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SEARCH FOR MULTIPLY-IMAGED QUASARS IN THE GAIA DR2

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Abstract. Gaia was mainly designed for the study of stars in our Galaxy. However, by continuously scanning the entire sky, it also provides informations on all kind of objects that fall in its fields of view, including extragalactic objects. Amongst these extragalactic sources, quasars stand out to be some of the most peculiar objects that Gaia observe. Beside the fact that they play a crucial role in fixing the Gaia Celestial Reference Frame, they also have their intrinsic interest in cosmology. One of their important application occurs when a massive galaxy stands along the line of sight joining the quasar and the observer as, in this case, multiple images of this quasar may form. The time delays measurement between these lensed images then provide a reliable estimation of H0 that is independent of the commonly used cosmic distance ladder. We describe here how the precise relative positions and magnitudes, as provided by Gaia, can be used in order to probe the lensing nature of clusters of objects coming from the Gaia DR2. We present some newly discovered lenses that were spectroscopically confirmed in recent follow-up observations.

Keywords: Gravitational lensing: strong, Quasars: general, Astrometry, Methods: data analysis, Catalogues, Surveys

1 Introduction

Strong gravitational lenses probe many facets of cosmology: dark matter halos of galaxies, substructures in galaxy halos, the determination of the Hubble constant independently of the cosmic distance ladder, and properties of dark energy. However, their detection requires exceptional imaging capabilities, posing a challenge to present day all-sky surveys from the ground since these count on limited spatial resolution due to atmospheric seeing. Thus, the limited number of lensed systems has historically plagued many of the potential studies that can be performed with these objects, due to local systematics at the individual objects modelling. The data from the second release of ESA/Gaia Space Mission (Gaia Collaboration et al. 2018) is changing this situation dramatically. Gaia is at the present time conducting the largest and most accurate all-sky astrometric survey from space. Its main goal is to produce a three-dimensional dynamical map of the Milky Way based on the measurement of positions, parallaxes, proper motions and spectrophotometric parameters for more than one billion stars, but the instrument also detects millions of compact galaxies and QSOs (Krone-Martins et al. 2013; Ducourant et al. 2014; de Souza et al. 2014). Thus, a careful analysis of the GDR2 (Gaia Collaboration et al.

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2018) [5] presents a unique opportunity to perform the first magnitude-limited census of strongly lensed QSOs down to image separations of 0.18 ". Finet and Surdej Finet & Surdej (2016) estimated that from the 0.6 million QSOs to be observed by Gaia, about 2900 of them should be multiply imaged and resolved by the Gaia final data release including 250 systems formed by more than two lensed images. Gaia will lead to an increase in the number of known lensed QSOs by more than one order of magnitude with respect to what is known today, and will provide a unique dataset to study the individual lensed systems and to constitute a statistically significant sample for the study of the evolution of the population of the deflecting galaxies and to constrain cosmological parameters.

2 The Gaia GraL project

Since the Gaia DR2 (April 2018), the Gaia GraL (Gravitational Lenses) group has devoted large efforts to detect and extract from the Gaia DR2 a whole sky survey of new multiply imaged quasars. Our strategy is threefold.

First, our research focused on all known multiply imaged quasars by gravitational lensing. We first set up a database of 481 multiply imaged quasars (47 of these being quads with 4 images) and then searched counterparts of their components into the Gaia DR2. 172 lenses are detected by Gaia DR2 and 12 quads are fully detected by the satellite. A quick modelling demonstrates the improvement of fitting with the Gaia sub-mas astrometry when compared to Hubble Space Telescope measurements (Ducourant et al. 2018) and demonstrates the great potential of Gaia for a realist modelling of these complex phenomena.

In the second step, we considered all known quasars and candidates AGNs available in the litterature that we compiled in a state-of-the-art list of 3 millions objects. We then searched for the presence in the Gaia DR2 of one or more nearby (6 arcsecond) objects. The $\sim$ 20 000 resulting clusters of sources were then filtered out to exclude galactic plane and to reject clusters with discrepant parallaxes of proper motions between the components and finally a machine learning lens classifier using astrometry has been applied to the remaining clusters to test the reproducibility of the configuration by a simple model of Gravitational Lenses (NSIE) (with noise and missing images). This left us with three good candidates each with 4 images (Krone-Martins et al. 2018).

