16. Quasars, as seen by Gaia

QUASARS ARE the highly luminous nuclei of distant active galaxies. Their light is dominated by emission from an accretion disk as matter falls towards a central supermassive black hole, millions to billions times the mass of the Sun. The radio source 3C 273 was the first whose redshift, $z = 0.158$, was determined in 1963.

There are more than a million quasars known today, many discovered from the Sloan Digital Sky Survey. The most distant are at redshifts above $z = 7.5$, meaning that they date from a 'mere' 700 Myr after the Big Bang. Quasar activity was more common in the distant past, peaking at around 10 billion years ago.

THE MOST IMPORTANT role that quasars have in Gaia is in their direct manifestation of the global reference system. Their enormous cosmological distances means that their individual proper motions are effectively zero.

More than 500 000 are being observed by Gaia. Reasonably well distributed across the sky, they serve to define a highly accurate inertial reference system – a subject that I cover in more detail elsewhere.

MANY QUASARS are also of individual interest, for example because of their use as probes of cosmological evolution and structure formation. Many are radio sources, some show outflowing 'jets' that appear to be superluminal due to relativistic effects and line-of-sight orientation, and a few occur in physical groups.

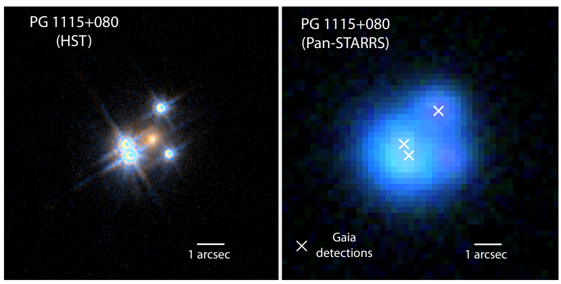
Several hundred show multiple images as a result of gravitational lensing, and these can be used for detailed studies both of the source itself, and of the lensing galaxies. Source variability results in measurable time delays between the separate images, and these can be used to determine the Hubble constant, today reaching a precision of just a few percent (e.g. Bonvin et al., 2016).

On-board sampling of Gaia's CCDs provides source images with an ultimate resolution of about 0.1–0.2 arcsec in the scanning direction (Gaia's astrometric accuracy is much better than this because the image centroid can be determined much more accurately than this effective resolution). This angular resolution is much better than can be routinely measured from the ground.

Accordingly, Gaia should be able to discover lensed quasars with image separations below about 1 arcsec. Small-separation lenses are the most common, and can be used to probe high-redshift/low-mass lensing galaxies. But they are more difficult to find from the ground.

Lemon et al. (2016) demonstrated this discovery potential with Gaia DR1, showing that Gaia correctly identified the three brightest images in the previously-known 5-image system PG 1115+080. Indeed, out of 49 known lensed quasars with image separations below 2 arcsec, they recovered 8 from Gaia DR1, discovered four new lensed systems with sub-arcsec separation, and estimated that Gaia would eventually be able to discover some 1400 with image separations above 0.5 arcsec.

A further 24 gravitationally lensed quasars were similarly discovered and characterised using the DR1 data by Lemon et al. (2018), and an additional 22 using the Gaia DR2 data by Lemon et al. (2019).



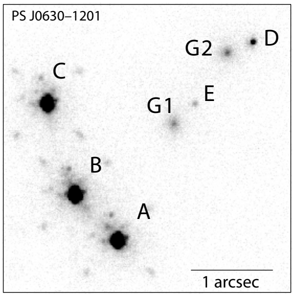
Lemon et al. (2017)

A DIFFERENT APPROACH was taken by Krone-Martins et al. (2018) with Gaia DR2. From the various compilations of known or possible quasars, they constructed a starting list of 3 112 975 objects, of which 1 839 143 have a Gaia DR2 counterpart within 0.5 arcsec of that starting position. They then matched these with other Gaia DR2 detections within a radius of 6 arcsec.

Applying other astrometric and photometric tests, as well as physical modelling, they finally extracted two new high-reliability quadruple-lens candidates, GraL 113100–441959 and GraL 203802–400815 (GraL designating a gravitational lens system). Five previously known lensed systems were also re-discovered.

Further examination of Gaia DR2 by Ducourant et al. (2018) showed that out of 481 known multiply imaged quasars at that time, 206 had at least one image in Gaia DR2. Among the 44 known quadruply-imaged systems, 29 had at least one image in DR2. For twelve of these, all 4 components were found in DR2, while eight have 4 components, eight have 2, and one has only 1.

