Bull. Soc. R. Sci. Liège, 2024, **93**(2), 752–765 *Peer-reviewed conference paper*
doi:10.25518/0037-9565.11868

GraL Spectroscopic Identification of Multiply Imaged Quasars

Priyanka JALAN[1,*], Vibhore NEGI[2], Jean SURDEJ[3], Céline BOEHM[4], Ludovic DELCHAMBRE[3], Jakob Sebastian DEN BROK[5], Dougal DOBIE[6], Andrew DRAKE[7], Christine DUCOURANT[8], S. George DJORGOVSKI[7], Laurent GALLUCCIO[9], Matthew J. GRAHAM[7], Jonas KLÜTER[10,11], Alberto KRONE-MARTINS[12,13], Jean-François LECAMPION[8], Ashish A. MAHABAL[7], François MIGNARD[9], Tara MURPHY[6], Anna NIERENBERG[14], Sergio SCARANO[15], Joseph SIMON[14], Eric SLEZAK[9], Dominique SLUSE[3], Carolina SPÍNDOLA-DUARTE[16], Daniel STERN[14], Ramachrisna TEIXERA[16] and Joachim WAMBSGANSS[10,17]

[1] Center for Theoretical Physics, Polish Academy of Sciences, al. Lotników 32/46, 02–668 Warsaw, Poland

[2] Aryabhatta Research Institute of Observational Sciences, Nainital, Uttarakhand, India

[3] Institut d'Astrophysique et de Géophysique, Université de Liège, Allée du Six-Août 19c, 4000 Liège, Belgium

[4] School of Physics, The University of Sydney, NSW 2006, Australia

[5] Sydney Institute for Astronomy, School of Physics, University of Sydney, NSW 2006, Australia

[6] Argelander-Institut für Astronomie, Universität Bonn, Auf dem Hügel 71, D–53121 Bonn, Germany

[7] Cahill Center for Astronomy and Astrophysics, California Institute of Technology, 1216 E. California Blvd., Pasadena, CA 91125, USA

[8] Laboratoire d'Astrophysique de Bordeaux, Univ. Bordeaux, CNRS, B18N, allée Geoffroy Saint-Hilaire, 33615 Pessac, France

[9] Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, Boulevard de l'Observatoire, CS 34229, 06304 Nice, France

[10] Zentrum für Astronomie der Universität Heidelberg, Astronomisches Rechen-Institut, Mönchhofstr. 12–14, 69120 Heidelberg, Germany

[11] Department of Physics & Astronomy, Louisiana State University, 261 Nicholson Hall, Tower Dr., Baton Rouge, LA 70803-4001, USA

[12] Donald Bren School of Information and Computer Sciences, University of California, Irvine, Irvine CA 92697, USA

[13] CENTRA, Faculdade de Cincias, Universidade de Lisboa, 1749-016, Lisbon, Portugal

[14] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Mail Stop 264–789, Pasadena, CA 91109, USA

[15] Departamento de Física – CCET, Universidade Federal de Sergipe, Rod. Marechal Rondon s/n, 49.100-000, Jardim Rosa Elze, São Cristóvão, SE, Brazil

[16] Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, Rua do Matão, 1226, Cidade Universitária, 05508–900 São Paulo, SP, Brazil

[17] International Space Science Institute (ISSI), Hallerstraße 6, 3012 Bern, Switzerland

* Corresponding author: priyajalan14@gmail.com

Paper presented at the 3rd BINA Workshop on "Scientific Potential of the Indo-Belgian Cooperation", held at the Graphic Era Hill University, Bhimtal (India), 22nd–24th March 2023.

Abstract

Gravitational lensing is one of the most efficient tools for studying the Universe. However, spectral confirmation of such sources necessitates thorough calibration. This paper discusses the spectral extraction technique for the case where multiple source spectra are close to each other. Using the *masking technique*, we first identify high signal-to-noise (S/N) peaks in the CCD spectral image corresponding to the location of the source spectra. This technique calculates the cumulative signal via a weighted sum, providing a reliable approximation for the total counts contributed by each source spectrum. Subsequently, we proceed with the removal of the contaminating spectra. Through the application of this method, we confirm the nature of 11 candidate lensed quasars.

Keywords: Quasar, gravitational lensing, spectroscopy, multiply imaged quasars

1. Introduction

The two primary methods for estimating the Hubble–Lemaître constant (H_0) are (i) examining the relationship between the distances and redshifts of the objects in the Universe (see, e.g., Lemaître, 1927; Hubble, 1929), and (ii) interpolating the expansion rate from models based on the Cosmic Microwave Background Radiation (see, e.g., Efstathiou et al., 1990; Jimenez et al., 2003) and Type-1a supernovae (see, e.g., Riess et al., 1998; Perlmutter et al., 1999). However, the study of gravitational lens systems has emerged as a complementary tool for determining H_0 in a model-independent manner (see, e.g., Refsdal, 1964; Blandford and Narayan, 1992; Surdej and Refsdal, 1994; Kelly et al., 2023).

Gravitational lensing occurs due to the deflection of light from a background source caused by a massive foreground structure (see, e.g., Fig. 1). The mass of the foreground object leads to a curved space-time, which bends the light travelling from the background source to the observer. The degree of light deflection depends on the mass distribution within the foreground structure and the distances between the observer, the lens, and the source. This phenomenon can result in the formation of multiple images and/or amplification of the background source. The time delay between the arrival times corresponding to the various lensed images carries information about H_0. In addition to estimating H_0, gravitational lens systems also offers insights into the mass of the foreground structure, as well as properties of dark energy and matter (see, e.g., Cao et al., 2015, and references therein). Moreover, the transverse correlation of Lyα forest clouds in the intergalactic medium (IGM) can be studied using gravitationally lensed quasars (Bechtold and Yee, 1995; Dolan et al., 2000; Rauch et al., 2001; Tzanavaris and Carswell, 2003).

