Insights into AGN parsec-scale emission from radio to GeV gamma rays from VLBI, Gaia EDR3, and Fermi-LAT

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The study

- The VLBI [Ma *et al.*, 1998, Fey *et al.*, 2015, Charlot *et al.*, 2020] and Gaia mission —> positioning of radiosources from AGN family (Active Galactic Nuclei) radio and optical with precision of 0.1 mas.
- Differences in positions between radio and optical centroid up to more than 1 mas are observed properties of AGNs.
- The blazars make good reference points due to their lack of proper motion and parallax.
- Gaia [Prusti *et al.*, 2016, Brown *et al.*, 2016, Brown *et al.*, 2018, Brown *et al.*, 2021]—> provide an ICRF in optical band with a precision similar to the VLBI.
- Study aiming at identifying which mechanisms are behind the optical emission : is it from a jet feature – also observable in radio – or a mix between the jet, the accretion disk, an extended halo or host galaxy ?

Different view points on the study

- Reference frame : Differences in positions prevent from « perfect » connection between VLBI and Gaia.
- Astrophysics : the optical centroids positions seem to be located downstream but not always.

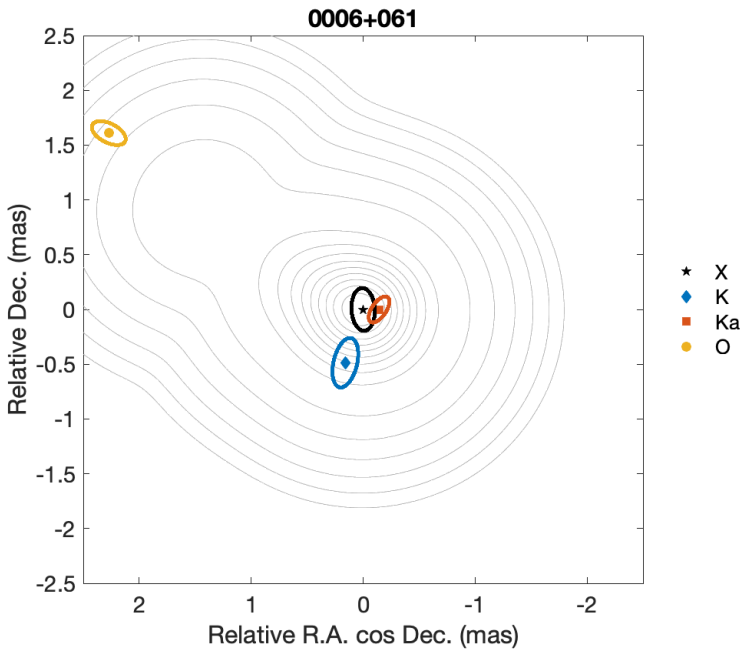


Figure – Map of the relatives positions in radio and optical bands for the source 0006+061 (IERS name) between *Gaia* EDR3 et ICRF3. The point (0,0) is the ICRF3 *core* .

AGNs Classification

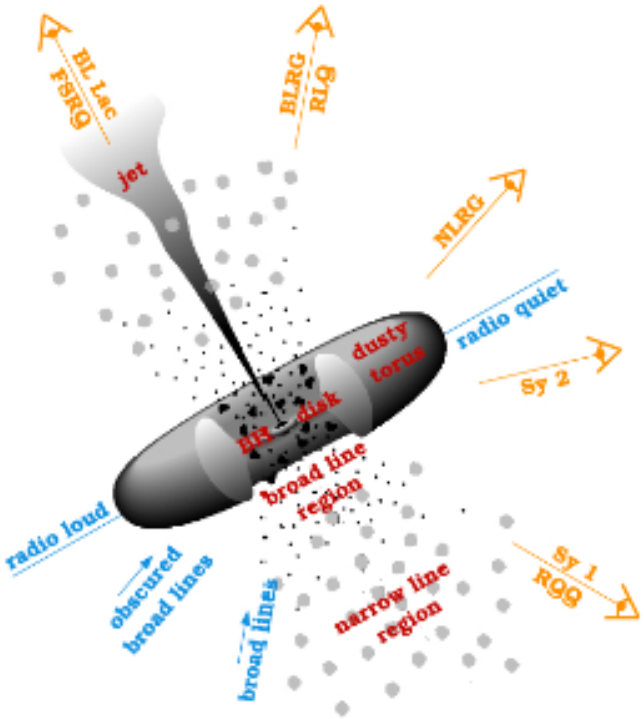


Figure – Unified theory of the AGNs classification (Crédits : thèse de J.Biteau, LLR, Urry Padovani 1995)

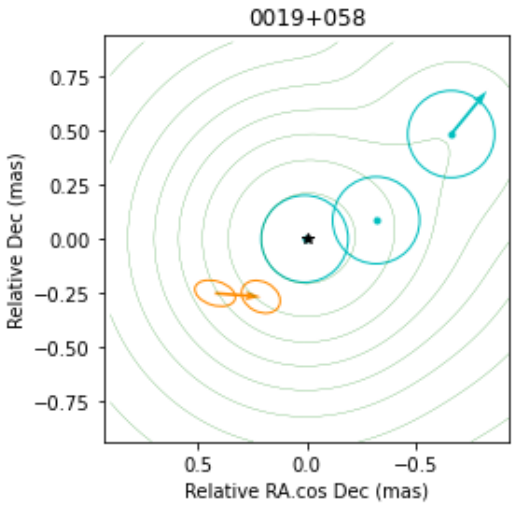
- There exist different AGNs categories, divided in two families : *radio loud* and *radio quiet*.
- The *radio quiet* include Seyfert galaxies and certain quasars, The *radio loud* include radio-galaxies and blazars.
- Blazars are AGNs with a relativistic jet directed on our line of sight.