Their physical modelling of the quadruple system HE 0435–1223 shows that models are much better constrained when using Gaia astrometry, in particular for the relative positions of the background quasar and the lensing object. It follows that more detailed modelling will benefit from Gaia's sub-milliarcsec astrometry.



Ostrovski et al. (2018)

Gaia DR1 data was used in the discovery and modelling of the five-image quasar PS J0630–1201, at $z = 3.34$ (Ostrovski et al. 2018). Four of the images, ABCD, lie in a canonical 'cusp' configuration, of which A, B, and C were detected and flagged by Gaia, with G magnitudes of 19.95, 19.76, and 19.61 respectively. In addition, Keck near-infrared imaging revealed two lensing galaxies, G1 and G2, and an additional point source E. The relatively bright fifth image raises the possibility of measuring a total of ten time delays, all predicted to lie in the range of 1–245 days.

Of course, brightness variations, whether caused by physical effects intrinsic to the quasar (notably source variability), or extrinsic (specifically gravitational lensing), all have an effect on the apparent position of the quasar, and can affect linking of the Gaia reference frame to an inertial one. Details of these and related effects have been given by Bachchan et al. (2016), and many other studies have been carried out subsequently.

The Gaia data is being widely used to re-visit earlier compilations of quasars, and possible quasars, using the new high-accuracy proper motions or colours to validate or refute such candidates.

This has been carried out using Gaia DR2 applied to the 190 000 quasar candidates in the Kilo-Degree Survey Data Release 3 (KiDS DR3) by Nakoneczny et al. (2019).

Cross-matching with Gaia DR2 similarly assisted in the fifth release of the Large Quasar Astrometric Catalogue (LQAC–5), resulting in a list of 592 809 objects with 398 697 Gaia counterparts (Souchay et al. 2019).

Gaia DR2 data was also used in the finalisation of the Sloan Digital Sky Survey IV quasar catalogue from Data Release 16 of the extended Baryon Oscillation Spectroscopic Survey (eBOSS). Their 'quasar-only' subset contains 750 414 quasars, and is estimated to be 99.8% complete, with 0.3–1.3% contamination (Lyke et al. 2020).

The huge quantity of data acquired by Gaia each day, around 40–50 Gbytes, and the vast numbers of sources observed each day, means that the data processing on ground has to rely on semi-automated methods of object classification and parameter estimation.

An insight into results expected from Gaia DR3 was given by Delchambre (2018). He used the blue ($B_{\rm P}$) and red ($R_{\rm P}$) spectra from the satellite to determine, through supervised machine-learning, the astrophysical parameters of quasars, including estimates of their redshift, their continuum slope, and the total equivalent width of their emission lines.

More details of the classification using Gaia DR2 data alone are given by Bailer-Jones et al. (2019).

Pre-Gaia, extremely luminous quasars were not easy to discover, because high-redshift candidates are heavily outnumbered by nearby stars, these contaminants being typically of low mass and temperature. As a result, spectroscopic follow-up was often biased against the brightest and most interesting candidates.

Using Gaia astrometry and photometry, the main contaminants can be recognised and rejected, and true quasars identified as red objects (in $B_{\rm P} - R_{\rm P}$) at very large distances, i.e. with proper motions consistent with zero.

Wolf et al. (2018) used the Gaia DR2 proper motions in this way to facilitate the discovery of SMSS J215728.21–360215.1, at $G = 18.286$ mag and $z = 4.75$. Seen by Gaia as an isolated single source, and thus unlikely to be strongly gravitationally lensed, they concluded that this is the quasar with the highest unlensed ultraviolet–optical luminosity known to date.

Damped Lyman-α absorbers are a class of quasar with intervening absorption-line systems along our line-of-sight. They provide important information on the cosmic chemical evolution of galaxies. Finding them involves searching for objects that are reddened by metal-rich and dusty foreground absorbers.

Geier et al. (2019) used Gaia DR2 astrometry with existing optical and infrared photometry to discover a $z = 2.60$ quasar strongly reddened by dust in a heavilty damped Lyman-α absorber at $z = 2.226$. Another similar example discovery is given by Fynbo et al. (2020).

By the end of 2020 nearly 100 scientific publications have used the Gaia DR1 or DR2 data to examine the reliability of earlier quasar surveys, to identify other particularly interesting objects, to isolate and classify numerous gravitationally lensed systems, and to quantify various effects important in further refining the extragalactic reference frame link.

Work on quasars using the Gaia data is clearly set to enter a new and vigorous phase over the coming years as the improving quantity and quality of the Gaia astrometry, photometry, and imaging data becomes available.