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The Large Quasar Astrometric Catalog (LQAC): principle and construction

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Abstract. The huge and increasing number of quasars detected and identified from various sky surveys leads to a large quantity of data which brings various and inhomogeneous information concerning celestial coordinates with respect to the ICRF, photometry, spectroscopic and radio properties. The aim of the LQAC (Large Quasar Astrometric Catalog) is to compile all the recorded quasars until the present date, gathering the information above, when available, with the best estimation of their celestial coordinates with respect to the ICRF.

Key words. reference systems – astrometry – quasars: general

1. Introduction

Since the identification of the first quasar 3C273 by Maarten Schmidt in 1962 as an extragalactic radio source with high redshift and the construction of the first quasars catalog by De Veny et al.(1971) containing 202 objects, the number of known quasars has steadily increased, in particular in the past decade, thanks to huge surveys like the 2dF QSO's survey (Croom et al.2004) and for a large part to the Sloan Digital Sky Survey (Fan et al., 1999; Adelman-Mc.Carthy et al., 2006). Nowadays the number of recorded quasars that can be compiled reach more than 180,000 objects.

Quasars represent ideal objects for modern astrometry, for they *a priori* materialize quasi-inertial directions in space. As they are supposed to present no detectable proper motion on contrast to stars, they constitute the basis of a primary reference frame. It is the case of the ICRF2 (Ma et al., 2009; Boboltz et al., 2010). The impressive increase of the number of quasars discovered in the recent years, in particular from automated surveys, as the Sloan Digital Sky Survey (SDSS) motivates the construction of a global compilation of all the quasars which have been reckoned at the present time. This kind of systematic archiving has been successfully done with various up dates by Véron-Cetty and Véron from 1984 to 2010 (see for instance Véron-Cetty and Véron, 2010). Nevertheless two kinds of disadvantages can be found in these various up dated catalogs : first they do not take into account all the data available. Second, there is no guarantee of precision and accuracy concerning the

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equatorial coordinates of the radio sources included. To improve this situation Souchay et al. (2009) carried out the construction of the Large Quasar Astrometric Catalogue, referred as the LQAC.

2. The Large Quasar Astrometric Catalog

The improvements brought by the LQAC-2 of catalogs with respect to other compilations can be summarized as follows : it includes the maximum number of objects; it gives *a priori* the most accurate celestial coordinates of the quasars with respect to the ICRF ; it gives a clear and direct information about the cross-identification between the catalogs involved in the compilation ; for the purpose of homogeneity, it systematically privileges large surveys to small catalogs; it is based on a compilation strategy in relation with the astrometric quality of the catalogs; it contains exhaustive information on the photometry of the objects, thanks to cross-identifications between the constituent catalogs as well as between large surveys such as the 2MASS catalog (Cutri et al.,2003), the USNO B1.0 catalog (Monet et al.,2003) or the GSC2.3 catalog (Lasker et al., 2008). Finally the LQAC determines the absolute magnitudes of quasars in both bands i and r, by using up-to-date models of galactic extinction and recent values of cosmological parameters.

3. The up-dated version LQAC-2

Several reasons led us to construct a new version of the LQAC, called the LQAC-2 (Souchay et al., 2011). At first we considered a significant amount of new data from different origins, such as the ICRF2 (Ma et al.,2009; Boboltz et al.,2010) and the VCS (Petrov et al., 2008) at radio wavelengths, as well as the 8th release (DR8) of the Sloan Digital Sky Survey at optical wavelengths (Aihara et al.,2011). A second important reason is to include the equatorial coordinates of the quasars as determined from the LQRF (Large Quasar Reference Frame), which *a priori* gives a more accurate optical determination of celestial coordinates with respect to the ICRF (Andrei et al,2009), compared with those given by original catalogs, for a high percentage of objects (except of course those observed with the VLBI). Finally another reason comes from a decision to densify the data compared to the first LQAC catalog. One of the improvements is to include an LQAC identification number based on the celestial coordinates of the objects. Another significant improvement is to determine three kinds of indexes, thereby allowing a morphological classification. These indexes are obtained by comparison to the average morphology of the surrounding stars, thus freed of image aberrations. They are obtained from B,R,I images and their first interpretation is to point out the signature of the host galaxy.

