

XXI SERBIAN ASTRONOMICAL CONFERENCE

Linking Gaia CRF with ICRF by means of V and R magnitudes of selected quasars

Miljana D. Jovanović

Astronomical Observatory, Belgrade, Serbia

E-mail: miljana@aob.rs

5-8 OCTOBER, Belgrade, Serbia, 2026

Introduction – I

- ▶ Astrometry (positional astronomy) – the field of astronomy that deals with the positions of celestial bodies.
- ▶ 1963. discovery of the quasar (Quasar - Quasi-Stellar Radio Object)
 - ▶ ICRF1 - 212 objects defining it (1998),
 - ▶ ICRF2 - 297 _____||_____ (2010),
 - ▶ ICRF3 - 303 _____||_____ (2019).
- ▶ In 1989, the HIPPARCOS (High Precision PARallax COLlecting Satellite) satellite was launched
 - ▶ Hipparcos – 118,218 stars, epoch J1991.25,
 - ▶ Tycho – 1,058,332, J1991.25,
 - ▶ Tycho2 – 2,539,913, J2000.0,
 - ▶ new Hipparcos catalog – 117 955, J1991.25 (van Leeuwen 2007a,b).

Introduction – II

- ▶ In 2013, the Gaia satellite (Global Astrometric Interferometer for Astrophysics) was launched
 - ▶ Gaia DR1 (2016) – 1 142 679 769 sources, epoch J2015.0,
 - ▶ Gaia DR2 (2018) – 1 692 919 135, J2015.5,
 - ▶ Gaia eDR3 (2020), Gaia DR3 (2022) – 1 811 709 771, J2016.0,
 - ▶ Gaia DR4 – (2026) and Gaia DR5 (2030).

Introduction – III

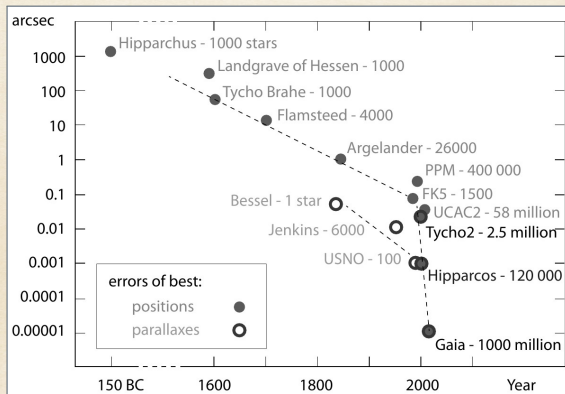


Figure 1: Standard deviation of astrometric catalogs through time (Perryman 2012).

Introduction – IV

Active Galactic Nuclei (AGN)

AGN brightness variability:

- ▶ intra-day variability (IDV),
- ▶ short-term variability (STV),
- ▶ long-term variability (LTV).

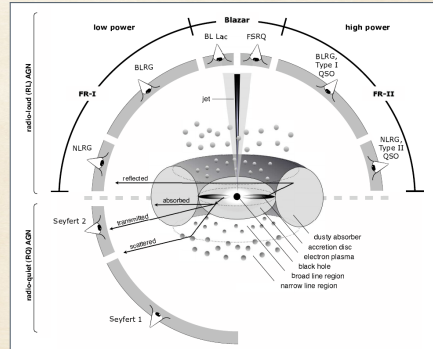


Figure 2: Schematic representation of the unification model AGN (Beckmann and Shrader 2012).

Introduction – V

Suitable objects for linking the optical Gaia and radio ICRF celestial coordinate systems:

- ▶ with a small optical–radio offset,
- ▶ that are not extended galaxies, nor binary or multiple sources,
- ▶ without detected morphological structures in the radio domain (radio jet, radio ovals, ...).

