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Multiply imaged quasars in the Gaia DR1

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Abstract. Because of to its exceptional resolving power, Gaia should detect a few thousands gravitational lensed systems. These consist in multiple images of background quasars. The estimated number of lens phenomena in the sky, however, depends on the cosmological model considered. By taking into account the observational bias that will restrict the detection of lensed quasars, identification of these up to a given limiting magnitude will constrain the cosmological parameters.

We have investigated the known gravitationally lensed quasars present in the Gaia DR1, and found that a significant number of components of these systems have been measured and are present in the Gaia DR1 catalogue although quasi none of them have all their components detected. We additionally examined the immediate surroundings of QSOs from the large Quasar catalogue, LQAC3, and detected several configurations compatible with gravitational lensing phenomena. A more global strategy to systematically detect the potential candidates in the various releases of the Gaia catalogue is presented.

Keywords. astrometry, gravitational lensing, quasars: general

1. Introduction

Although it has been designed for the exploration of the Milky Way, the ESA - Gaia satellite (Perryman *et al.* 2001, Gaia Collaboration 2016b) is observing many extragalactic objects. It is expected to detect about one million of galaxies (De Souza *et al.* 2014) and 0.5 million quasars (Mignard 2012). These distant objects may be subject to lensing phenomena and in some cases multiple images of quasars will be detected by the satellite (Finet and Surdej 2016). Depending on the model of Universe considered and on the deflecting population of galaxies, thousands quasar gravitational lenses (GL) could be present in the Gaia catalogue. These ones would be for most composed of 2 images but several with 3 and 4 images should also be detectable. Counts of GL will bring independent constraints on the cosmological parameters (H_0, Ω_0, Λ_0) (Finet and Surdej 2016).

Up to now, quasar gravitational lensing phenomena have been discovered from ground with the limitation of poor resolving power and only a few hundreds systems are known today. They were either discovered in quasar studies or by mining essentially the Sloan Digital Sky Survey (Inada *et al.* 2012, More *et al.* 2016, etc.) which is not an all-sky survey. In this respect Gaia will be the first all-sky survey of gravitational lenses.

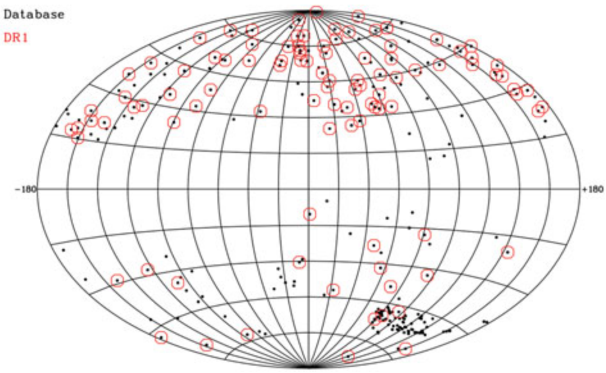

Figure 1. Distribution of the known multiply imaged quasars in galactic coordinates. Circles indicate the detection by Gaia (as given in DR1) of at least one of the images of the quasars.

Moreover, since Gaia observes from space its resolving power is exceptional and should allow to disentangle multiple images that would be merged into a single image viewed from ground and that would thus remain undetectable without Gaia.

We present here the efforts that we dedicate to detect GL from the various data releases of Gaia (Gaia Collaboration 2016). These efforts are in three directions : 1- search for known GL, 2- explore the surrounding of known quasars for neighbours (i.e. potential multiple images of the central quasar) and 3- blind search the Gaia data releases for lensing configurations.

2. The known quasar gravitational lenses

To evaluate the potentiality of Gaia in terms of detection of gravitational lens systems we searched the litterature to set up an updated database of multiply imaged quasars. The main source of data comes from the Gravitational Lens Database of Castles (Munoz *et al.* 1999) (see https://www.cfa. harvard.edu/castles/) which unfortunately seems not to have been updated since several years. We completed these data essentially with the SQLS - SDSS Quasar Lens Survey (Inada *et al.* 2012) that contains resolved and unresolved GL candidates and with the SDSS - III BOSS quasar lens survey (More *et al.* 2016). Our database comprises 272 GL systems from which 20 have 3 or more images. We present in Fig. 1 the locations on the sky of the gravitational lenses from our database together with their detection by Gaia as published in the Gaia DR1 (Gaia Collaboration 2016a). Most of the known multiply imaged quasars are partially present in the Gaia DR1 but most of these do not have all their components published. The selection of the objects to be published in this first release is at the origin of the absence of many of these components and the situation should be much improved in the Gaia DR2 with this respect.