3.1. Definition of a quasar

One of the crucial points of the LQAC is the definition itself of a quasar, which must be clearly given before making a compilation. In their recent catalog updates, Véron-Cetty and Véron (2006,2010) define a quasar as a starlike object or as an object with a starlike nucleus with broad emission lines and with an absolute magnitude below a given threshold M_0. This is a purely arbitrary definition that also depends on the changes in the value of fundamental cosmological parameters considered for determining the absolute magnitude. For instance, we can see that in the two updates mentioned above the magnitude threshold M_0 was shifted from $M_0 = -23.00$ to $M_0 = -22.25$ when considering the change of the Hubble constant from $H_0 = 50kms^{-1}Mpc^{-1}$ to $H_0 = 71kms^{-1}Mpc^{-1}$. The disadvantage of adopting this kind of conventional definition is both that it does not seem to correspond to any discontinuity in the physical nature of the object and that it is directly dependent on cosmological parameters and of their revision.

In contrast for the LQAC-2 the definition of "quasar" does not rely on those arbitrary cosmological parameters: it designates any object that can be seen as a classical quasar from a given point of view and with a specific set of image parameters. Notice that this definition may include some AGN usually sorted as Seyfert galaxies or radio galaxies, and yet it seems consistent with our aim of gathering data on a specific physical object. In the paper devoted to their last catalog update, Véron-Cetty and Véron (2010) point out that some objects present in the LQAC (Souchay et al.,2009) were not strictly quasars as they have no optical identification or measured redshift. They refer to 2921 objects observed by the radio VLBI technique present in the ICRF2, VLBA, VLA, and JVAS catalogs (with respective flags A,B,C and D). In fact these objects can indeed be considered as quasars because of their very compact core-dominated VLBI radio map structure at the scale of the mas (milliarcsecond) level.

3.2. The recent catalogs in the LQAC-2 compilation

New data has been included in the LQAC-2 when compared with the first version of the LQAC (Souchay et al., 2009). This data comes in complement to surveys which were already included in the LQAC and which remain unchanged since this first version, such as the VLBA calibrator survey (Beasley et al.,2002), the FIRST catalog (Becker et al.,1995; Becker et al.,2001), the 2-degree Field quasar redshift Survey, quoted as 2QZ (Croom et al.,2004), the Hewitt and Burbridge(1993) catalog. This new data is described in the following :

• The ICRF2

The second realization of the International Celestial Reference Frame, called the ICRF2 (Ma et al.,2009; Boboltz et al.,2010), resulting from a considerable number of VLBI sessions, contains the equatorial coordinates of 3414 compact radio sources,that is more than five times the number of objects in the first version of the ICRF (Ma et al.,1998). The improvement also concerns the astrometric accuracy, with a noise floor for positions of only $\approx 40\mu as$ (microarcseconds), and an axis stability around $10\mu as$. The alignment of the ICRF2 to the ICRF1 was made using 138 stable common sources. A set of 295 new defining sources was selected on the basis of both positional stability and lack of intrinsic source structure. These sources have a more uniform sky distribution and better stability as in the case of the first ICRF(Ma et al.,1998) and the ICRF1-Ext.2 (Fey et al., 2004).

• The VLBI global solution rfc2010d

The VLBI astrometric global solution rfc2010d used all the available VLBI observations at 8.6 GHz and 2.2 GHz, as well as 5 and 22 GHz from April 1984 to June 2010. These observations were done during a large number of VLBI sessions dedicated to specific surveys, such as the VLBA Calibrator Survey (VCS), the VLBA Galactic Plan Survey, the Australian LBA Calibrator Survey, the IFGL AGN4s on parsec scales, VLBI2MASS radio astronomy project, and the EVN Galactic Plan Survey. The total number of delays in this rfc2010d update reaches 8027588 estimates.