The concept of gravitational lensing can be traced back to 1704 when Isaac Newton, in his work *Opticks*, speculated on whether objects might interact with light at a distance and cause

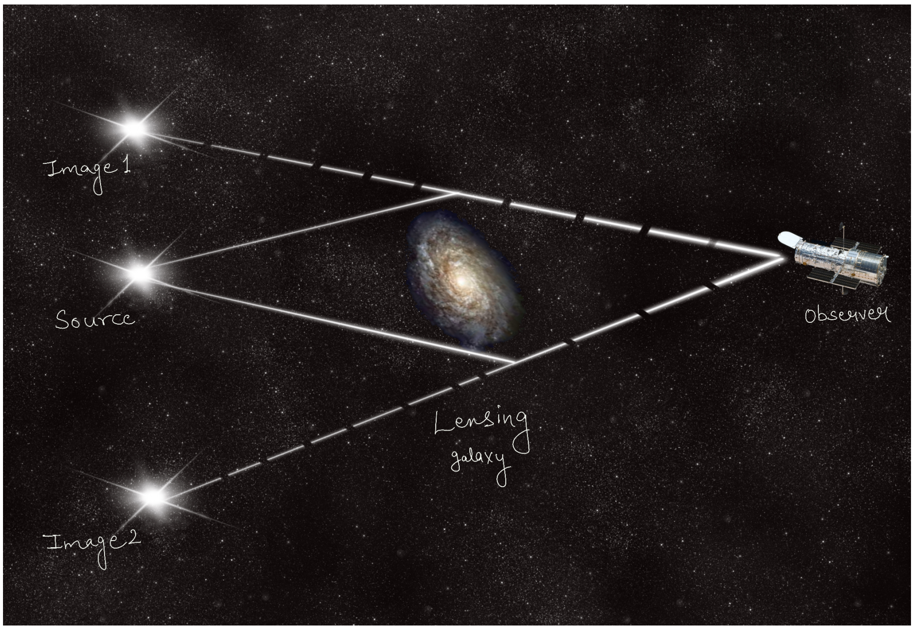

Figure 1: Artistic representation illustating light deflection from a background quasar by a foreground galaxy, resulting in the formation of two lensed images of the quasar.

the bending of light beams. In 1784, Henry Cavendish computed the deflection angle of light due to a point mass, utilizing Newton's gravitational theory and Newtonian optics. Cavendish supposed that light was composed of corpuscles that were influenced by a gravitational field in a manner akin to material particles (detailed in Lotze and Simionato, 2022). Subsequently, Johann Georg von Soldner calculated the angle of deflection of light passing at a distance b from a mass M as

$$\alpha_N = \frac{2GM}{c^2 b},$$

where G is the gravitational constant, and c is the speed of light in a vacuum.

In 1915, Albert Einstein calculated the deflection angle of light by the Sun using his general theory of relativity and found that this angle was twice that previously predicted. In 1937, Fritz Zwicky argued that this phenomenon could potentially allow galaxy clusters to act as gravitational lenses (Zwicky, 1937).

It was not until 1979 that the detection of the twin quasars SBS 0957+561 by Walsh et al. (1979) was shown to be the first instance of a doubly imaged quasar.

The discovery of such exotic sources poses several observational challenges. Not only are these objects rare, but they are also difficult to identify within large catalogues. Therefore, only two hundred spectroscopically confirmed gravitational systems (https://research.ast.cam.ac.uk/lensedquasars/index.html) are currently known. Recent studies have attempted to discover these systems using machine learning algorithms and large astronomical surveys. One such effort is undertaken by the *Gaia* GraL (*Gaia* Gravitational Lens systems) group using data from the *Gaia* mission – an all-sky survey space-based mission designed to catalogue the stars in the Milky Way. However, in the process of identifying gravitational lenses, various extragalactic sources are also uncovered (Tsalmantza et al., 2012; Krone-Martins et al., 2013; de Souza et al., 2014; Delchambre, 2018; Bailer-Jones et al., 2019; Creevey et al., 2023). The best angular resolution of $0.18''$ achievable with *Gaia* does provide an excellent opportunity to search for gravitational lens candidates (Agnello et al., 2018; Lemon et al., 2018). Finet and Surdej (2016) predicted the discovery of ~ 2900 lensed quasar candidates in the *Gaia* survey. Since then, the *Gaia* GraL team has spectroscopically confirmed 15 quadruply imaged systems and seven doubly imaged ones (see, e.g., Krone-Martins et al., 2018, 2019; Ducourant et al., 2018; Delchambre et al., 2019; Wertz et al., 2019; Stern et al., 2021).

In this paper, we discuss one of the data reduction techniques developed to spectroscopically confirm that these sources are indeed gravitationally lensed quasars.

2. Observations

The spectroscopic observations of the gravitationally lensed candidates were performed using EFOSC2 installed at the New Technology Telescope (https://www.eso.org/sci/facilities/lasilla/instruments/efosc.html) and ADFOSC, which is equipped on the 3.6 m Devasthal Optical Telescope (https://www.aries.res.in/facilities/astronomical-telescopes/360cm-telescope/Instruments).