Introduction – VI

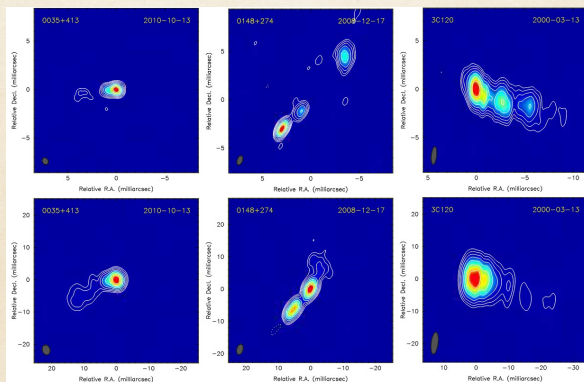


Figure 3: VLBI maps in X (top) and S (bottom) domain for objects 0035+413, 0148+274 and 0430+052 from *ICRF3* (from left to right), taken from the paper Witt et al. 2022.

Introduction – VII

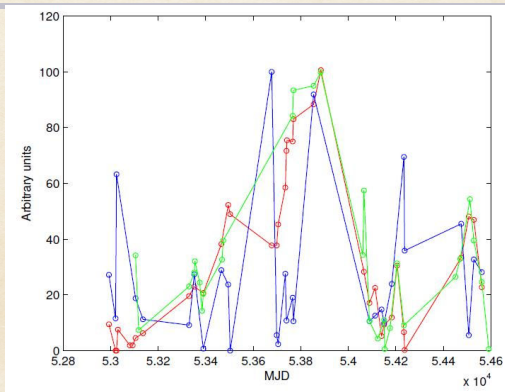


Figure 4: Relationship between changes in the photocenter position and changes in brightness in the *B* and *R* domains - QSO 39437 (Andrei et al. 2012).

Introduction – VIII

Sample selection

- ▶ 10% ICRF1 objects are suitable for astrometry (Bourda et al. 2008),
- ▶ 47 (34 ICRF3) "point-like" sources in the radio domain (Bourda et al. 2011),
- ▶ 19 FSRQ, 15 BL Lac, 8 Sy, 3 QSO and 2 BL Lac/FSRQ,
- ▶ $0.049 \leq z \leq 3.050$, one object has no determined redshift,
- ▶ 02. 07. 2013 – 01. 09. 2019,
- ▶ ~ 30 CCD images in V and ~ 40 R band.

Data, data reduction and analysis – I

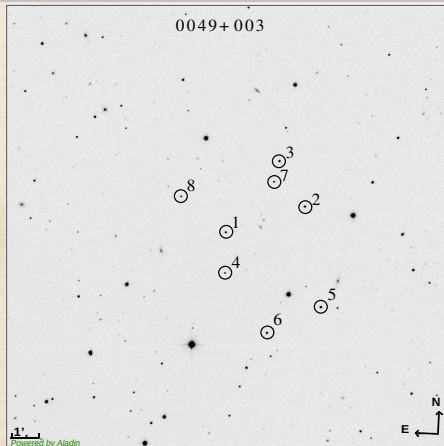
The data consists of a set of images:

- ▶ Own observations with the telescopes of the Astronomical Station Vidojevica - ASV (2016–2019),
- ▶ observations by Dr Goran Damjanović with the telescopes of ASV, the National Astronomical Observatory Rozhen and the Belogradchik Astronomical Observatory in Bulgaria, as well as with the telescope of the Leopold Figl Astrophysical Observatory - LFOA in Vienna, Austria (2013–2015),
- ▶ and observations by Dr François Taris with the robotic telescope Joan Oró Telescope - TJO, located at the Montsec Astronomical Observatory in Spain (2014-2015).

Data, data reduction and analysis – II

- ▶ At least two images were taken in the V and R filters,
- ▶ bias, dark and flat images, hot and dead pixel map (IRAF),
- ▶ cosmic ray map (L.A.Cosmic; van Dokkum 2001) was removed.
- ▶ The brightness of the objects was determined by differential photometry (MaxIm DL).
- ▶ Magnitudes of the comparison and control stars are taken from APASS, Pan-STARRS1 and SDSS DR 14, and for object 1722+119 from Doroshenko et al. 2014.
- ▶ Transformations from catalog magnitudes to V and R are taken from the papers Chonis and Gaskell 2008; Tonry et al. 2012.

Data, data reduction and analysis – III



The field of view is $16' \times 16'$ (ASV 60 cm, CCD camera Apogee Alta U42).

Figure 5: Field of view of object 0049+003.

