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THE FUTURE OF OPTICAL REFERENCE SYSTEMS

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Abstract. Optical reference frames have been traditionally limited in astrometric accuracy compared to radio reference frames which have long reached a sub-milliarcsecond accuracy. The next decade holds promises for big changes in this area with the launch of the Gaia space astrometric mission which unlike Hipparcos will be able to observe several hundred thousands of extragalactic objects with an astrometric accuracy of a few tens of microarcseconds. After reviewing the current status of optical and radio reference frames, this paper draws prospects for building the Gaia optical frame and its alignment with the current International Celestial Reference Frame (ICRF) which is based on radio-interferometric measurements.

1 Introduction

The extragalactic reference system is defined based on the positions of active galactic nuclei (AGN), a class of objects located at the center of distant active galaxies and characterized by extremely compact and bright emission on milliarcsecond (mas) scales. These sources show various observational properties over the whole electromagnetic spectrum, ranging from radio to γ-ray energies, most of which are explained by unified theories of active galactic nuclei. According to the standard representation (Urry & Padovani 1995), illustrated in Fig. 1a, the key elements of a radio-loud active galactic nucleus are a central supermassive black hole, an accretion disk, a broad-line region (fast-moving gas clouds) surrounded by a dusty torus region, an extended narrow-line region (slow-moving gas clouds), and a pair of relativistically out-flowing jets emitting synchrotron radiation which originate within a few tens of Schwarzschild radii from the black hole.

The inner compact radio structure (usually called the source core) detected by Very Long Baseline Interferometry (VLBI) arrays, originates at the base of the jet where the optical depth is approximately unity. Orientation has a major influence on the observed AGN properties since relativistic beaming strongly amplifies kinematics and brightness for jets that are pointed towards us while it attenuates these for jets that are pointed away from us. As a result, most sources show a one-sided morphology with a dominant core component on VLBI scales (Figs. 1b & c) due to sensitivity limitations and selection effects. The most suitable sources for defining a celestial reference frame are those that are the most compact on these scales. Due to their cosmological distances, such extragalactic sources show no transverse motion and therefore define a quasi-inertial system in a kinematical way, i.e. the system is non-rotating with respect to a local inertial frame.

2 The current IAU fundamental frame

The official IAU reference frame in use since 1 January 1998 is the International Celestial Reference Frame (ICRF), which is currently based on the VLBI positions of 717 extragalactic radio sources (Fig. 2). Of these, 608 sources are from the original ICRF (Ma et al. 1998), built from geodetic/astrometric VLBI data obtained between 1979 and 1995. The ICRF source categorization comprised 212 well-observed *defining* sources (which served to orient the axes of the frame), 294 less-observed *candidate* sources, and 102 *other* sources showing coordinate instabilities. The accuracy in the individual ICRF source positions has a floor of 250 microarcseconds (μas), while the axes of the frame are stable to about 20 μas in orientation (Fig. 2). Since then the position of the non-defining sources has been improved and the frame has been extended by 109 *new* sources in ICRF-Ext.1 and ICRF-Ext.2 using additional data acquired in the period 1995–2002 (Fey et al. 2004a).