3. Spectroscopy

The extraction process that uses the `apall` task in IRAF is relatively straightforward if the two nearby source spectra are well separated. However, in the case of most gravitational lens systems, where multiple lensed quasar images are closely positioned, the extraction process of individual non-contaminated spectra becomes complicated (e.g., left panel of Fig. 2). When extracting the spectrum of a designated source component, it is crucial to accurately subtract the contamination from all other sources. The right panel of Fig. 2 depicts counts versus pixel numbers along a fixed row of the CCD spectral image illustrated in the left panel. Firstly, we assume a *Gaussian distribution* of photon counts from a source for a particular CCD row, i.e., the point spread function (PSF). Hence, we overlay two Gaussian profiles associated with the two nearby spectra (for instance, due to component C_1 and component C_2) along with the background in cyan colour. In the right panel of Fig. 2, the red colour represents the area contaminated by the neighbouring source. The region of C_2 contaminating the flux of C_1 is similar to sub_1 (shown in orange dashed lines). Similarly, the region of C_1 contaminating the flux of C_2 is similar to sub_2 (shown in green dashed lines). So in order to retain uncontaminated spectra,

$$C_1^{\mathrm{decont}} = C_1^{\mathrm{cont}} - sub_1 \;\; ; \;\; C_2^{\mathrm{decont}} = C_2^{\mathrm{cont}} - sub_2.$$

The extraction technique using IRAF yields good results for bright and well-separated sources. However, with faint and closely positioned sources, a more intricate extraction technique is necessary.

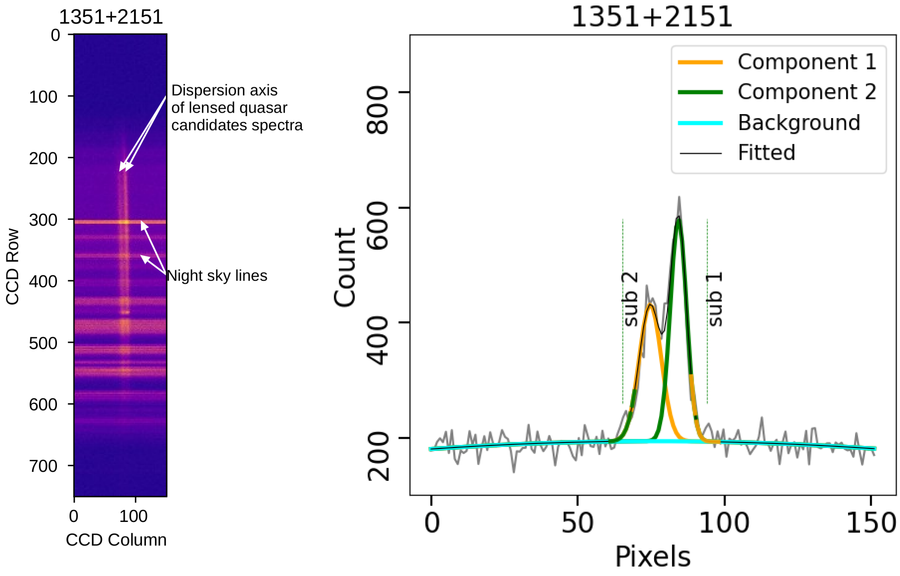

Figure 2: (*left*) CCD frame highlighting the spectra of two closely neighbouring lensed quasar images, with superimposed night skylines. (*right*) Slice of the CCD along row number 270 displaying the superposition of two nearly Gaussian profiles. Section 3.1 provides detailed information on the technique used to remove contamination of neighbouring sources.

3.1. Decontamination of nearby spectra: masking technique

The optimal spectral extraction method we propose utilizes a *masking technique*, as briefly discussed below. This technique proves advantageous in cases of doubly imaged quasars, where both spectra lie close to each other and substantially contaminate each other. Additionally, this algorithm effectively reduces the statistical noise of the extracted spectra by assigning non-uniform pixel weights during extraction.

[1] After pre-processing the science image, the CCD image $(I_* + Sky)$ depicted in the left panel of Fig. 2, is used to create several other images (see below).

[2] The background image (Sky) is created after application of a sigma clipping algorithm to the spectra along each row. The sky array is obtained as the median of the remaining pixels along each row. We subsequently subtract this median sky background from each column.

[3] We then create a binary mask which, in the case of a single source, mirrors the shape of the displayed source spectrum. Each pixel inside the mask is assigned a value of 1, while all other pixels are assigned a value of 0. In the case of a double source spectrum, we generate the mask by fitting its shape to that of the brightest source spectrum.

[4] The science image from step [1] is then multiplied with the mask, resulting in the masked image $(I_* + Sky)_{\mathrm{M}}$, where the subscript 'M' indicates that the frame has been masked.

[5] We also multiply the background-subtracted image from step [2] with the mask, resulting in $(I_*)_\mathrm{M}$.

[6] Using the gain and readout-noise, *Ron*, of the CCD, we calculate the noise at the i^th pixel as $N_i = \sqrt{\frac{(I_*+Sky)_{i\mathrm{M}}}{gain} + Ron^2_\mathrm{ADU}}$. Here, *gain* represents the level of amplification a system provides, typically expressed in electrons per analog-to-digital unit, ADU.

[7] Steps [5] and [6] provide an estimate of the relative weight w_i at each pixel of the CCD: $w_i = (I_*)_{i\mathrm{M}}/N_i^2$.

[8] The weights calculated above are summed along the row: $\sum_{i=0}^{n}(I_*)_{iM}/N_i^2$.

[9] By normalizing the weights w_i of the pixels along the rows, we get $W_i = \frac{(I_*)_{i\mathrm{M}}/N_i^2}{\sum_{i=0}^{n}(I_*)_{i\mathrm{M}}/N_i^2}$.