Data, data reduction and analysis – IV

Statistical tests were applied:

► Abe's criterion (Hald 1952) $q = \frac{1}{2} \frac{\sum_{i=1}^{n-1} (x_{i+1} - x_i)^2}{\sum_{i=1}^n (x_i - \bar{x})^2}$,

$$q_A : x = M - A, \quad q_B : x = M - B.$$

► F – test (de Diego 2010)

$$H_0 : \text{Var}X = \text{Var}Y, \quad H : \text{Var}X > \text{Var}Y; \quad Y = A - B,$$
$$F_A : X = M - A, \quad F_B : X = M - B \text{ and } F_{A/B} = F_A / F_B.$$

► Variability amplitude parameter (Heidt and Wagner 1996)

$$VAP = 100 \sqrt{(M_{MAX} - M_{MIN})^2 - 2\sigma^2} (\%).$$

► The object is variable: $q_{A,B} < q_c$, $F_{A,B} > F_c$, $\alpha = 0.001$ and the number of data points n .

Data, data reduction and analysis – V

- ▶ Time series with trend and periodic changes
- ▶ Time series with trend - simple linear regression
- ▶ Time series with periodic changes
 - ▶ Date-Compensated Discrete Fourier Transform (DCDFT),
 - ▶ Weighted Wavelet Z-transform (WWZ) and
 - ▶ Generalised Lomb-Scargle Periodogram (GLSP).

Data, data reduction and analysis – VI

Color change

- ▶ relative to the color change of the comparison stars,
- ▶ over time,
- ▶ with brightness change (in the R domain):
 - ▶ bluer when brighter (BWB) variability,
 - ▶ redder when brighter (RWB) variability.
- ▶ We determined the coefficients of linear dependence using the least squares method and the Pearson correlation coefficient with the probability of the hypothesis of no correlation.

Short-term and long-term brightness and color changes and color changes – I

The data is fitted with:

- ▶ By linear function - 0907+336, 1345+735, 1607+604, 1722+119, 1741+597, 1811+317 and 2111+801 (V and R); 0210+515 and 0741+294 (R).
- ▶ By periodic function - 0049+003, 0907+336, 0952+338, 1034+574, 1212+467, 1242+574, 1312+240, 1345+735, 1535+231, 1603+699, 1607+604, 1612+378, 1722+119, 1730+604, 1741+597 and 2111+801 (V and R); 0109+200, 0210+515, 0651+428, 0741+294, 2247+381 and 2322+396 (R); 0854+334, 1145+321, 1518+162, 1818+551 (V).

Short-term and long-term brightness and color changes and color changes – II

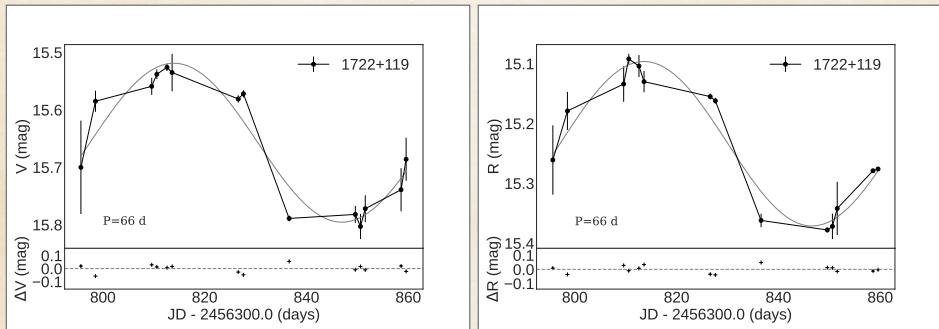


Figure 6: Light curves of object 1722+119 (BL Lac) with a fitting function whose parameters are determined by the DCDFT method: in the V domain (left) and R domain (right), only TJO observations. In the lower left corner is the period value in days.