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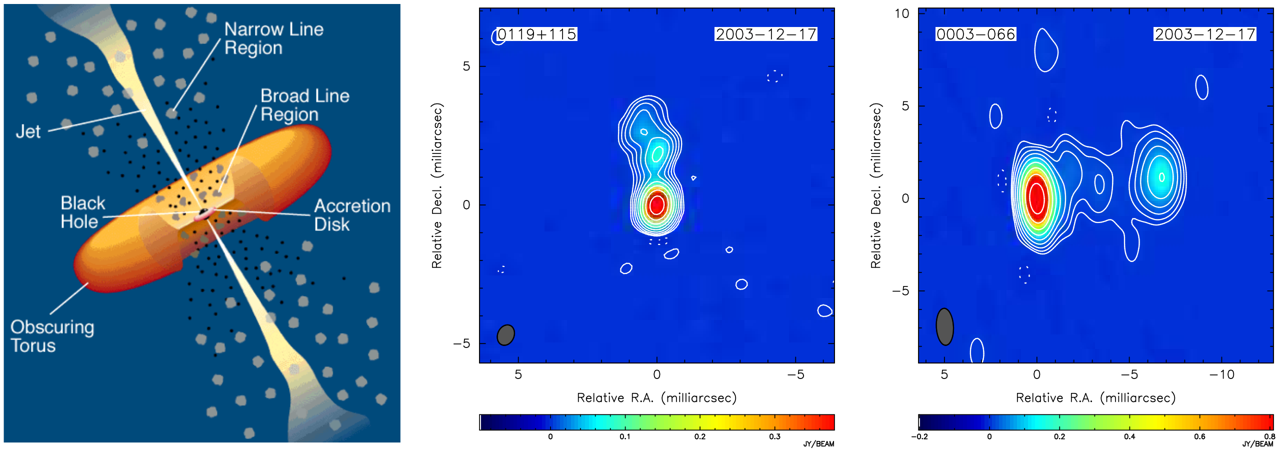

Fig. 1. *Left panel:* Schematic view of the key elements of an active galactic nucleus (credit: C. M. Urry & P. Padovani). *Middle/right panels:* VLBI images at 8.6 GHz for two ICRF sources (0003−066 and 0119+215) observed on 2003/12/17.

Continued VLBI observation of the ICRF sources is essential to maintain the viability and integrity of the frame on the long term because the intensity and VLBI morphology of extragalactic objects evolve in impredictable ways. Densification of the frame through the identification and observation of new high-quality sources is equally important to facilitate routine differential phase-referenced astrometry, e.g. for spacecraft navigation, and to control any local deformations of the frame which might be caused by tropospheric propagation effects or apparent source motions due to variable intrinsic VLBI structure. The VLBA Calibrator Survey (VCS) provides single-epoch VLBI images and astrometric positions at the milliarcsecond level for approximately 3500 additional sources (Petrov et al. 2008 and references therein). This survey forms the basis for the ICRF densification north of $-45°$ declination. Increasing the density of sources further south has been more difficult because of the limited number of VLBI antennas in the southern hemisphere. Dedicated programs have now been initiated (Fey et al. 2004b, 2006), which should improve the situation, but progress is slower than for the northern sky.

At the IAU XXVI$^{\rm th}$ General Assembly in Prague (August 2006), the community decided to engage in the realization of the successor of the ICRF, to be presented at the next IAU General Assembly in 2009. The motivation for generating this new celestial frame is to benefit from recent improvements in VLBI modeling (e.g. for the troposphere) and to take advantage of the wealth of VLBI data that have been acquired since the time the ICRF was built. A specific issue to be addressed is whether and how to incorporate the VCS sources in this new realization. Another major issue is the revision of the source categorization, in particular the choice of the defining sources. Such a revision is necessary because some of the original ICRF defining sources were found to have extended structures (Fey & Charlot 2000) or position instabilities (e.g. MacMillan 2006), and are therefore improper for defining the celestial frame with the highest accuracy.

3 Towards the Gaia optical frame

The most comprehensive optical catalog available to date is the Large Quasar Astrometric Catalog (LQAC) recently compiled by Souchay et al. (2008). This catalog comprises 113666 objects, an increase of 25% compared to the previous compilation by Véron-Cetty & Véron (2006) which reported only about 85000 objects. The construction of the LQAC was guided by the aim of reporting the most accurate position for every identified quasar, as available through 11 major optical catalogs from which the LQAC was derived. Among these, the largest contributing catalog was the DR5 release of the Sloan Digital Sky Survey which comprises about 75000 quasars (Schneider et al. 2007). In addition to source position estimates, the LQAC also provides redshift and photometric information when available as well as estimates of absolute magnitudes. It is anticipated that the LQAC will be updated on an annual basis by adding newly-discovered quasars with the goal of obtaining the most complete and the most precise optical catalog of quasars by the time Gaia is launched in 2011.