[10] The signal from step [5] is then multiplied with these weights, i.e, $W_i \times (I_*)_{i\mathrm{M}}$.

[11] Due to the masking zero values are present elsewhere except within the mask width, where they are set to unity. Therefore, summing the weighted signal along the row yields the total signal: $S = \sum W_i \times (I_*)_{i\mathrm{M}}$. This process provides a one-dimensional extracted spectrum with a length equal to that of the CCD columns.

[12] To calculate the total noise, we multiply the weights by the noise from step [6], i.e., $W_i^2 \times N_i^2$.

[13] The total noise along the mask width is computed similar to step [10]: $N = \sqrt{\sum W_i^2 \times N_i^2}$. Consequently, akin to the signal spectrum, a one-dimensional noise spectrum with a length equal to that of the CCD columns is generated.

[14] Finally, we slide the mask along the rows, and for each column position, we calculate the corresponding S/N. The presence of a source spectrum leads to a maximum value for S/N; the presence of two extrema (at positions X_1 and X_2), is interpreted as the signature of two source spectra present on the CCD frame (see Fig. 3).

[15] After detecting such peaks, the process outlined above is repeated for various mask widths to optimally extract the spectra ($I[X_1]$ and $I[X_2]$). These spectra are shown in blue in Fig. 4.

[16] We also extract the spectra at positions $X_1 - (X_2 - X_1)$ and $X_2 + (X_2 - X_1)$ (depicted in orange in Fig. 4) and then construct the following de-contaminated spectra: $I_\mathrm{D}[X_1] = I[X_1] - I[X_2 + (X_2 - X_1)]$ and $I_\mathrm{D}[X_2] = I[X_2] - I[X_1 - (X_2 - X_1)]$.

Figure 3 displays two S/N peaks using the masking technique for the corresponding spectra depicted in the left panel of Fig. 2. As can be seen in Fig. 4, the contaminated and decontaminated spectra exhibit notable differences..

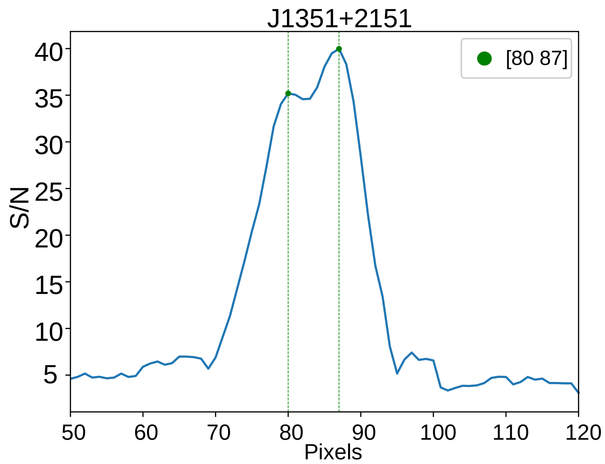

Figure 3: Signal-to-noise ratio (S/N) plotted against pixel number for the CCD image depicted in the left panel of Fig. 2.

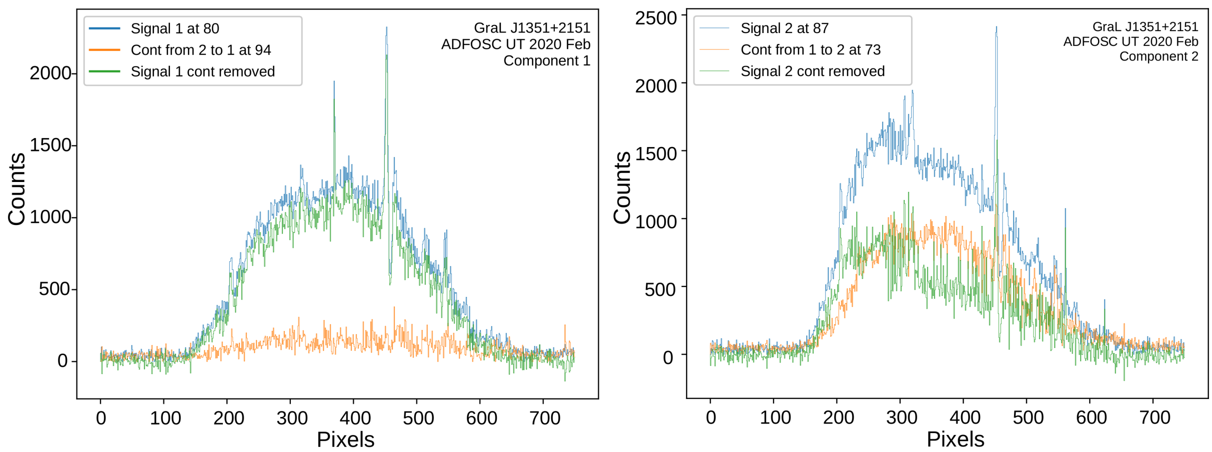

Figure 4: The spectra drawn in blue are those extracted at positions $X_1 = 80$ and $X_2 = 87$ from the spectral CCD frame depicted in Fig. 2. The flux from the contamination at positions $X_1 - (X_2 - X_1)$ and $X_2 + (X_2 - X_1)$ are shown in orange. The decontaminated spectra $I_D[X_1] = I[X_1 = 80] - I[X_2 + (X_2 - X_1) = 94]$ and $I_D[X_2] = I[X_2 = 87] - I[X_1 - (X_2 - X_1) = 73]$ are shown in green.