In the third and major axis of action of our strategy, we designed a method to blindly identify clusters of sources from the DR2 using the Hierarchical Triangular Mesh technique that are compatible with gravitationally lensed quasars (Delchambre et al. 2019). The list of clusters extracted with these approaches is expected to be polluted with contaminants. To discard the most obvious ones, we thus applied soft astrometric filters derived from the behaviour of known GL (Ducourant et al. 2018) as we did in the second step, to differentiate genuine candidates from fortuitous clusters of stars. Gaia also provides broad band photometric measurements in the G-band and a colour indicator for a fraction of the not too faint objects . Because the gravitational lensing phenomenon is achromatic, we also rejected clusters for which the individual colour indicators was available and significantly differ from each other. The local density of sources around the clusters have also been calculated and clusters in too dense regions were also discarded. Then we classified the remaining clusters that successfully passed the filters by assigning them a probability that reflects the match between a candidate and the learning set composed of $\sim 10^8$ simulated image configurations that we used to build Extremely Randomised Trees. From the most probable clusters thirty appeared good candidates with 4 images. From them, 15 correspond to known lenses and 15 are unknown that require spectroscopic validation.

3 Spectroscopic validation

The GraL group has applied for observing time to several large telescopes spread over both hemisphere to spectroscopically validate the candidates. Proposal were submitted to Keck/LRIS, Palomar/P200,DOT/imager, ESO-VLT/Muse, ESO-NTT/EFOSC, SOAR, Gemini south/GMOS, AAT/KOALA and LBT/MOD1-2.

The group has have been granted of one night at Keck and 2 nights at Palomar by semester for 2018 and 2019, 2h at ESO-VLT, 3 nights at ESO-NTT in 2018 and 2019, 6h at Gemini and few hours at LBT. Preliminary reduction of these observations led to the validation of 9 quadruply-imaged quasars and several doubly imaged ones (Wertz et al. 2019). We present in Figure 1 the preliminary spectroscopic validation at ESO-NTT of GRAL165105371-041724936, one of our candidates together with the Pan-STARRS image of the system with components identified.