• The new release of the Sloan Digital Sky Survey (SDSS)

The Sloan Digital Sky Survey (SDSS) is one of the most ambitious and influential surveys in the history of astronomy. In operation for more than eight years it obtained deep, multi-color images covering more than a quarter of the sky with three dimensional maps of the universe containing a little less than 1 million galaxies and more than 120 000 quasars. The construction of the survey started from a dedicated 2.5 m telescope located at Apache Point, New Mexico, USA. Images are obtained in five broad optical bands (designated u, g,r, i, z) covering the wavelength range of the CCD response from atmospheric ultraviolet cut-off to the near infrared (Fukugita et al., 1996). The present SDSS-III, a program of four new surveys, began its observational sessions in July 2008, and will continue through 2014. More information on the SDSS-III can be found on the web site http://www.sdss3.org/. The SDSS quasar's catalog used here comes from the first data release of the SDSS-III and the eight data release (DR8) counting from the beginning of the SDSS (Aihara et al., 2011). This five band imaging release includes a new

5200 deg^2 area in the Southern Galactic cap, bringing the total area of the SDSS imaging to 14,555 deg^2, roughly a third of the celestial sphere. The various quasars sub-catalogs coming from successive releases (from DR1 to DR8) of the SDSS show some incoherence for a significant amount of objects disappear from one given release to the next one, for various reasons (Schneider et al.,2010): for instance suspected pairs arising from cross matching the DR5 and the DR7 and showing offsets larger than 1 arcsecond were excluded for safety, and changes in the photometric measurements dropped the luminosity below the absolute magnitude criterion for quasar selection. Therefore instead of packing all the quasars present in some releases and not in other ones, as was done in the Véron-Cetty and Véron (2010) compilation procedure, we only considered the last release (DR8) as the reference for our compilation.

• The 2dF-SDSS LRG and QSO (2SLAQ) Survey

The 2SLAQ Survey, which stands for the 2dF-Sloan Digital Sky Survey luminous red galaxy (LRG) and QSO Survey (2dF-SDSS LRG and QSO) (da Angela et al.,2008), is an extension of the previous 2QZ survey at fainter magnitudes. For the main aspects of this survey, we can refer to the explanations in Richards et al. (2005), who give the results of the first semesters of data collection with the corresponding luminosity function for a sample of roughly 5600 QSOs. Nowadays, the survey has been extended to a total of around 9000 QSO's, with $z < 3$. The strategy of the survey consisted in combining photometric and spectroscopic data from the same objects, from the Sloan telescope and from the 2dF one respectively. The sky regions covered by the 2dF instrument consist of two 2° wide equatorial strips containing QSO candidates, observed by the SDSS survey. Spectroscopic fibers were allocated simultaneously to the LRGs (luminous red galaxies) linked to the red spectrograph and to the QSOs linked to the blue spectrograph. The two strips were located in the north Galactic cap (NGC) and the south galactic cap (SGC). In the NGC, 6680 objects (57.9 %) were classified as QSOs whereas 2977 ones (18.0 %) were identified as NELGs (narrow emission line galaxies) and 1829 ones (15.9 %) as stars. In the SGC the numbers are respectively 2378 QSO's(49.7 %) ,905 NELG's (18.9 %), and 835 stars (17.4 %).

• Complementary information from the USNO B1.0, the GSC2.3, and the 2MASS catalogs

The three all-sky surveys USNOB1.0 (Monet et al.,2003), GSC2.3 (Lasker et al.,2008) and 2MASS (Cutri et al.,2003) will not bring any additional quasar for our compilation, but thanks to cross-identifications, they add significant new photometric information, filling a substantial amount of gaps in the data. The USNO-B1.0 catalog (Monet et al.,2003), as well as the GSC2.3 catalog (Lasker et al.,2008) come both from photographic plates and contain around 1 million objects each, add B, R, I magnitudes to our compilation, whereas the 2MASS catalog (Cutri et al.,2003) results from an all-sky infrared survey working at J, H, and K_s bands, to a $3 - \sigma$ sensitivity of 17.1, 16.4, and 15.3 mag., respectively.