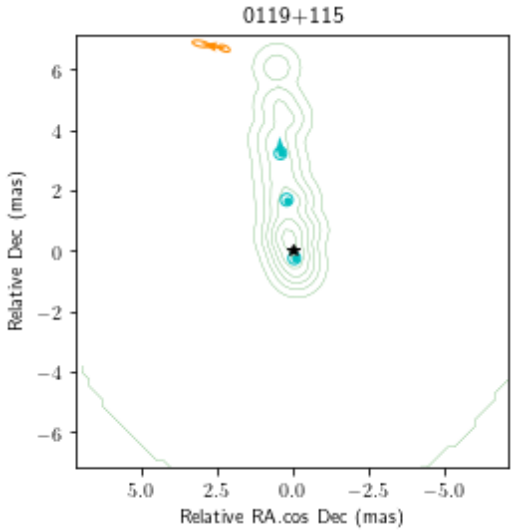
First approach of the data

- Data : *ICRF3* 4588 in total, 4537 sources at 8 GHz, 824 at 22 GHz, 678 at 32 GHz.
- *Gaia EDR3* (1.5 M extragalactic sources) optical counterpart of the *ICRF3* sources : 3477/4537.
- *MOJAVE* [Lister & Homan, 2005, Lister *et al.*, 2019] study with the VLBA at 15 GHz, 409 sources with jet features.
- Sample of 350 sources —> crossing between *MOJAVE*, *Gaia EDR3* and *ICRF3* X (8 GHz).
- We will use the gamma emission from the Fermi-LAT used by MOJAVE [Kramarenko *et al.*, 2021]

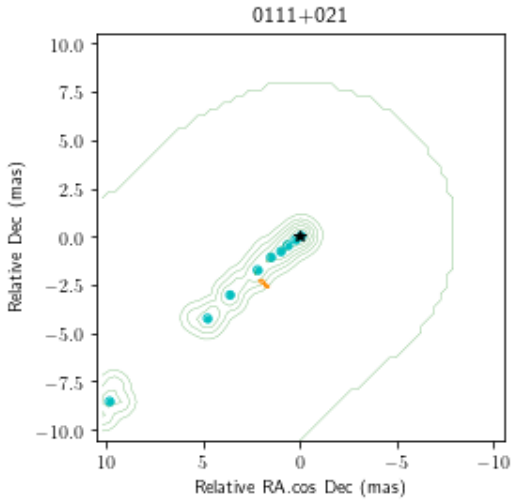
Positions maps

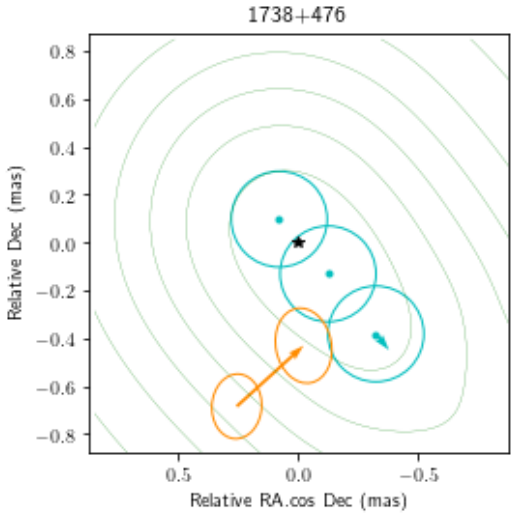
FSRQ class :





BL Lac class :





Positions maps

- Positions and proper motion were projected in right ascension and declination.
- Taking into account the errors and correlations between right ascension and declination with the error ellipses.
- The flux for source structure —> DIFMAP programm.
- The sources are divided independently of their classification in the different types of configurations.
- The positions maps show that the classification alone of an object do not permit us to conclude whether or not the origin of the optical and radio emission are the same.