The Gaia space astrometric mission will survey all stars and quasars down to an apparent magnitude of 20 (Perryman 2002). Position accuracies will range from a few tens of microarcseconds at magnitude 15–18 to about 200 μas at magnitude 20. Based on current estimates from local surveys, it is expected that 500 000 such

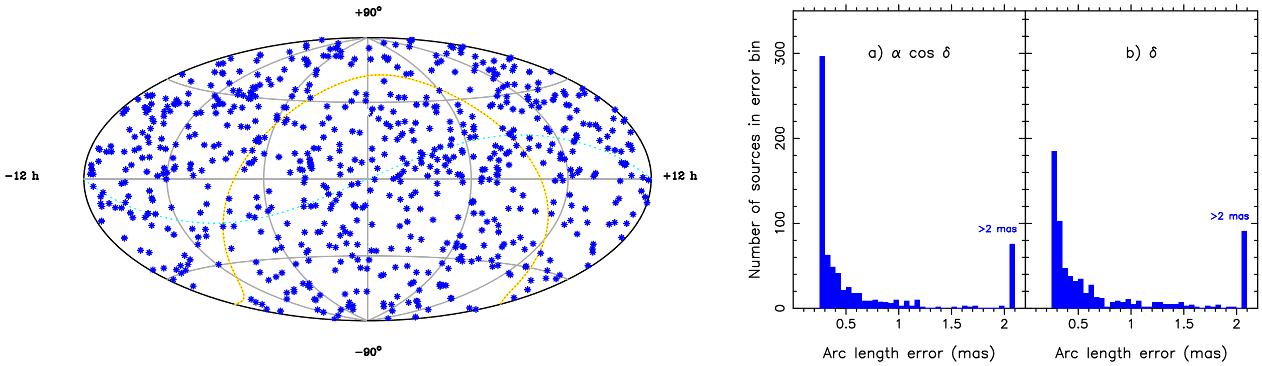

Fig. 2. *Left panel:* Distribution of the current 717 ICRF sources on an Aitoff equal-area projection of the celestial sphere. *Right panel:* Histogram of source position errors in *(a)* right ascension and *(b)* declination.

quasars should be detected; unlike Hipparcos, Gaia will thus be able to construct a dense optical reference frame *directly* in the visible wavebands. Initial simulations showed that the residual spin of the Gaia reference frame could be determined to 0.5 μas/yr with a *clean sample* of 10 000 defining sources (Mignard 2002). In practice, the ultimate accuracy of the frame may be limited by random instability of the sources which may show extended and variable structure on these spatial scales, similar to that observed at radio wavelengths (Fey & Charlot 2000). Despite this limitation, the Gaia reference frame should surpass the current ICRF, both in accuracy and in source density. Hence, it is likely that the realization of the fundamental celestial frame will be brought back to visible wavebands in about 10 years when the Gaia catalog is published, although the VLBI reference frame should remain for specific applications such as the monitoring of the Earth's rotation.

4 Issues in realizing the Gaia frame

Prior to acquiring data, simulations will be essential in order to determine how to best use the thousands of quasars that will be detected by Gaia for realizing the celestial frame. In particular, it will important to study the impact of the lack of sources in the galactic plane and more generally the effect of the distribution of the sources on the quality of the frame. Another important parameter to decide on is the magnitude limit of the sources to consider for inclusion in the clean sample that will define the Gaia frame. Should this magnitude be strictly limited to a value of 18 as originally anticipated (Mignard 2002) or should this criterion be relaxed in order include more sources at the expense of coordinate accuracy? In this respect, the actual magnitude distribution in the LQAC should be quite useful to determine the best compromise between having more sources of lesser astrometric quality or less sources of higher astrometric quality. One should also note that these objects may vary in magnitude, especially the blazar-type objects (a class of objects with jets oriented close to the line of sight) which can show changes of several magnitudes over short time scales (see Fig. 2b). Such variability needs to be investigated as it may affect the choice of the Gaia-defining sources and the quality of the frame.