Short-term and long-term brightness and color changes and color changes – III

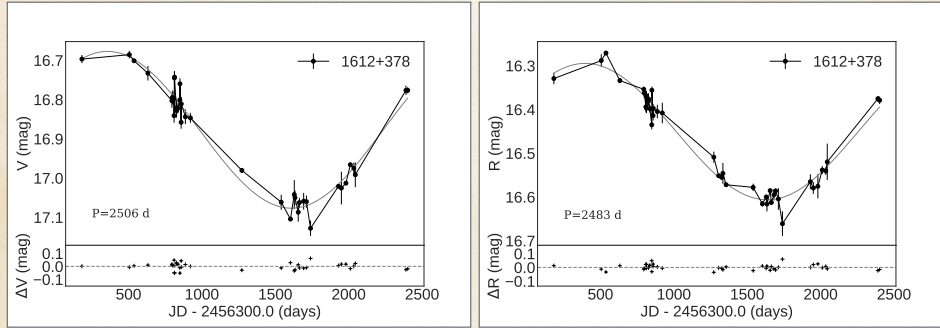


Figure 7: Light curves of object 1612+378 (FSRQ) with a fitting function whose parameters are determined by the DCDFT method: in the V domain (left) and R domain (right). In the lower left corner is the value of the period P .

Short-term and long-term brightness and color changes and color changes – IV

Variability
RWB and BWB

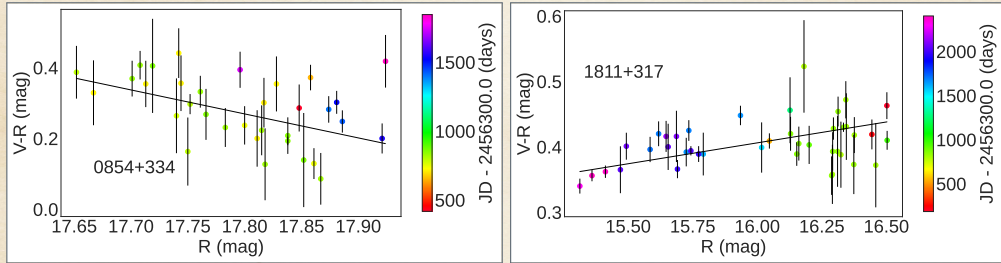


Figure 8: Color index ($V - R$) versus magnitude R for objects: FSRQ 0854+334 (left) and BL Lac 1811+317 (right).

Conclusion – I

The most stable objects are:

- ▶ *FSRQ* - 1556+335, 1618+530, 1759+756;
- ▶ *QSO* - 1228+077;
- ▶ *Sy* - 1429+249.

The variable objects (in both domains) are:

- ▶ *BLLac* - 0907+336, 0952+338, **1034+574**, 1242+574, 1312+240, 1607+604, **1722+119**, 1741+597, 1811+317;
- ▶ *FSRQ* - 0049+003, 1212+467, 1603+699, 1612+378, 1730+604;
- ▶ *BLLac/FSRQ* - 1535+231;
- ▶ *Sy* - 1345+735.

In the R domain, the variable sources are: *Sy* 2111+801 and *BL Lac* 2322+396.

A brightness increase (1811+317), *STV* (1034+574 and 1722+199), *LTV* (other objects) was detected.

Conclusion – II

BWB variability:

- ▶ *BLLac* - 1607+604, 1722+119, 1741+697, 1811+317, 2274+381;
- ▶ *FSRQ* - 0049+003, 1741+294, 0950+326, 1612+378;
- ▶ *Sy* - 1818+551, 2111+801.

RWB variability:

- ▶ *FSRQ* - 0838+235, 0838+456, 0854+334, 1145+321, 1618+530, 1759+756;
- ▶ *BLLac* - 0907+336, 0952+338;
- ▶ *QSO* - 1228+077;
- ▶ *Sy* - 1345+735.

1722+119 - 2013–2016 RWB trend, and from 2016–2019 BWB variability.

Periodic color changes 1603+699, 1838+575, 2247+381; 1612+378; 1201+454.

Conclusion – III

Lambert and N. J. Secrest 2024; Nathan J. Secrest 2022

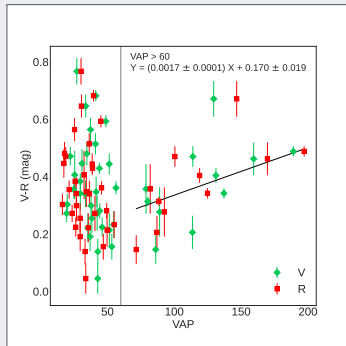


Figure 9: Dependence of color index ($V - R$) and VAP .