Core-shift and errors

- We made an error building our maps —> *core-shift*, apparent position of the *core* depend on the frequency.
- Identification of the MOJAVE *core* (15 GHz) with *ICRF3* centroid X (8 GHz).
- Ratio of the offsets due to the *core-shift* —> estimation of our error done by choosing a reference point.
- We choose a 0.2 mas error which is in accordance with of the estimation we could make using the results of [Kovalev *et al.*, 2008]. By choosing a 0.2 mas error we are being cautious.

$$\frac{\Delta_{12}}{[mas]} = \frac{1,65.10^{-21}}{\zeta_\theta}(\frac{D_M}{[pc]})^{-1}(\frac{L_{syn}}{[erg/s]})^{\frac{2}{3}}(\frac{\frac{\nu_1\nu_2}{\nu_1-\nu_2}}{[GHz]})^{-1} \quad (1)$$

Identification

- Offset feature by feature —> selection of the minimal distance.
- For certain sources it is not always pertinent.
- Error on the offset and if $R/\sigma < 3$ we consider having a good identification.
- 350 sources : 150 identified to jet features, 21 don't have clear identification, 179 identified to the *core*.

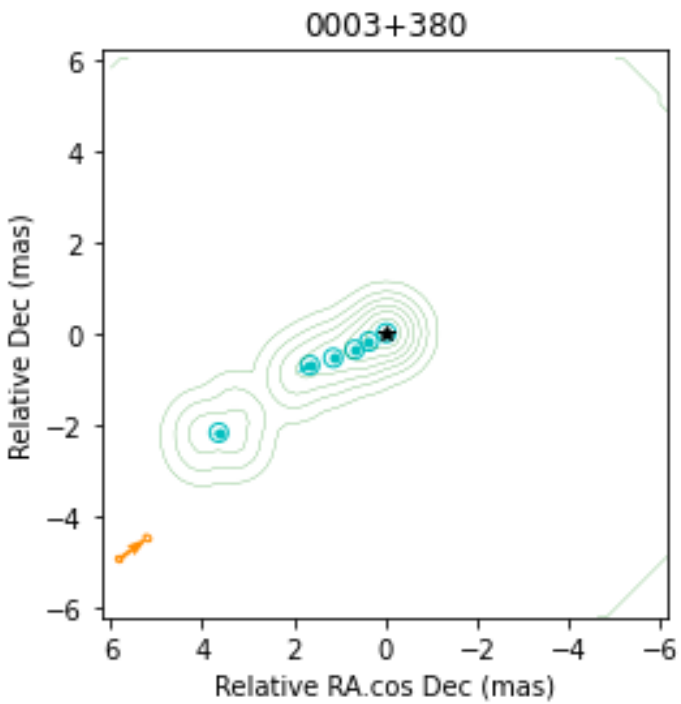


Figure – Positions map and proper motion *Gaia* and *MOJAVE* source 0003+380(IERS name).

Correlations

- Identification method —> expected and unexpected correlations.
- Statistical tests on the 150 sources sample –> correlation values of 0.3 which at 3σ can be the result of random gaussian processes appear.
- The proper motion and distances seem in good correlation. No possible conclusion on the correspondence of proper motion.

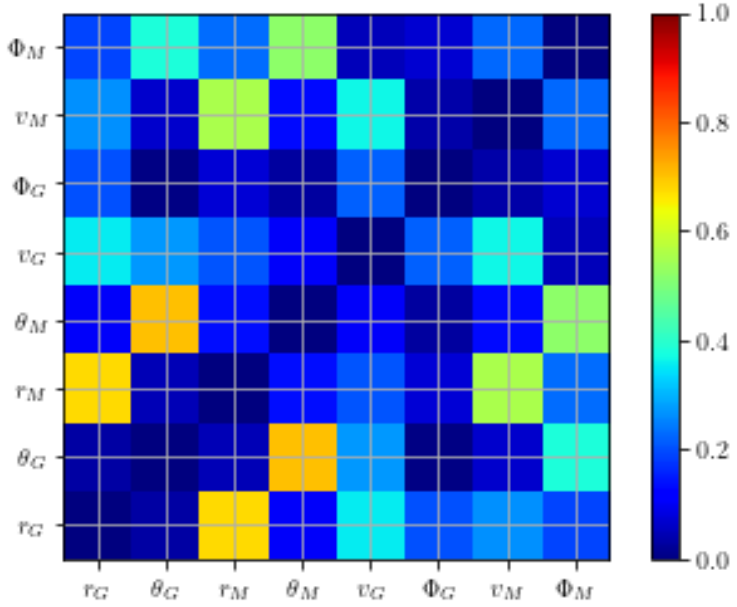


Figure – Graph representing the significance correlations between r_G,θ_G,r_M,θ_M,v_G,Φ_G,v_M,Φ_M).

Photometry : angular offset and color index

- The optical offset can come from a composite emission.
- We look at the angular offset distribution $\Psi = \theta_G - \theta_M$. 25 sources at 180°, 110 à 0° —> preferred directions.
- Peaks —> effect of the jet affecting the positions. Strong optical jet structure for $\Psi = 0°$. *core-shift*, instrumental resolution, disk emission for $\Psi = 180°$.