4. Data Log and Results

The masking technique for removing the contamination from very closely separated quasars offers a unique method for extracting the spectra of doubly imaged quasar candidates. Table 1 lists the sources for which the spectra were extracted in this paper and confirmed to be lensed. Out of 57 sources, we have confirmed 11 as gravitationally lensed quasars. Among these, ten are doubly imaged quasars, whereas one quasar is a quadruply imaged quasar. The spectra can be accessed at https://github.com/PriyankaJalan14/Lens_spectra.

5. Conclusions

The *Gaia* Gravitational Lenses group (GraL) is dedicated to discovering more gravitationally lensed quasars. A key challenge lies in removing spectral contamination due to the proximity of lensed images. An optimized extraction technique is essential to to address this challenge. In this paper, we have discussed the spectral extraction technique tailored for cases involving closely neighboring lensed components. We employ a masking technique to identify high signal-to-noise (S/N) peaks in the CCD image. This technique computes the cumulative signal using a weighted sum, providing a robust approximation of the total counts. We then subtract the mutual spectral contamination due to the proximity of the lensed images. The width of the mask is determined through an iterative process. In this paper, we have efficiently extracted the spectra to confirm or refute 57 quasar lens candidates using this technique. Out of fifty-seven candidates, 11 are identified as lensed quasars.

Acknowledgments

This work is partially based on the observations obtained at the 3.6 m Devasthal Optical Telescope (DOT) under programme ID DOT-2020-C2-P49, DOT-2020-C2-P50, DOT-2020-C2-P54, DOT-2020-C2-P59, DOT-2021-C1-P11, DOT-2021-C1-P12, DOT-2021-C1-P17, DOT-2021-C1-P33, which is a National Facility run and managed by Aryabhatta Research Institute of observational sciencES (ARIES), an autonomous Institute under the Department of Science and Technology, Government of India. The observations are also based on the European Organisation for Astronomical Research in the Southern Hemisphere under ESO programme(s) P103.A-0077, P104.A-575, P105.A-205, P106.A.215V, P108.223G, P111.24HD. PJ was supported by the Polish National Science Center through grant no. 2020/38/E/ST9/00395. This work is supported by the Belgo-Indian Network for Astronomy and astrophysics (BINA), approved by the International Division, Department of Science and Technology (DST, Govt. of India; DST/INT/BELG/P-09/2017) and the Belgian Federal Science Policy Office (BELSPO, Govt. of Belgium; BL/33/IN12).

Table 1: Observation log of the gravitational lens candidates. The lensing nature is also confirmed in the quoted references.

Quasar	Date	For each component			Lens
	Telescope	RA	DEC	m_r	confirmation
0013+5119	10-01-2021	00:13:23.5	+51:19:05.9	21.43	Probable lensed QSO
	DOT	00:13:23.5	+51:19:04.6	20.79	(Lemon et al., 2019)
		00:13:23.6	+51:19:07.5	20.52	
0645–1929	10-01-2021	06:45:44.0	−19:29:36.6	21.13	Doubly imaged QSO
	DOT	06:45:44.1	−19:29:35.7	21.22	
		06:45:44.1	−19:29:37.6	19.10	
0803+3908	10-01-2021	08:03:57.7	+39:08:23.9	18.84	Doubly imaged QSO
	DOT	08:03:57.7	+39:08:23.1	19.71	
		08:03:57.8	+39:08:23.1	18.26	
0859–3011	08-04-2019	08:59:11.9	−30:11:34.7	20.23	Doubly imaged QSO
	NTT	08:59:11.9	−30:11:34.6	20.99	
		08:59:11.9	−30:11:35.4	20.87	
0911+0550	09-04-2019	09:11:27.6	+05:50:54.8	19.74	Doubly imaged QSO
	NTT	09:11:27.6	+05:50:53.9	19.50	(Delchambre et al., 2019)
1008–2215	22-02-2020	10:08:53.5	−22:15:16.9	20.53	Doubly imaged QSO
	NTT	10:08:53.5	−22:15:17.9	20.94	
		10:08:53.6	−22:15:18.2	19.75	
1124+5710	19-03-2021	11:24:55.3	+57:10:56.6	18.46	Doubly imaged QSO
	DOT	11:24:55.5	+57:10:58.1	19.76	
1145–0850	11-02-2021	11:45:26.0	−08:50:06.4	21.68	Probable lensed QSO
	DOT	11:45:25.9	−08:50:07.5	21.28	
		11:45:24.0	−08:50:04.0	20.62	
1554–2818	23-02-2020	15:54:2.3	−28:18:36.4	19.49	Doubly imaged QSO
	NTT	15:54:2.2	−28:18:34.6	19.99	
		15:54:2.2	−28:18:35.6	19.76	
1651–0417	09-04-2019	16:51:04.5	−04:17:25.0	20.29	Quadruply imaged QSO
	NTT	16:51:05.5	−04:17:27.3	19.48	(Stern et al., 2021)
		16:51:05.1	−04:17:27.8	18.98	
		16:51:05.2	−04:17:23.2	20.04	
1654+3318	13-02-2021	16:54:23.5	+33:18:02.9	20.82	Probable lensed QSO
	DOT	16:54:23.4	+33:18:02.2	20.83	
		16:54:23.5	+33:18:03.1	20.50	