Conclusion – IV

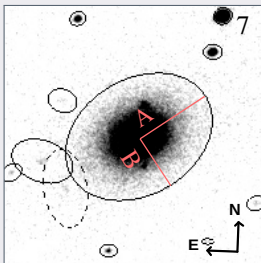


Figure 10: Object 0652+426 with host galaxy.

	A/B	1 - B/A	A	B	Θ
V	1.366	0.268	$(6.360 \pm 0.018)''$	$(4.656 \pm 0.012)''$	$117^{\circ}51.$
R	1.351	0.260	$(6.588 \pm 0.018)''$	$(4.878 \pm 0.012)''$	$120^{\circ}54.$

Conclusion – V

Andrei et al. 2009; Makarov et al. 2019

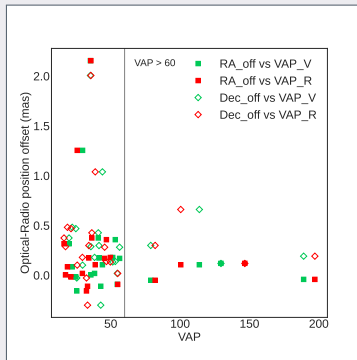


Figure 11: Dependence of the optical-radio position offset and VAP.

Conclusion – VI

Objects suitable for linking ICRF and Gaia CRF:

- ▶ from *ICRF3* - 0049+003, 0446+074, 0838+456, 0850+284, 0952+338, 1032+354, 1518+162, 1556+335, 1730+604, 1759+756, 1818+551, 2316+238;
- ▶ out of *ICRF3* - 0741+294, 0854+334, 1228+077, 1345+735, 1810+522 - Radio Fundamental Catalog (Petrov and Kovalev 2024).

Plans for future work

- ▶ Publish results for the period after 2019.
- ▶ Publish results for the remaining objects (35 of them).
- ▶ Investigate IDV, SED and morphology of the objects.
- ▶ Continue cooperation with Dr Z. Malkin (OCARS catalog, Pulkovo Observatories).
- ▶ Continue observations of these and other objects that are important for connecting the two Gaia CRF and ICRF systems.

Scientific papers in the field of research presented in the dissertation – I

Results were published in 3 refereed journals and presented at 7 conferences.

1. Damljanović, G., Taris, F., Boeva, S., Jovanović, M. D., Marković, G.: 2017, The link between future Gaia CRF and ICRF and the observing facilities of the 60 cm ASV telescope, PROCEEDINGS OF THE XVII NATIONAL CONFERENCE OF ASTRONOMERS OF SERBIA, Belgrade, 23. - 27. Sep, 2014, *Publ. Astron. Obs. Belgrade No. 96*, pp.119-122.
2. Jovanović, M. D., Damljanović, G., Vince, O.: 2018, Flux-stability Analysis for the Comparison Stars for Some Quasars Important to ICRF – Gaia CRF Link, Proceedings of the XI Bulgarian-serbian Astronomical Conference, 14-18 May, 2018, Belogradchik, Bulgaria, *Publ. Astron. Soc. Rudjer Bošković, No. 18*, pp.197-205.

Scientific papers in the field of research presented in the dissertation – II

3. Jovanović, M. D. Damljanović, G., Vince, O.: 2018, Monitoring of Quasars Important for the Link Between ICRF and the Future Gaia CRF in V and R Band, Proceedings of the XVIII Serbian Astronomical Conference, October 17 - 21, 2017, Belgrade, Serbia, *Publ. Astron. Obs. Belgrade No. 98*, pp.293-296.
4. Jovanovic, M. D.: 2019, Optical Variability of Some Quasars Important to ICRF-GAIA CRF Link, Serbian Astronomical Journal, Volume 199, pp.55-64, doi:10.2298/SAJ1999055J.
5. Jovanović, M. D., Damljanović, G., Cvetković, Z., Pavlović, R., Stojanović, M.: 2020, Color Variability of Some Quasars Important to the ICRF – Gaia CRF Link, Proceedings of the XII Serbian-Bulgarian Astronomical Conference, held 25-29 September, 2020 in Sokobanja, Serbia, *Publ. Astron. Soc. Rudjer Bošković, No. 20*, pp.23-31.