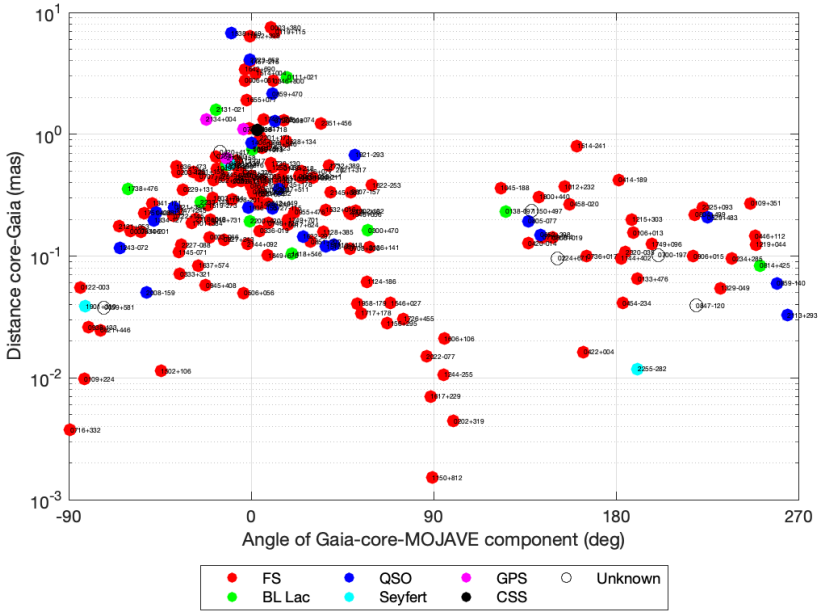


Figure – Joint distribution of the angular offset written Ψ with the distance to the *core* of *Gaia*. The color represents the source classification.

Photometry : angular offset and color index

- Color index of *Gaia* : $BP - RP$ allows to separate the contributions from the jet and from the disk.

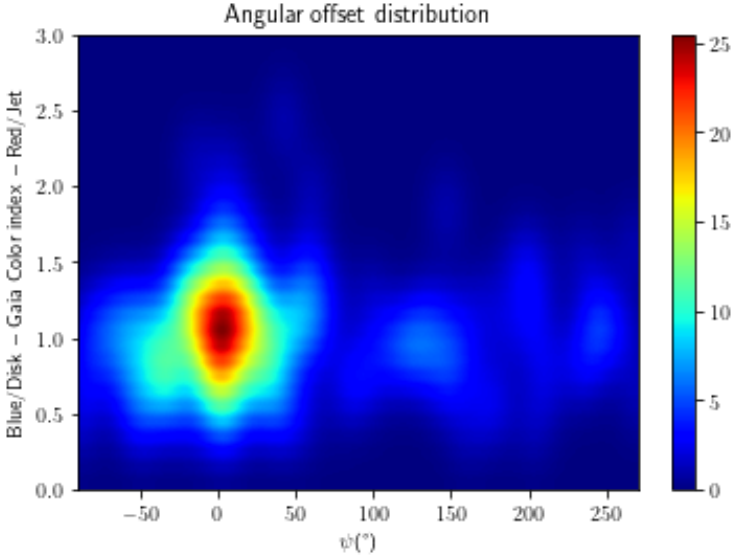
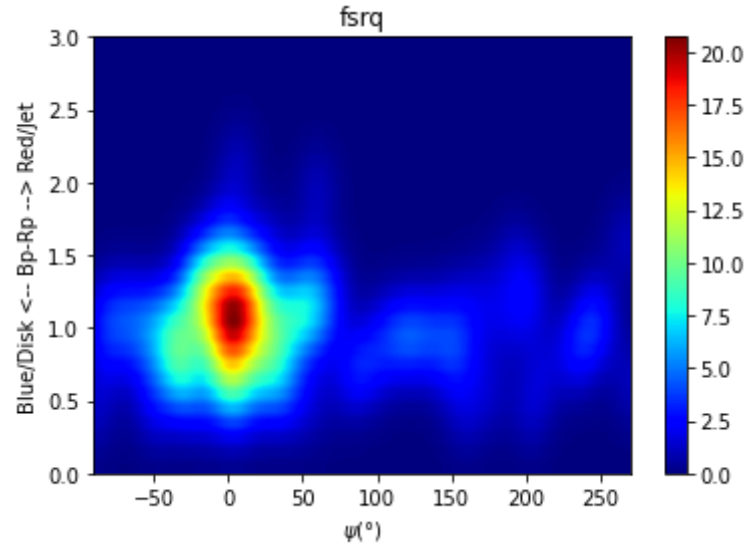
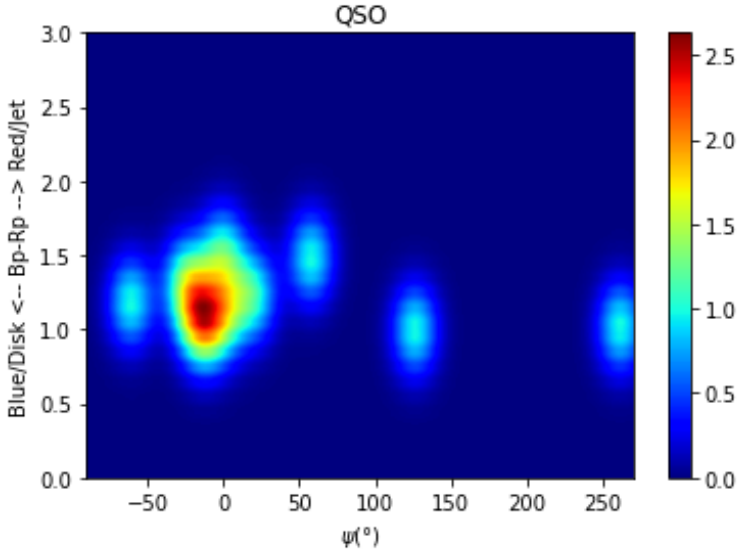