Further Information

Authors' ORCID identifiers

0000-0002-0524-5328 (Priyanka JALAN)
0000-0001-5824-1040 (Vibhore NEGI)
0000-0002-7005-1976 (Jean SURDEJ)
0000-0002-5074-9998 (Céline BOEHM)
0000-0003-2559-408X (Ludovic DELCHAMBRE)
0000-0002-8760-6157 (Jakob Sebastian DEN BROK)
0000-0003-0699-7019 (Dougal DOBIE)
0000-0003-0228-6594 (Andrew DRAKE)
0000-0003-4843-8979 (Christine DUCOURANT)
0000-0002-0603-3087 (S. George DJORGOVSKI)
0000-0002-8541-0476 (Laurent GALLUCCIO)
0000-0002-3168-0139 (Matthew J. GRAHAM)
0000-0002-3469-5133 (Jonas KLÜTER)
0000-0002-2308-6623 (Alberto KRONE-MARTINS)
0000-0003-2242-0244 (Ashish A. MAHABAL)
0000-0002-2686-438X (Tara MURPHY)
0000-0001-6809-2536 (Anna NIERENBERG)
0000-0003-3739-4288 (Sergio SCARANO)
0000-0003-1407-6607 (Joseph SIMON)
0000-0003-4771-7263 (Eric SLEZAK)
0000-0001-6116-2095 (Dominique SLUSE)
0000-0002-8052-7763 (Carolina SPÍNDOLA-DUARTE)
0000-0003-2686-9241 (Daniel STERN)
0000-0002-6806-6626 (Ramachrisna TEIXERA)
0000-0002-8365-7619 (Joachim WAMBSGANSS)

Author contributions

This work results from a long-term collaboration (GAIA-GRAL) to which all authors have made significant contributions.

Conflicts of interest

The authors declare no conflict of interest.

References

Agnello, A., Lin, H., Kuropatkin, N., Buckley-Geer, E., Anguita, T., Schechter, P. L., Morishita, T., Motta, V., Rojas, K., Treu, T., Amara, A., Auger, M. W., Courbin, F., Fassnacht, C. D., Frieman, J., More, A., Marshall, P. J., McMahon, R. G., Meylan, G., Suyu, S. H., Glazebrook, K., Morgan, N., Nord, B., Abbott, T. M. C., Abdalla, F. B., Annis, J., Bechtol, K., Benoit-Lévy, A., Bertin, E., Bernstein, R. A., Brooks, D., Burke, D. L., Rosell, A. C., Carretero, J., Cunha, C. E., D'Andrea, C. B., da Costa, L. N., Desai, S., Drlica-Wagner, A., Eifler, T. F., Flaugher, B., García-Bellido, J., Gaztanaga, E., Gerdes, D. W., Gruen, D., Gruendl, R. A., Gschwend, J., Gutierrez, G., Honscheid, K., James, D. J., Kuehn, K., Lahav, O., Lima, M., Maia, M. A. G., March, M., Menanteau, F., Miquel, R., Ogando, R. L. C., Plazas, A. A., Sanchez, E., Scarpine, V., Schindler, R., Schubnell, M., Sevilla-Noarbe, I., Smith, M., Soares-Santos, M., Sobreira, F., Suchyta, E., Swanson, M. E. C., Tarle, G., Tucker, D. and Wechsler, R. (2018) DES meets *Gaia*: discovery of strongly lensed quasars from a multiplet search. MNRAS, 479(4), 4345–4354. https://doi.org/10.1093/mnras/sty1419.

Bailer-Jones, C. A. L., Fouesneau, M. and Andrae, R. (2019) Quasar and galaxy classification in *Gaia* Data Release 2. MNRAS, 490(4), 5615–5633. https://doi.org/10.1093/mnras/stz2947.

Bechtold, J. and Yee, H. K. C. (1995) High spatial resolution spectroscopy of the Lyman-alpha absorption towards the gravitational lens system B1422+2309. AJ, 110, 1984–1992. https://doi.org/10.1086/117664.

Blandford, R. D. and Narayan, R. (1992) Cosmological applications of gravitational lensing. ARA&A, 30, 311–358. https://doi.org/10.1146/annurev.astro.30.1.311.

Cao, S., Biesiada, M., Gavazzi, R., Piórkowska, A. and Zhu, Z.-H. (2015) Cosmology with strong-lensing systems. ApJ, 806(2), 185. https://doi.org/10.1088/0004-637X/806/2/185.

Creevey, O. L., Sordo, R., Pailler, F., Frémat, Y., Heiter, U., Thévenin, F., Andrae, R., Fouesneau, M., Lobel, A., Bailer-Jones, C. A. L., Garabato, D., Bellas-Velidis, I., Brugaletta, E., Lorca, A., Ordenovic, C., Palicio, P. A., Sarro, L. M., Delchambre, L., Drimmel, R., Rybizki, J., Torralba Elipe, G., Korn, A. J., Recio-Blanco, A., Schultheis, M. S., De Angeli, F., Montegriffo, P., Abreu Aramburu, A., Accart, S., Álvarez, M. A., Bakker, J., Brouillet, N., Burlacu, A., Carballo, R., Casamiquela, L., Chiavassa, A., Contursi, G., Cooper, W. J., Dafonte, C., Dapergolas, A., de Laverny, P., Dharmawardena, T. E., Edvardsson, B., Le Fustec, Y., García-Lario, P., García-Torres, M., Gomez, A., González-Santamaría, I., Hatzidimitriou, D., Jean-Antoine Piccolo, A., Kontiza, M., Kordopatis, G., Lanzafame, A. C., Lebreton, Y., Licata, E. L., Lindstrøm, H. E. P., Livanou, E., Magdaleno Romeo, A., Manteiga, M., Marocco, F., Marshall, D. J., Mary, N., Nicolas, C., Pallas-Quintela, L., Panem, C., Pichon, B., Poggio, E., Riclet, F., Robin, C., Santoveña, R., Silvelo, A., Slezak, I., Smart, R. L., Soubiran, C., Süveges, M., Ulla, A., Utrilla, E., Vallenari, A., Zhao, H., Zorec, J., Barrado, D., Bijaoui, A., Bouret, J.-C., Blomme, R., Brott, I., Cassisi, S., Kochukhov, O., Martayan, C., Shulyak, D. and Silvester, J. (2023) *Gaia* Data Release 3. Astrophysical parameters inference system (Apsis). I. Methods and content overview. A&A, 674, A26. https://doi.org/10.1051/0004-6361/202243688.

de Souza, R. E., Krone-Martins, A., dos Anjos, S., Ducourant, C. and Teixeira, R. (2014) Detection of galaxies with *Gaia*. A&A, 568, A124. https://doi.org/10.1051/0004-6361/201423514.