Scientific papers in the field of research presented in the dissertation – III

6. Damljanić, G., Taris, F., Jovanović, M. D.: 2020, Short-term and Long-term Flux Variability of Extragalactic Objects Useful for the Future Gaia CRF, SESSION I (GAIA mission), Proceedings of the Journées 2019: Astrometry, Earth Rotation and Reference systems in the Gaia era, 7 - 9 October 2019, Paris, France, pp.21-26.
7. Jovanović, M. D. and Damljanić, G.: 2020, Quasiperiodicity of some quasars important to ICRF–Gaia CRF link, Bulgarian Astronomical Journal, Volume 33, pp.38-46.
8. Jovanovic, M. D., Damljanić, G., Taris, F.: 2021, Control Stars Around Quasars Suitable for the ICRF – Gaia CRF Link, Proceedings of the XIX Serbian Astronomical Conference October 13 - 17, 2020, Belgrade, Serbia, Publ. Astron. Obs. Belgrade No. 100, pp.253-258.
9. Jovanovic, M. D., Damljanić, G., Taris, F., Gupta, A. C., Bhatta, G.: 2023, Multi-band optical variability of a newly discovered twelve blazars sample from 2013–2019, Monthly Notices of the Royal Astronomical Society, Volume 522, Issue 1, pp.767-791, doi.org/10.1093/mnras/stad904.

Scientific papers in the field of research presented in the dissertation – IV

10. Jovanović, M. D., Damljanović, G., Taris, F.: 2023, Comparison and Control Stars Around Quasars Suitable for the ICRF – Gaia CRF Link, Proceedings of the XIII Bulgarian-Serbian Astronomical Conference Velingrad, Bulgaria, October 3-7, 2022, Publ. Astron. Soc. Rudjer Bošković, No 25., 2023, pp.75-84.

Bibliography I

- [1] A. H. Andrei et al. “Morphology of QSOs-the gridpoints of the Gaia Celestial Reference Frame”. In: *IAU Joint Discussion*. IAU Joint Discussion. Aug. 2012, 31, p. 31.
- [2] A. H. Andrei et al. “The large quasar reference frame (LQRF). An optical representation of the ICRS”. In: *Astronomy & Astrophysics* 505.1 (Oct. 2009), pp. 385–404. DOI: 10.1051/0004-6361/200912041. arXiv: 0907.2403 [astro-ph.CO].
- [3] V. Beckmann and C. Shrader. “The AGN phenomenon: open issues”. In: *Proceedings of “An INTEGRAL view of the high-energy sky (the first 10 years)” - 9th INTEGRAL Workshop and celebration of the 10th anniversary of the launch (INTEGRAL 2012). 15-19 October 2012. Bibliotheque Nationale de France*. Jan. 2012, 69, p. 69. DOI: 10.22323/1.176.0069. arXiv: 1302.1397 [astro-ph.HE].

Bibliography II

- [4] G. Bourda, P. Charlot, and J. -F. Le Campion. “Astrometric suitability of optically-bright ICRF sources for the alignment with the future Gaia celestial reference frame”. In: *Astronomy & Astrophysics* 490.1 (Oct. 2008), pp. 403–408. DOI: 10.1051/0004-6361:200810667. arXiv: 0809.1369 [astro-ph].
- [5] G. Bourda, A. Collioud, P. Charlot, R. Porcas, and S. Garrington. “VLBI observations of optically-bright extragalactic radio sources for the alignment of the radio frame with the future Gaia frame. II. Imaging candidate sources”. In: *Astronomy & Astrophysics* 526, A102 (Feb. 2011), A102. DOI: 10.1051/0004-6361/201014249.
- [6] Taylor S. Chonis and C. Martin Gaskell. “Setting UBVRI Photometric Zero-Points Using Sloan Digital Sky Survey ugriz Magnitudes”. In: *Astronomical Journal* 135.1 (Jan. 2008), pp. 264–267. DOI: 10.1088/0004-6256/135/1/264. arXiv: 0710.5801 [astro-ph].