• The Véron-Cetty and Véron catalog

Recently, Véron-Cetty and Véron (2010) have published the 13th edition of their catalog of quasars, quoted in the following as VV2010 and itself consisting in a compilation of all the quasars discovered up to now, including those coming from very small catalogs, some of them containing only a few objects. As our compilation procedure in this paper is essentially based on the using of only nine catalogs, characterized either by their very good accuracy (as the ICRF2) or by their large dataset (as the SDSS), we cannot avoid missing a significant number of objects that are not included in any of the nine catalogs above. Therefore we rely on the VV2010 catalog to add these missing quasars. Finally 22,440 objects were picked up from the VV2010 catalog to complete our LQAC-2 catalog, which represents 11.96 % of the total number of quasars included. Among these 22,440 objects, 7,869 are classified as QSO's and 14,571 as AGN's.

On the other hand, in the LQAC-2, Souchay et al.(2011) did not take all the VV2010 quasars coming from the SDSS into account, that is to say, 88274 objects which represent 52.25 % of the whole VV2010 catalog. The rationale of this choice is that the SDSS quasars in VV2010 come from various releases of the SDSS and that for the reasons already explained in Sect. 3.4, a significant number of them were not present in the last DR8 release, maybe because their existence as a quasar is doubtful. This choice does not affect the completeness of the LQAC-2, for the SDSS (DR8) catalog is included in our compilation (flag "E").

3.3. *The cross-identification algorithm*

The method used in the LQAC-2 to insure cross-identification between quasars belonging to two distinct catalogs is significantly different from the one used in the first version of the LQAC. There is no fixing of an arbitrary threshold (typically 1") of the angular distance beyond which two cross identified objects are considered as distinct (instead of representing a single object). Indeed, this threshold value is determined from a previous round of cross identifications, with a relatively high value of the threshold. The value of the rms σ of the angular distances is calculated. Then the rejection threshold for common identification is fixed to 5σ.

4. Conclusion

The LQAC-2 (Souchay et al.,2011) is a compilation of all the recorded quasars at a given date (2011). It is an improved version of the first release (Souchay et al.,2009). It contains 187 504 objects, which is a 65 % increase over the 113,666 quasars in the first LQAC catalog. Moreover, it includes new features that considerably extend the information for the objects. These are: adopting of a LQAC classification number based on the celestial coordinates; adding of the celestial coordinates of the quasars in the LQRF (Andrei et al.,2009), which are generally significantly more accurate than the celestial coordinates found in the original catalogs; determining three morphological indexes (skewness, roundness, normalness) for each of the three bands *B*, *R*, and *I*. The quasars in the LQAC-2 come principally from a set of nine leading quasars catalogs chosen for their optimal accuracy (as the ICRF2) or their density (as the SDSS). In addition, 22,440 objects not included in these nine catalogs are picked up from the Véron-Cetty and Véron (2010) catalog, in order to insure a complete sample. To provide some missing information concerning the photometry (apparent magnitudes of the quasars), we used the GSC2.3 (Lasker et al.,2008), B1.0 (Monet et al.,2003), and 2MASS (Cutri et al.,2003)all-sky surveys.

The LQAC-2 is particularly useful for listing all the recorded quasars with emphasis on their astrometric accuracy. Moreover it should help to carry out statistical studies in various fields : analysis of the spatial density, correlation between parameters (redshift, absolute magnitudes, colors etc...), preparation for the Gaia space mission, comparison of the radio and optical positions of radio stars (Andrei et al.,1995) etc. It should be fully used for determining the close approaches between quasars and moving objects such as asteroids and planets (Souchay et al.,2007; Nedelcu et al.,2010) or easy comparisons between catalogs (Souchay et al.,2008).

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