Delchambre, L. (2018) Determination of astrophysical parameters of quasars within the *Gaia* mission. MNRAS, 473(2), 1785–1800. https://doi.org/10.1093/mnras/stx2417.

Delchambre, L., Krone-Martins, A., Wertz, O., Ducourant, C., Galluccio, L., Klüter, J., Mignard, F., Teixeira, R., Djorgovski, S. G., Stern, D., Graham, M. J., Surdej, J., Bastian, U., Wambsganss, J., Le Campion, J.-F. and Slezak, E. (2019) *Gaia* GraL: *Gaia* DR2 gravitational lens systems. III. A systematic blind search for new lensed systems. A&A, 622, A165. https://doi.org/10.1051/0004-6361/201833802.

Dolan, J. F., Michalitsianos, A. G., Nguyen, Q. T. and Hill, R. J. (2000) Ultraviolet spectral variability and the Lyα forest in the lensed quasar Q0957+561. ApJ, 539(1), 111–123. https://doi.org/10.1086/309206.

Ducourant, C., Wertz, O., Krone-Martins, A., Teixeira, R., Le Campion, J.-F., Galluccio, L., Klüter, J., Delchambre, L., Surdej, J., Mignard, F., Wambsganss, J., Bastian, U., Graham, M. J., Djorgovski, S. G. and Slezak, E. (2018) *Gaia* GraL: *Gaia* DR2 gravitational lens systems. II. The known multiply imaged quasars. A&A, 618, A56. https://doi.org/10.1051/0004-6361/201833480.

Efstathiou, G., Sutherland, W. J. and Maddox, S. J. (1990) The cosmological constant and cold dark matter. Natur, 348, 705–707. https://doi.org/10.1038/348705a0.

Finet, F. and Surdej, J. (2016) Multiply imaged quasi-stellar objects in the *Gaia* survey. A&A, 590, A42. https://doi.org/10.1051/0004-6361/201425411.

Hubble, E. (1929) A relation between distance and radial velocity among extra-galactic nebula. PNAS, 15(3), 168–173. https://doi.org/10.1073/pnas.15.3.168.

Jimenez, R., Verde, L., Treu, T. and Stern, D. (2003) Constraints on the equation of state of dark energy and the Hubble constant from stellar ages and the cosmic microwave background. ApJ, 593(2), 622–629. https://doi.org/10.1086/376595.

Kelly, P. L., Rodney, S., Treu, T., Oguri, M., Chen, W., Zitrin, A., Birrer, S., Bonvin, V., Dessart, L., Diego, J. M., Filippenko, A. V., Foley, R. J., Gilman, D., Hjorth, J., Jauzac, M., Mandel, K., Millon, M., Pierel, J., Sharon, K., Thorp, S., Williams, L., Broadhurst, T., Dressler, A., Graur, O., Jha, S., McCully, C., Postman, M., Schmidt, K. B., Tucker, B. E. and von der Linden, A. (2023) Constraints on the Hubble constant from supernova Refsdal's reappearance. Sci, 380, abh1322. https://doi.org/10.1126/science.abh1322.

Krone-Martins, A., Delchambre, L., Wertz, O., Ducourant, C., Mignard, F., Teixeira, R., Klüter, J., Le Campion, J.-F., Galluccio, L., Surdej, J., Bastian, U., Wambsganss, J., Graham, M. J., Djorgovski, S. G. and Slezak, E. (2018) *Gaia* GraL: *Gaia* DR2 gravitational lens systems. I. New quadruply imaged quasar candidates around known quasars. A&A, 616, L11. https://doi.org/10.1051/0004-6361/201833337.

Krone-Martins, A., Ducourant, C., Teixeira, R., Galluccio, L., Gavras, P., dos Anjos, S., de Souza, R. E., Machado, R. E. G. and Le Campion, J.-F. (2013) Pushing the limits of the *Gaia* space mission by analyzing galaxy morphology. A&A, 556, A102. https://doi.org/10.1051/0004-6361/201219697.

Krone-Martins, A., Graham, M. J., Stern, D., Djorgovski, S. G., Delchambre, L., Ducourant, C., Teixeira, R., Drake, A. J., Scarano, S., Surdej, J., Galluccio, L., Jalan, P., Wertz, O., Klüter, J., Mignard, F., Spindola-Duarte, C., Dobie, D., Slezak, E., Sluse, D., Murphy, T., Boehm, C., Nierenberg, A. M., Bastian, U., Wambsganss, J. and LeCampion, J. F. (2019) *Gaia* GraL: *Gaia* DR2 gravitational lens systems. V. Doubly-imaged QSOs discovered from entropy and wavelets. arXiv e-prints: 1912.08977. https://doi.org/10.48550/arXiv.1912.08977.