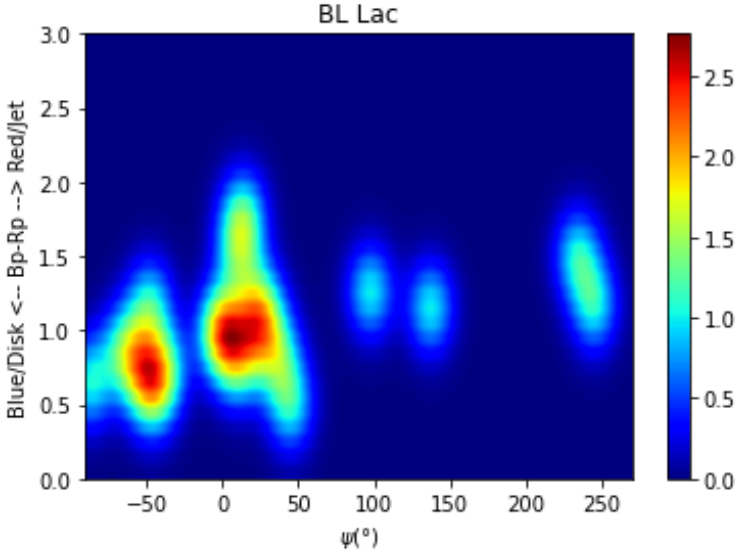
Figure – Joint distribution of the angular offset written Ψ and the color index of *Gaia*

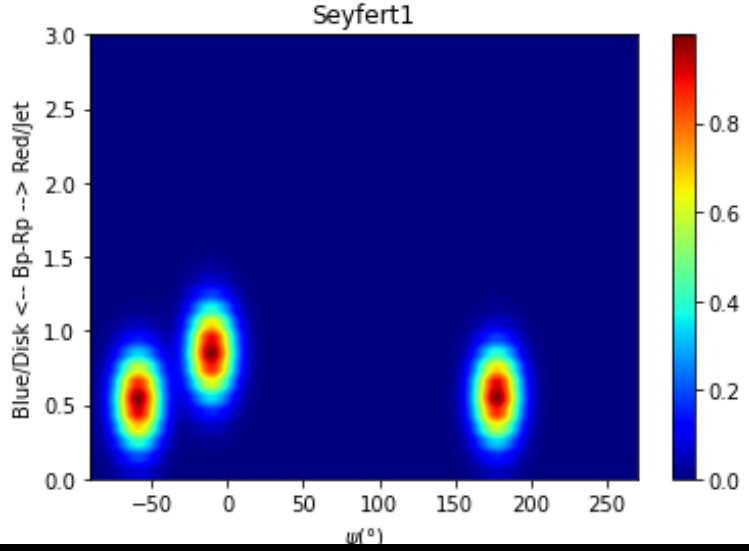
- We study the two populations at 0° et 180 ° in each of the classes.
- More red than expected —> Jet domination, expected for the *MOJAVE* sources that are particularly active.