3. Automatic search around known quasars

To detect new multiply imaged quasars, we searched the Gaia DR1 for companions around known quasars. We thus considered the $\sim 322\,000$ sources of the Large Quasars Astrometric Catalogue LQAC3 (Souchay *et al.* 2015) and searched the Gaia DR1 in a radius of 3". In the case of about 209 000 quasars, a single counterpart is found. But in 1300 cases, 2 sources (including the LQAC3 quasar) are found, in 70 cases 3 sources and in 10 cases 4 and more sources. Most of these cases correspond to optical

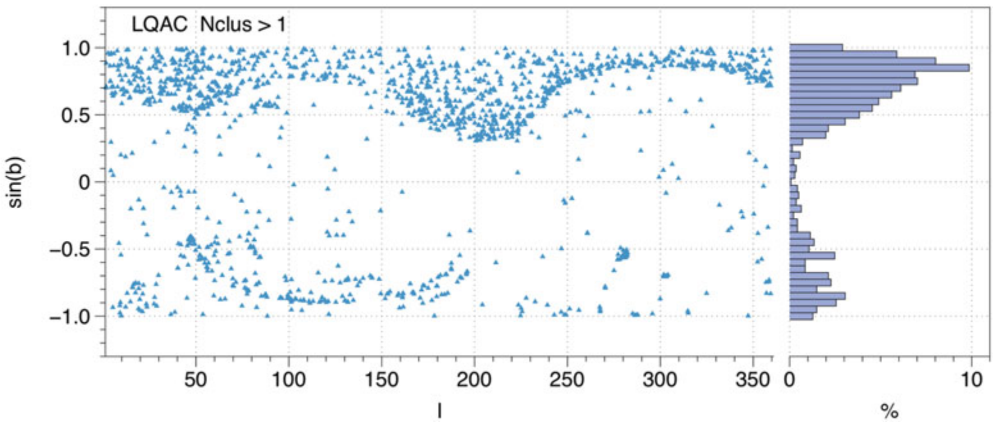

Figure 2. Distribution of clusters of objects including a LQAC3 quasar in Gaia DR1 (Galactic coordinates). On right part frequency of clusters as function of galactic latitude.

projections of stars in the direction of the quasar but several of these configurations may be gravitational lens systems. We notice that some well known gravitational lenses are recovered by this method; the unknown configurations need serious analysis and additional observations for validation. We present in Fig. 2 the locations on the sky of the clusters of objects around LQAC3 quasars that comprise 2 or more sources found in Gaia DR1. The inhomogeneous repartition of candidates clearly reproduces the footprint of the LQAC3 catalogue (mostly SDSS footprint).

4. Automatic blind detection of Gravitational Lenses in Gaia DR1

To systematically detect the gravitational lens systems in Gaia releases we developed the SELenA (Systematic Exploration of Lenses from Astrometry) pipeline. This is an *intelligent* and adaptable framework designed to search lenses in astrometric catalogues and to model them. It may incorporate additional informations and constraints such as photometry, spectroscopy, time-series, etc. The Gaia DR1 is obviously an excellent benchmark for this framework. At first the full Gaia DR1 is handled and clusters of objects in the (RA,Dec) space are isolated and their similarity in other spaces such as G magnitudes, color, proper motions, etc... is also tested (see Fig. 3-*Left* for the known properties of images of lensed quasars). Then a machine learning based classifier is applied to exclude the low probability configurations. The classifier is beforehand trained with simulations. Finally a forward model implemented in OpenCL (that may run in CPU, GPU or FPGA) performs an efficient sampling of the parameter space of the lens system (deflector : axis ratio, major axis, Einstein radius (H0+Mass+redshift), position angle, shear terms – background quasar : angular distance to the lens, position angle) for the Bayesian inference process (see for example Fig. 3-*Right* for the results of one modelling). This model is able to test millions of lens configurations per second. We applied the first step of SELenA to the whole Gaia DR1, and could derive a list of a few thousands candidates GL with 3 and 4 images outside the galactic plane ($\mid b \mid \geqslant 50$), with differences of positions smaller than 3" and differences in magnitude less than 3 magnitudes. Indeed the availability of proper motions and BP/RP photometry in the next data release will greatly help to reduce the number of candidates. The candidates are under analysis in order to propose the most promising ones for validation via multi colour imaging.

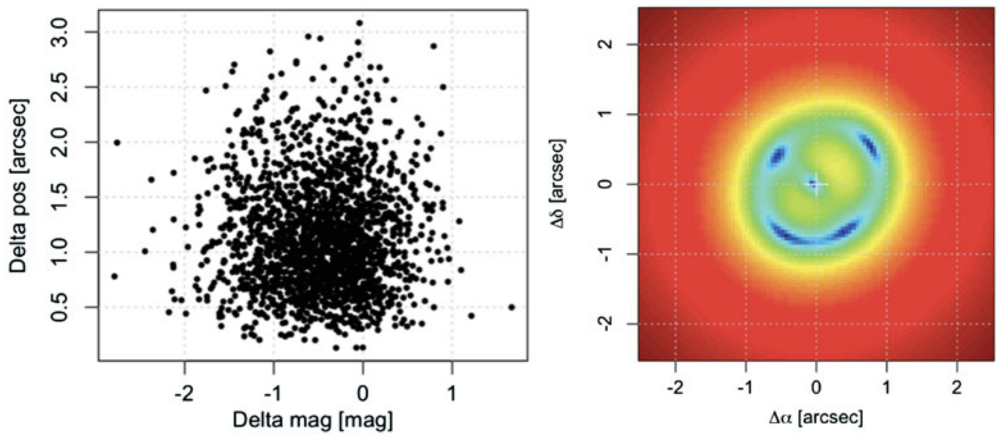

Figure 3. Left : known properties (differences of magnitude, differences of position) of images of lensed quasars (as given by model from Wertz and Surdej (2014)). **Right** : SELenA simulated "happy" lens.

5. Conclusion

We presented here three strategies to detect and recover gravitational lenses from the Gaia DR1. A preliminary list of good candidates has been established and is under evaluation for validation.

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