Lemaître, G. (1927) Un Univers homogène de masse constante et de rayon croissant rendant compte de la vitesse radiale des nébuleuses extra-galactiques. ASSB, 47, 49–59.

Lemon, C. A., Auger, M. W. and McMahon, R. G. (2019) Gravitationally lensed quasars in *Gaia* – III. 22 new lensed quasars from *Gaia* data release 2. MNRAS, 483(3), 4242–4258. https://doi.org/10.1093/mnras/sty3366.

Lemon, C. A., Auger, M. W., McMahon, R. G. and Ostrovski, F. (2018) Gravitationally lensed quasars in *Gaia* – II. Discovery of 24 lensed quasars. MNRAS, 479(4), 5060–5074. https://doi.org/10.1093/mnras/sty911.

Lotze, K.-H. and Simionato, S. (2022) Henry Cavendish on gravitational deflection of light. AnP, 534(7), 2200102. https://doi.org/10.1002/andp.202200102.

Perlmutter, S., Aldering, G., Goldhaber, G., Knop, R. A., Nugent, P., Castro, P. G., Deustua, S., Fabbro, S., Goobar, A., Groom, D. E., Hook, I. M., Kim, A. G., Kim, M. Y., Lee, J. C., Nunes, N. J., Pain, R., Pennypacker, C. R., Quimby, R., Lidman, C., Ellis, R. S., Irwin, M., McMahon, R. G., Ruiz-Lapuente, P., Walton, N., Schaefer, B., Boyle, B. J., Filippenko, A. V., Matheson, T., Fruchter, A. S., Panagia, N., Newberg, H. J. M., Couch, W. J. and The Supernova Cosmology Project (1999) Measurements of Ω and Λ from 42 high-redshift supernovae. ApJ, 517(2), 565–586. https://doi.org/10.1086/307221.

Rauch, M., Sargent, W. L. W., Barlow, T. A. and Carswell, R. F. (2001) Small-scale structure at high redshift. III. The clumpiness of the intergalactic medium on subkiloparsec scales. ApJ, 562(1), 76–87. https://doi.org/10.1086/323523.

Refsdal, S. (1964) On the possibility of determining hubble's parameter and the masses of galaxies from the gravitational lens effect. MNRAS, 128, 307–310. https://doi.org/10.1093/mnras/128.4.307.

Riess, A. G., Filippenko, A. V., Challis, P., Clocchiatti, A., Diercks, A., Garnavich, P. M., Gilliland, R. L., Hogan, C. J., Jha, S., Kirshner, R. P., Leibundgut, B., Phillips, M. M., Reiss, D., Schmidt, B. P., Schommer, R. A., Smith, R. C., Spyromilio, J., Stubbs, C., Suntzeff, N. B. and Tonry, J. (1998) Observational evidence from supernovae for an accelerating universe and a cosmological constant. AJ, 116(3), 1009–1038. https://doi.org/10.1086/300499.

Stern, D., Djorgovski, S. G., Krone-Martins, A., Sluse, D., Delchambre, L., Ducourant, C., Teixeira, R., Surdej, J., Boehm, C., den Brok, J., Dobie, D., Drake, A., Galluccio, L., Graham, M. J., Jalan, P., Klüter, J., Le Campion, J. F., Mahabal, A., Mignard, F., Murphy, T., Nierenberg, A., Scarano, J., S., Simon, J., Slezak, E., Spindola-Duarte, C. and Wambsganss, J. (2021) *Gaia* GraL: *Gaia* DR2 gravitational lens systems. VI. Spectroscopic confirmation and modeling of quadruply imaged lensed quasars. ApJ, 921(1), 42. https://doi.org/10.3847/1538-4357/ac0f04.

Surdej, J. and Refsdal, S. (1994) Gravitational Lensing as a Tool: Future Observational Prospects, pp. 409–419. Springer Netherlands, Dordrecht. https://doi.org/10.1007/978-94-011-0794-5_40.

Tsalmantza, P., Karampelas, A., Kontizas, M., Bailer-Jones, C. A. L., Rocca-Volmerange, B., Livanou, E., Bellas-Velidis, I., Kontizas, E. and Vallenari, A. (2012) A semi-empirical library of galaxy spectra for gaia classification based on SDSS data and PÉGASE models. A&A, 537, A42. https://doi.org/10.1051/0004-6361/201117125.

Tzanavaris, P. and Carswell, R. F. (2003) Size estimates for intervening CIV absorbers from high-resolution spectroscopy of APM 0827+5255. MNRAS, 340(3), 937–948. https://doi.org/10.1046/j.1365-8711.2003.06355.x.

Walsh, D., Carswell, R. F. and Weymann, R. J. (1979) 0957+561 A, B: twin quasistellar objects or gravitational lens? Natur, 279, 381–384. https://doi.org/10.1038/279381a0.

Wertz, O., Stern, D., Krone-Martins, A., Delchambre, L., Ducourant, C., Gråe Jørgensen, U., Dominik, M., Burgdorf, M., Surdej, J., Mignard, F., Teixeira, R., Galluccio, L., Klüter, J., Djorgovski, S. G., Graham, M. J., Bastian, U., Wambsganss, J., Boehm, C., LeCampion, J.-F. and Slezak, E. (2019) *Gaia* GraL: *Gaia* DR2 gravitational lens systems. IV. Keck/LRIS spectroscopic confirmation of GRAL 113100-441959 and model prediction of time delays. A&A, 628, A17. https://doi.org/10.1051/0004-6361/201834573.

Zwicky, F. (1937) Nebulae as gravitational lenses. PhRv, 51(4), 290–290. https://doi.org/10.1103/PhysRev.51.290.