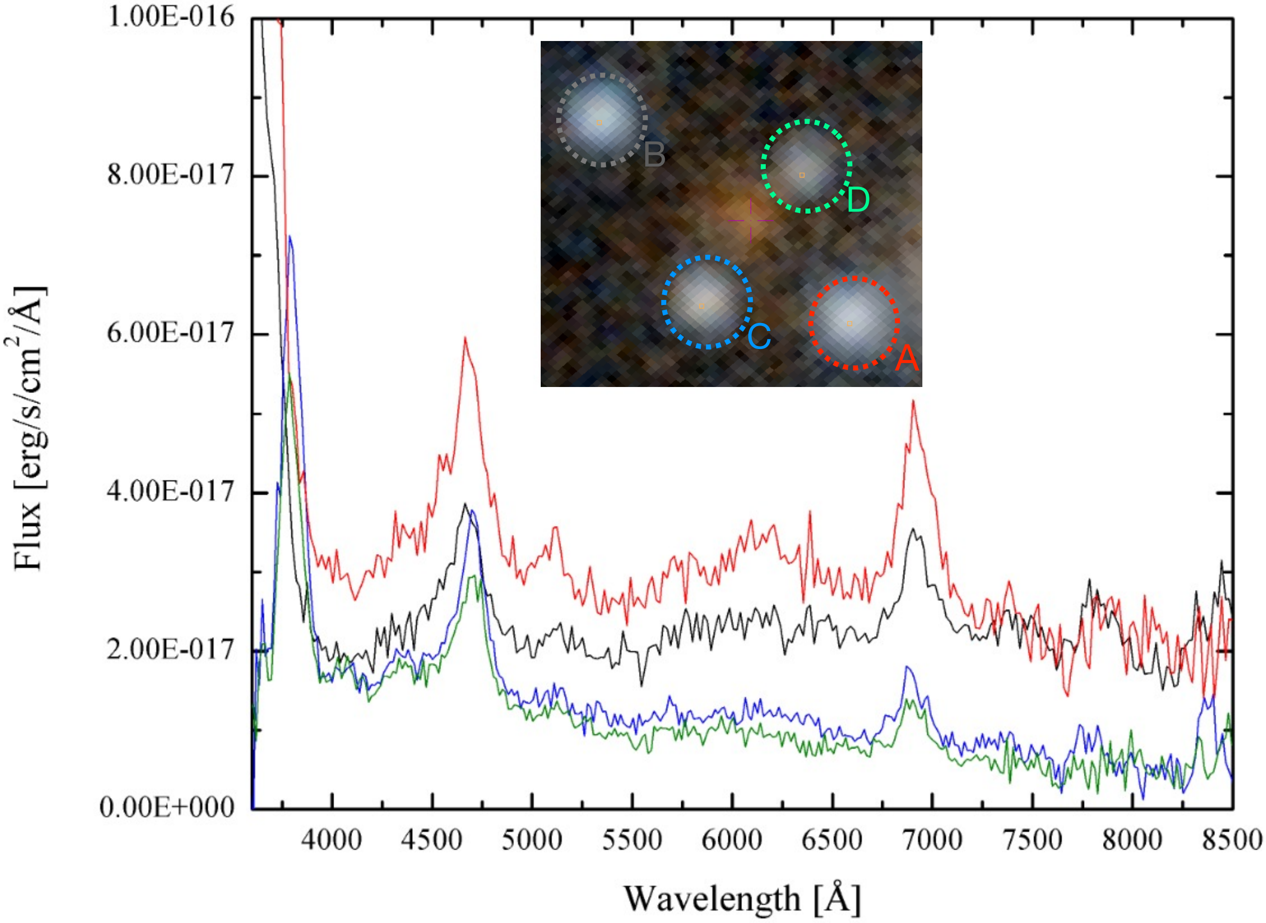

Fig. 1. GRAL165105371-041724936, a multi-imaged quasar candidate spectroscopically confirmed with NTT/EFOSC2 observations. Preliminary reduction indicates a redshift of 1.5 for the quasar. In the upper part of the spectrum is shown the Pan-StARRS image of the system with the identification of the components.

The general observational strategy of observation to reduce observing time consists in observing the candidates placing 2 components in the same slit and comparing the spectral characteristics of the components. Then another observation targets the remaining components and so forth. The spectra were processed using the IRAF package for long-slit reduction. Overscan, bias and flat were applied to all frames. No sky-flat corrections frames were available for illumination corrections. However it does not affect our results significantly, since all targets placed in the slit were very near each other (distances lower than 10 arcsec). Wavelength calibration was done using HeAr arc lamps, in slits of 1.5 and 5 arcsecs. The spectral resolution at ESO-NTT was limited by the seeing (about 1 arcsec) and the grating (smaller than 15 A), and for the observed z the velocity dispersion is lower than 1%. Flux calibration and extinction corrections were performed using spectrophotometric standards observed one night before. To recognise spectral line it was used the procedure of cross correlation of the observed spectra with an adaptation of the SDSS DR6 quasar spectral lines, with 58 emission lines. For the determination of the radial velocities of each spectra it was used the RVSAO package Kurtz & Mink (1998).

With the Keck and Palomar observations we could confirm so far the lens status of 8 quadruply-imaged quasars. With the ESO-NTT/EFOSC2 observations were able to confirm 1 new gravitational lenses with 4 images and 4 with two images., all selected from the cluster list with high ERT probability. The Gemini observations are being reduced and preliminary results indicate that probably one quad more is to be included in our list of validated lenses (Krone-Martins et al., in prep, 2019).

4 Conclusion

The Gaia GraL group has devoted large efforts, using the most advanced machine learning algorithms, to blindly extract multiply-imaged quasars from the Gaia data releases from astrometry and photometry only. Spectroscopic validation have so far shown that the method is efficient and the group is in the way to set up the first ever census of gravitational lenses (within the limitations of the Gaia instrument). The first two data releases of Gaia are known to be largely incomplete at small angular distances, where lye most multiple images of quasars. If the forthcoming Gaia EDR3 (mid 2020) is more complete to this respect we can hope to unveil a new population of these phenomena.

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