Photometry : angular offset and color index



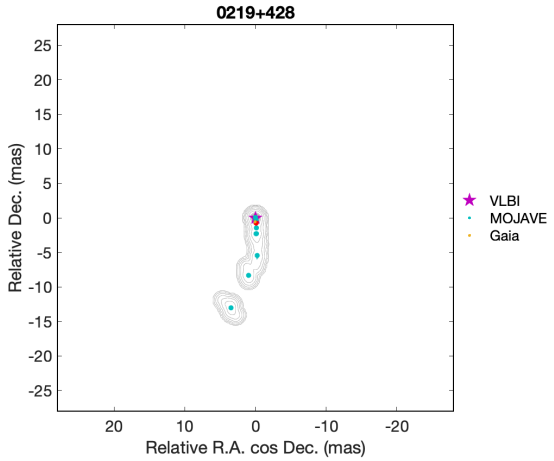




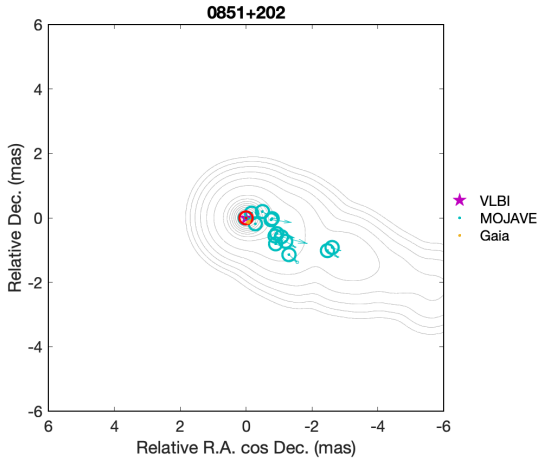


Positions maps

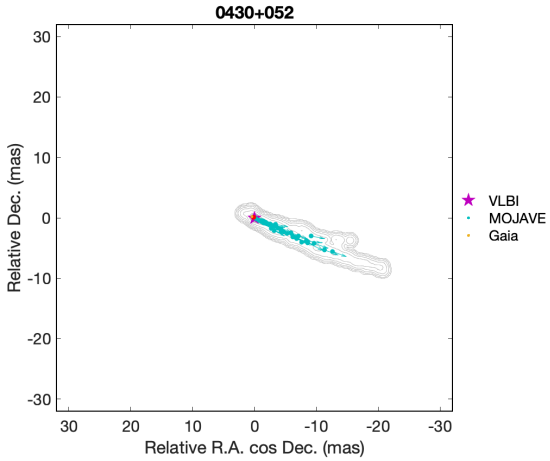
3C66A :



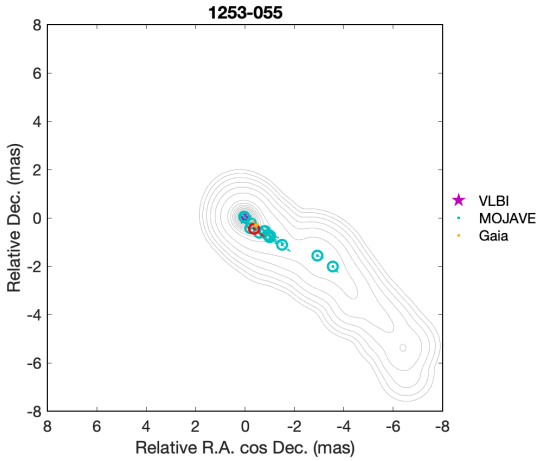
OJ287 :



3C120 :

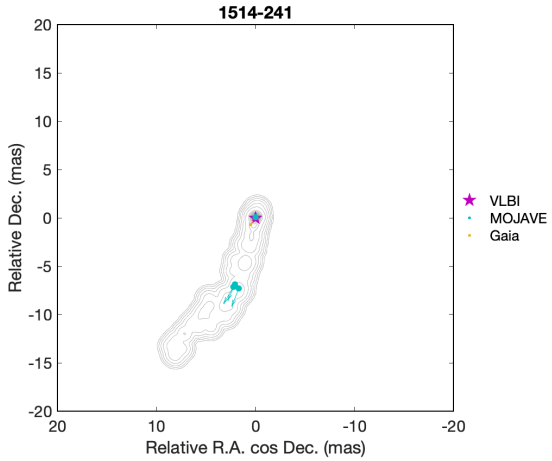


3C279 :

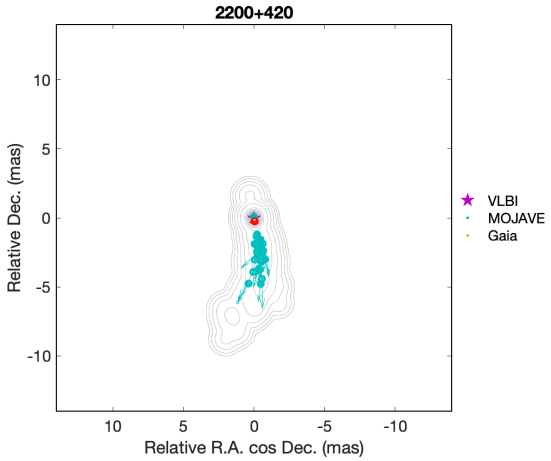


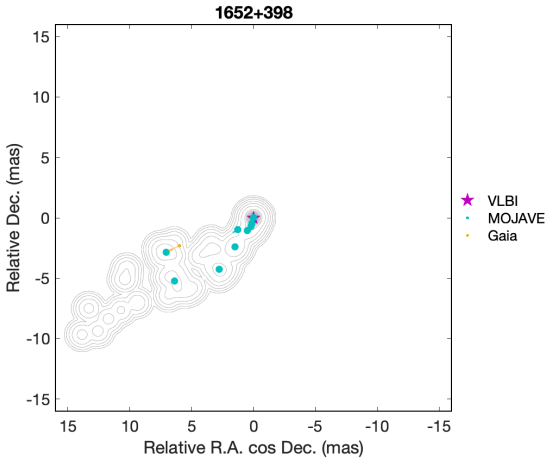
Positions maps

AP lib :