During the construction process for the Gaia frame, an essential element will be its alignment with the current ICRF in order to maintain consistency with the International Celestial Reference System (Arias et al. 1995) when the transition from radio to optical wavelengths is made. Such alignement, to be obtained with the highest accuracy, requires a large number of sources common to the two frames. A study by Bourda et al. (2008a) revealed that only 10% of the current ICRF sources may be used for this purpose when considering the source magnitude and their VLBI position accuracy and compactness. This prompted the development of new VLBI observing program, targeted to weaker sources, in order to identify further high-quality sources for this alignment (Bourda et al. 2008b). Also to be investigated in this framework is the registration between the VLBI and Gaia positions since the spatial location of the radio and optical emission may differ due to opacities in the quasar jets. Kovalev et al. (2008) showed that on average the optical-radio *core shifts* in a sample of 29 ICRF objects are at the level of 100 μas, which is significant considering the expected accuracy of the Gaia catalog and that foreseen for the ICRF by 2015–2020. Such effects would thus have to be accounted for when aligning the two frames. On the other hand, the differences between the optical and radio positions may provide a direct measurement of such core shifts, which would be of high interest for probing AGN jet properties.

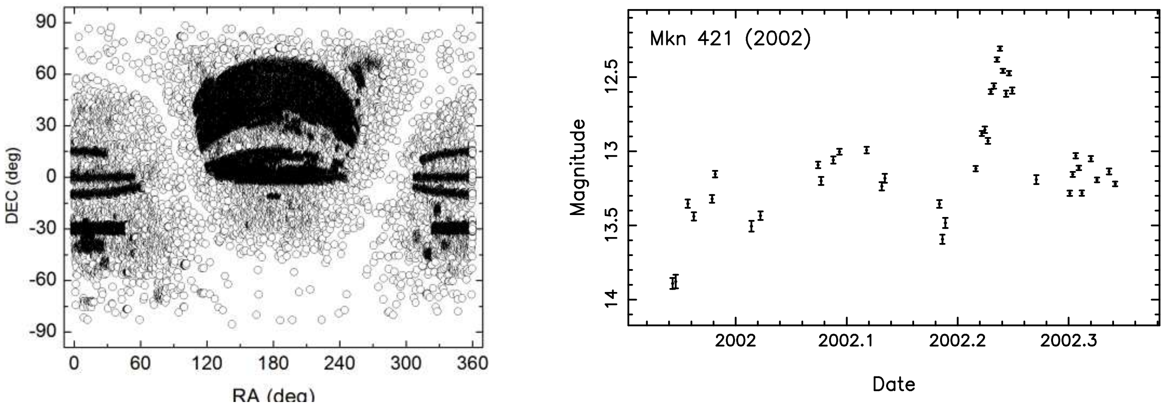

Fig. 3. *Left panel:* Distribution in equatorial coordinates of the 113666 quasars in the Large Quasar Astrometric Catalogue (reproduced from Souchay et al. 2008). *Right panel:* Optical variability of the BL Lac object Mkn 421 (corresponding to the ICRF source 1101+384) on scales of a few months in 2002.

5 Conclusion

The Gaia space astrometric mission will realize for the first time a highly-accurate extragalactic reference frame directly at optical wavelengths. This future frame will surpass the current radio-based ICRF both in accuracy (a few tens of microarcseconds in the individual source positions) and in the number of objects (500 000 sources). Simulations are necessary in order to determine the best strategy for constructing the frame (number of defining sources, sky distribution, magnitude limit) and assess the impact of limiting factors such as photometric variability. Particular attention should be paid to the alignment of the future Gaia frame with the current ICRF in order to maintain continuity in the International Celestial Reference System. Ultimately, comparisons of radio and optical positions may bring new insights into the physical properties of AGN jets.

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