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Astrometric search for gravitational lenses in the Gaia DR2

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Abstract. The Gaia GraL (Gaia Gravitational Lenses) group has devoted its efforts to perform for the first time a whole sky census of multiply imaged quasars by analysing the Gaia DR2 (GDR2) catalogue. The first step in this direction was to produce a list of candidates based on the astrometry and photometry of GDR2 via machine learning algorithm (Extremely Randomised Tree). The best candidates were selected for confirmation by spectroscopy in observations conducted at several observatories worldwide in both hemispheres. From these observations we increased significantly the number of gravitational lens systems, mainly for quadruply imaged quasars. So far, we have confirmed 21 of these structures including 9 quadruple images. We present here a review of this search and in particular, the results achieved with recent observations using the Gemini and NTT telescopes from which we have discovered one of the most extended gravitational lens known to date.

Resumo. O Grupo Gaia GraL (Gaia Gravitational Lenses) tem dedicado seus esforços para realizar o primeiro censo completo do céu de imagens múltiplas de quasares analisando o catálogo Gaia DR2 (GDR2). O primeiro passo nesta direção foi produzir uma lista de candidatas baseada na astrometria e fotometria do GDR2 por meio de um algoritmo de aprendizagem por máquina (Extremely Randomised Tree). Os melhores candidatos foram selecionados para confirmação espectroscópica por meio de observações conduzidas em diversos observatórios distribuídos por todo o mundo nos dois hemisférios. A partir destas observações nós ampliamos significativamente o número de sistemas de lentes gravitacionais conhecidas, principalmente imagens de quasares quadruplicadas. Nós confirmamos 21 destas estruturas, incluindo 9 imagens quadruplas. Nós apresentamos aqui uma revisão desta busca, em particular apresentando os resultados d e observações recentes utilizando o Gemini e o telescópio NTT, onde descobrimos uma das mais estendidas lentes gravitacionais conhecidas até o momento.

Keywords. Gravitational lensing: strong – Techniques: spectroscopic – Astrometry – Quasar – Catalog

1. Introduction

Strong gravitational lenses probe many facets of cosmology: dark matter halos of galaxies, sub-structures 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 2016) 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 (Robin et al. 2012, Krone-Martins et al. 2013 and de Bruijne et al. 2015). Thus, a careful analysis of the GDR2 Gaia Collaboration (2018) 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 2016 estimated that from the 0.6 million QSOs to be observed by Gaia, about 2,900 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. Strategy

Since the Gaia DR2 (April 2018), the Gaia GraL group has devoted a lot of efforts to scrutinise the full Gaia data set for new multiply-imaged quasar candidates. Our strategy is twofold.

First, our research focused on all known quasars that we compiled in a state-of-the-art list, searching for the presence in the Gaia DR2 of one or more nearby ($\lesssim$ 6") objects Krone-Martins et al. (2018). Secondly, we designed a method to blindly identify clusters of point-like objects from the DR2 using the Hierarchical Triangular Mesh technique (Delchambre et al. 2015).

The list of clusters extracted with these two 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), to differentiate genuine candidates from fortuitous clusters of stars. Gaia also provides broad band photometric measurements in the G-band and a colour indicator. Because the gravitational lensing phenomenon is achromatic, we also rejected clusters for which the individual colour indicators significantly differ from each other.

Then we classified the 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.

3. Confirming Candidates

Spectroscopic observations performed in both hemisphere with telescopes around the world confirmed 9 of quadruply-imaged and 12 doubly-imaged quasars or quad not completely solved. In South America we performed observations with the Gemini/GMOS/IFU and NTT/EFOSC2 telescopes for the first period of 2019. In the case of NTT, the observational strategy was to observe the candidates placing 2 images on the same slit and comparing their spectral characteristics.

The spectra were processed using the traditional IRAF tasks for long-slit reduction. Overscan, bias and flat were applied to all frames. No sky-flat 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 15 arcsec). Wavelength calibration was done using HeAr arc lamps, in slits of 1.5 and 5 arcsecs.

For all observations the spectral resolution was limited by the seeing ($\lesssim$ 1 arcsec) and the grating ($\lesssim$ 15Å). For the observed z the velocity dispersion is lower than 1%. Flux calibration and extinction corrections were performed using spectrophotometric standards (LTT3864 and LTT7379) observed one night before.

To recognise spectral lines the procedure of cross correlation of the observed spectra was used 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 and Mink (1998).

In this way, we were able to confirm 1 new gravitational lens systems with 4 components forming a cross. This quadruply-image quasar was confirmed with the NTT/EFOSC2 instrument. The Gemini observations are being reduced with a good possibility to confirm at least one candidate. In the following Figure we can see the Pan-STARRS image and the spectra of the confirmed exceptional gravitational lens with ESO–NTT observations in April 2019: the quadruply–imaged quasar GRAL165105371-041724936 with $z = 1.50 \pm 0.01$.

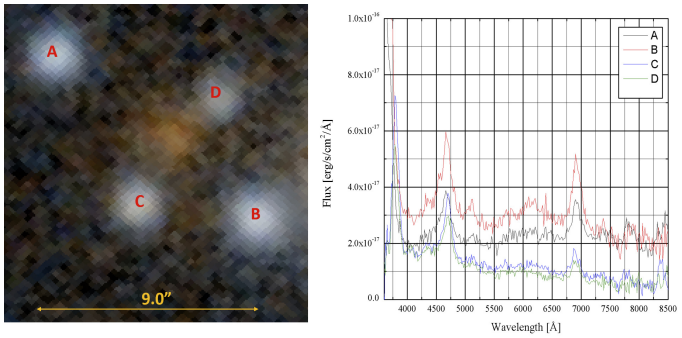

Figure 1. Pan–STARRS image and spectra of the new confirmed quadruply-imaged quasar observed at NTT/EFOSC2.

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