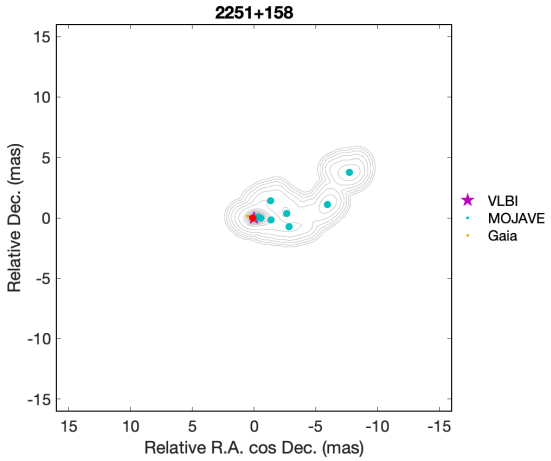


BL Lac :





Mrk501 :



3C454.3 :

Gamma emitting sources

- We investigated the sources 3C66A (0219+428), 3C120 (0430+052), OJ287 (0851+202), 3C279 (1253-055), AP lib (1514-241), Mrk501 (1652+398), BL Lac (2200+420) and 3C454.3 (2251+158).
- Except for Mrk501 all the other sources have their optical centroid identified with the *core* or a feature downstream the jet very close to the *core* .
- About half of the sources have an angle offset near 180° and the other half near 0°.
- Most of the FSRQ in these sources have a more blueish color index than the average of the sources in our sample, which indicate that a part of the optical emission could originate in the disk or its very closed vicinity. On the contrary most of the BL Lac are not particularly bluer.

Gamma emitting sources

- We conclude that for most of the gamma emitting sources the optical centroid seems to be emitted by the base of the jet or near it. The offset might be caused by the emission of the disk or a core-shift effect.
- This optical emission in the vicinity of the *core* may indicate that the gamma emission also comes from this part of the source. However it has yet to be confirmed.
- The optical emission can reveal a specifically more active synchrotron zone and that can indicate that a gamma emission zone.
- We must remain cautious as some other counter examples to this tendency like Mrk501 exist. We need to explore this possibility much further before we can conclude anything for certain.

Conclusion

- Identification —> both the radio and optic points are indeed emitted by the same part of the source (*core*, jet, disk).
- Existence of correlations between different quantities both in optic and radio.
- Joint distributions of the angular offset *Gaia-MOJAVE* and the distance to the *core* of *Gaia* or the color index of *Gaia*, allow to constraint the relative contibutions of the galaxy and the disk.
- Increasing the sample size with new refined data.
- Study where the MHD/radiative simulations would be made to reconstruct the jets, to take into account the observed jets and exploit the different results already obtained.

Thank you for your attention !

Beckmann, Volker, & Shrader, Chris. 2013.
Active galactic nuclei.
John Wiley & Sons.

Blandford, RD, & Payne, DG. 1982.
Hydromagnetic flows from accretion discs and the production of radio jets.
Monthly Notices of the Royal Astronomical Society, **199**(4), 883–903.

Blandford, Roger, Meier, David, & Readhead, Anthony. 2019.
Relativistic Jets from Active Galactic Nuclei.
Annu. Rev. Astron. Astrophys, **57**, 467–509.

Blandford, Roger D, & Znajek, Roman L. 1977.
Electromagnetic extraction of energy from Kerr black holes.
Monthly Notices of the Royal Astronomical Society, **179**(3), 433–456.

Brown, AGA, Vallenari, Antonella, Prusti, T, De Bruijne, JHJ, Babusiaux, C, Bailer-Jones, CAL, Biermann, M, Evans, Dafydd Wyn, Eyer, Laurent, Jansen, Femke, *et al.* 2018.

Gaia Data Release 2-Summary of the contents and survey properties.
Astronomy & astrophysics, **616**, A1.

Brown, Anthony GA, Vallenari, Antonella, Prusti, T, De Bruijne, JHJ, Mignard, F, Drimmel, Ronald, Babusiaux, C, Bailer-Jones, CAL, Bastian, U, Biermann, M, *et al.* 2016.
Gaia Data Release 1-Summary of the astrometric, photometric, and survey properties.
Astronomy & Astrophysics, **595**, A2.

Brown, Anthony GA, Vallenari, A, Prusti, T, De Bruijne, JHJ, Babusiaux, C, Biermann, M, Creevey, OL, Evans, DW, Eyer, L, Hutton, A, *et al.* 2021.
Gaia Early Data Release 3-Summary of the contents and survey properties.
Astronomy & Astrophysics, **649**, A1.

Charlot, P, Jacobs, CS, Gordon, D, Lambert, Sébastien, de Witt, A, Böhm, J, Fey, AL, Heinkelmann, R, Skurikhina, E, Titov, O, *et al.* 2020.

The third realization of the International Celestial Reference Frame by very long baseline interferometry.
Astronomy & Astrophysics, **644**, A159.

Fath, Edward Arthur. 1909.
The spectra of some spiral nebulae and globular star clusters.
Publications of the Astronomical Society of the Pacific, **21**(126), 138–143.

Fey, AL, Gordon, D, Jacobs, CS, Ma, C, Gaume, RA, Arias, EF, Bianco, G, Boboltz, DA, Böckmann, S, Bolotin, S, *et al.* 2015.
The second realization of the international celestial reference frame by very long baseline interferometry.
The Astronomical Journal, **150**(2), 58.

