changes in the atmospheric turbulence characteristics, which introduced changes in the AO response, these stars were proven to be poor PSF estimates. As a result, a new method for morphological fitting of AO data of gravitationally lensed quasars was introduced in this work. This consists in approximating the PSF analytically, and fitting it simultaneously to the quasar images and to the lensing galaxy (in the latter case, convolved with a Sersic profile). For the low Strehl ratios ($\lesssim 0.10$) typically obtained, it was empirically determined that the best simple analytical PSF approximation is a superposition of 2 Moffat profiles. For the systems with larger signal-to-noise, and a relatively isolated brighter image, a hybrid PSF was created where the observed brightness profile of the core is used, and the wings are replaced with analytical approximations, due to the high noise level. A variety of methods were used to obtain realistic error bars on the observed parameters, including simulations using the separately observed stars.

In addition, using the natural stretch of the quasar host galaxy into arc-like features, the host galaxy was characterized, or limits were placed on its brightness, for 5 systems. The 3 characterized hosts follow

the relations found in the literature with redshift, nuclear luminosity and black hole mass. This is the first time such study was attempted without an a-priori known PSF.

The typical achieved relative astrometry precision is ~ 1 - 2 miliarcseconds for the quasar images, but less for the lensing galaxies. This is comparable to the Hubble Space Telescope (HST) results. Based on the new astrometry, it is shown that for many systems the original low-resolution astrometry has led to unreliable mass models. Due to the necessity of modeling the PSF on the target, the morphological parameters of the lensing galaxy are typically less accurate than obtained with HST (for example, relative errors of ~ 20% for the effective radii).

By comparing several mass models such as the singular isothermal sphere plus external shear and the singular isothermal ellipsoid plus external shear, a study was conducted on the effects of environment on the mass modeling in each system. For 5 systems, it was found that the mass and light profiles of the lensing galaxy are aligned within 10 degrees, and therefore the intrinsic lens ellipticity is dominating the quadrupole. For the rest of the systems, the environment likely exerts a large influence in the form of external shear. It was shown that the tight correlation found for the elliptical galaxy lenses in the Sloan Lens ACS Survey between the mass and light ellipticity does not hold statistically for the present sample at ellipticity $e \gtrsim 0.3$. This is likely due to the larger mean ratio of the Einstein radius to the effective radius encountered in the present sample, as well as the more important environmental contribution.

By combining 6 of the systems with a large number of strong lens systems from the literature, under the assumption that the mass profile scales with the stellar mass and effective radius of each lensing galaxy, the total mass profile (dark and luminous matter) was shown to be well fitted by a power-law $\rho(r) \propto r^{\gamma}$ with best-fit slope $\gamma = -2.11 \pm 0.05$. This is in agreement with other studies based on individual samples.

The following are selected new results on individual systems:

SDSS J0819+5356, SDSS J0904+1512, SDSS J1322+1052 and SDSS J1515+1511: The host galaxy was characterized and/or its brightness constrained using a PSF built on the systems themselves (only for SDSS J1515+1511, a PSF star was available in the field). This is the first time such a technique was used. Considerations were given on the reliability of the technique.

SDSS J1001+5027: For this system with measured time delays, it was shown that the second galaxy must be a weaker perturber than inferred from its brightness, in order to avoid a negative convergence estimate, which is ruled out by the dense environment.

SDSS J1002+4449: This lensed quasar candidate was proven to be a binary quasar, based on simulations that show a lensing galaxy is not detected.

SDSS J1330+1810: In opposition to the discovery paper, it was shown that the lensing galaxy is a late-type galaxy. Also, astrometric anomalies were discovered when applying the customary singular isothermal ellipsoid plus external shear mass model. Although substructure in the form of lens galaxy satellites cannot be ruled out, a power law ($\gamma \sim 2.3$) model with a contribution from the complicated environment in the form of a third order perturbation fits the data well.

SDSS J1334+3315: This is the smallest-separation lensed quasar in the SQLS. The object was used to showcase the capabilities of the IRCS+AO188 system, and achieve accurate astrometry as well as resolve the individual objects.

SDSS J1405+0959: This is a unique new object where the AO observations have revealed dramatically more detail. A host galaxy arc in this binary lens system was discovered without a central quasar image, based on photometric redshift analysis from multi-band observations, and comparison with mass modeling. This is only the second known system discovered with such an arc. The system also likely consists of three quasar images instead of two, but this requires confirmation.

This work has shown that a large campaign to observe gravitationally lensed quasars with AO is feasible even with the lack of an a-priori known PSF. The data was used to obtain new results on individual systems, as well as used statistically in combination with other samples of objects. LGS/AO is a viable alternative to HST for the follow-up of the thousands of new lensed quasars that will be discovered by the Large Synoptic Survey Telescope and Subaru Hyper Suprime-Cam.