Bibliography III

- [7] José A. de Diego. “Testing Tests on Active Galactic Nucleus Microvariability”. In: *Astronomical Journal* 139.3 (Mar. 2010), pp. 1269–1282. DOI: 10.1088/0004-6256/139/3/1269. arXiv: 1001.2543 [astro-ph.CO].
- [8] V. T. Doroshenko, Yu. S. Efimov, G. A. Borman, and N. G. Pulatova. “BVRI CCD-Photometry of Comparison Stars in the Fields of Galaxies with Active Nuclei. VII”. In: *Astrophysics* 57.2 (June 2014), pp. 176–196. DOI: 10.1007/s10511-014-9324-y.
- [9] A. Hald. *Statistical theory with engineering applications*. New York–London : Wiley, 1952.
- [10] J. Heidt and S. J. Wagner. “Statistics of optical intraday variability in a complete sample of radio-selected BL Lacertae objects.”. In: *Astronomy & Astrophysics* 305 (Jan. 1996), p. 42. arXiv: astro-ph/9506032 [astro-ph].

Bibliography IV

- [11] S. Lambert and N. J. Secrest. “VLBI position variability of AGNs is inversely correlated with their photometric variability”. In: *Astronomy & Astrophysics* 684, A93 (Apr. 2024), A93. DOI: 10.1051/0004-6361/202348842.
- [12] Valeri V. Makarov, Ciprian T. Berghea, Julien Frouard, Alan Fey, and Henrique R. Schmitt. “The Precious Set of Radio-optical Reference Frame Objects in the Light of Gaia DR2 Data”. In: *The Astrophysical Journal* 873.2, 132 (Mar. 2019), p. 132. DOI: 10.3847/1538-4357/aafa1c. arXiv: 1811.10117 [astro-ph.GA].
- [13] Michael Perryman. “The history of astrometry”. In: *European Physical Journal H* 37.5 (Oct. 2012), pp. 745–792. DOI: 10.1140/epjh/e2012-30039-4. arXiv: 1209.3563 [physics.hist-ph].
- [14] Leonid Petrov and Yuri Kovalev. “The Radio Fundamental Catalogue. I. Astrometry”. In: *arXiv e-prints*, arXiv:2410.11794 (Oct. 2024), arXiv:2410.11794. DOI: 10.48550/arXiv.2410.11794. arXiv: 2410.11794 [astro-ph.IM].

Bibliography V

- [15] Nathan J. Secrest. “Optical-Radio Position Offsets Are Inversely Correlated with AGN Photometric Variability”. In: *The Astrophysical Journal Letters* 939.2, L32 (Nov. 2022), p. L32. DOI: 10.3847/2041-8213/ac8d5d. arXiv: 2209.09928 [astro-ph.GA].
- [16] J. L. Tonry et al. “THE Pan-STARRS1 PHOTOMETRIC SYSTEM”. In: *The Astrophysical Journal* 750.2 (Apr. 2012), p. 99. DOI: 10.1088/0004-637X/750/2/99. URL: <https://dx.doi.org/10.1088/0004-637X/750/2/99>.
- [17] Pieter G. van Dokkum. “Cosmic-Ray Rejection by Laplacian Edge Detection”. In: *Publications of the Astronomical Society of the Pacific* 113.789 (Nov. 2001), pp. 1420–1427. DOI: 10.1086/323894. arXiv: astro-ph/0108003 [astro-ph].
- [18] Floor van Leeuwen. *Hipparcos, the New Reduction of the Raw Data*. Vol. 350. Springer Science+Business Media B.V., 2007. DOI: 10.1007/978-1-4020-6342-8.
- [19] Floor van Leeuwen. “Validation of the new Hipparcos reduction”. In: *Astronomy & Astrophysics* 474.2 (Nov. 2007), pp. 653–664. DOI: 10.1051/0004-6361:20078357. arXiv: 0708.1752 [astro-ph].

Bibliography VI

- [20] Aletha de Witt, Patrick Charlot, David Gordon, and Christopher S. Jacobs.
“Overview and Status of the International Celestial Reference Frame as Realized by VLBI”. In: *Universe* 8.7 (2022). ISSN: 2218-1997. DOI: 10.3390/universe8070374.
URL: <https://www.mdpi.com/2218-1997/8/7/374>.

Thank you!