Hoyle, Fred, & Fowler, William A. 1962.
On the nature of strong radio sources.
Monthly Notices of the Royal Astronomical Society, **125**(2), 169–176.

Jackson, J David. 1975.

Electrodynamics.
The Optics Encyclopedia.

Kovalev, YY, Lobanov, AP, Pushkarev, AB, & Zensus, JA. 2008.
Opacity in compact extragalactic radio sources and its effect on astrophysical and astrometric studies.
Astronomy & Astrophysics, **483**(3), 759–768.

Kovalev, YY, Petrov, L, & Plavin, AV. 2017.
VLBI-Gaia offsets favor parsec-scale jet direction in active galactic nuclei.
Astronomy & Astrophysics, **598**, L1.

Kovalev, YY, Zobnina, DI, Plavin, AV, & Blinov, D. 2020.
Optical polarization properties of AGNs with significant VLBI–Gaia offsets.
Monthly Notices of the Royal Astronomical Society : Letters, **493**(1), L54–L58.

Kramarenko, IG, Pushkarev, AB, Kovalev, YY, Lister, ML, Hovatta, T, & Savolainen, T. 2021.
A decade of joint MOJAVE – Fermi AGN monitoring : localisation of the gamma-ray emission region.
arXiv preprint arXiv :2106.08416.

Krolik, Julian H. 1999.
Active galactic nuclei : from the central black hole to the galactic environment.
Vol. 60.
Princeton University Press.

Lindegren, Lennart, Lammers, U, Bastian, U, Hernández, J, Klioner, S, Hobbs, D, Bombrun, A, Michalik, D, Ramos-Lerate, M, Butkevich, A, *et al.* 2016.
Gaia Data Release 1-Astrometry : one billion positions, two million proper motions and parallaxes.
Astronomy & Astrophysics, **595**, A4.

Lister, ML, & Homan, DC. 2005.
MOJAVE : monitoring of jets in active galactic nuclei with VLBA experiments. I. First-epoch 15 GHz linear polarization images.
The Astronomical Journal, **130**(4), 1389.

Lister, ML, Homan, DC, Hovatta, T, Kellermann, KI, Kiehlmann, S, Kovalev, YY, Max-Moerbeck, W, Pushkarev, AB, Readhead, ACS, Ros, E, *et al.* 2019.
MOJAVE. XVII. Jet kinematics and parent population properties of relativistically beamed radio-loud blazars.
The Astrophysical Journal, **874**(1), 43.

Longair, Malcolm S. 1992.
High energy astrophysics. Vol. 1 : Particles, photons and their detection.

Ma, C, Arias, EF, Eubanks, TMm, Fey, AL, Gontier, A-M, Jacobs, CS, Sovers, OJ, Archinal, BA, & Charlot, P. 1998.

The international celestial reference frame as realized by very long baseline interferometry.
The Astronomical Journal, **116**(1), 516.

Mignard, F, Klioner, S, Lindegren, L, Bastian, U, Bombrun, A, Hernández, J, Hobbs, D, Lammers, U, Michalik, D, Ramos-Lerate, M, *et al.* 2016.
Gaia Data Release 1-Reference frame and optical properties of ICRF sources.
Astronomy & Astrophysics, **595**, A5.

Padovani, Paolo, Alexander, DM, Assef, RJ, De Marco, B, Giommi, P, Hickox, RC, Richards, GT, Smolčić, V, Hatziminaoglou, E, Mainieri, V, *et al.* 2017.
Active galactic nuclei : what's in a name ?
The Astronomy and Astrophysics Review, **25**(1), 1–91.

Plavin, AV, Kovalev, YY, & Petrov, Leonid Y. 2019.
Dissecting the AGN disk–Jet system with joint VLBI-Gaia analysis.
The Astrophysical Journal, **871**(2), 143.

Prusti, T, de Bruijne, JHJ, Vallenari, A, Babusiaux, C, Bailer-Jones, CAL, Bastian, U, Biermann, M, Evans, DW, Eyer, L, Jansen, F, *et al.* 2016.
The Gaia mission.
Astronomy & Astrophysics, **595**, A1.

Schmidt, Maarten. 1963.
3 C 273 : a star-like object with large red-shift.
Nature, **197**(4872), 1040–1040.

Seyfert, Carl K. 1943.
Nuclear Emission in Spiral Nebulae.
The Astrophysical Journal, **97**, 28.

Sol, H. 2021.
Jets relativistes et mécanismes aux très hautes énergies, in "Noyaux Actifs de Galaxies".
F. Combes, éditeur scientifique, Editions ISTE (sous presse).

Spruit, Henk C. 1996.

Magnetohydrodynamic jets and winds from accretion disks.
NATO ASI SERIES C MATHEMATICAL AND PHYSICAL SCIENCES, **477**, 249–286.

Thomson, Joseph J. 1906.
LXX. On the number of corpuscles in an atom.
The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, **11**(66), 769–781.

Weiler, Michael. 2018.
Revised Gaia Data Release 2 passbands.
Astronomy & Astrophysics, **617**, A138.