Constraints on the extreme brightness generation mechanisms in AGN from the *RadioAstron* survey and the long-term variability

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on behalf of the *RadioAstron* AGN survey team

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RadioAstron AGN survey

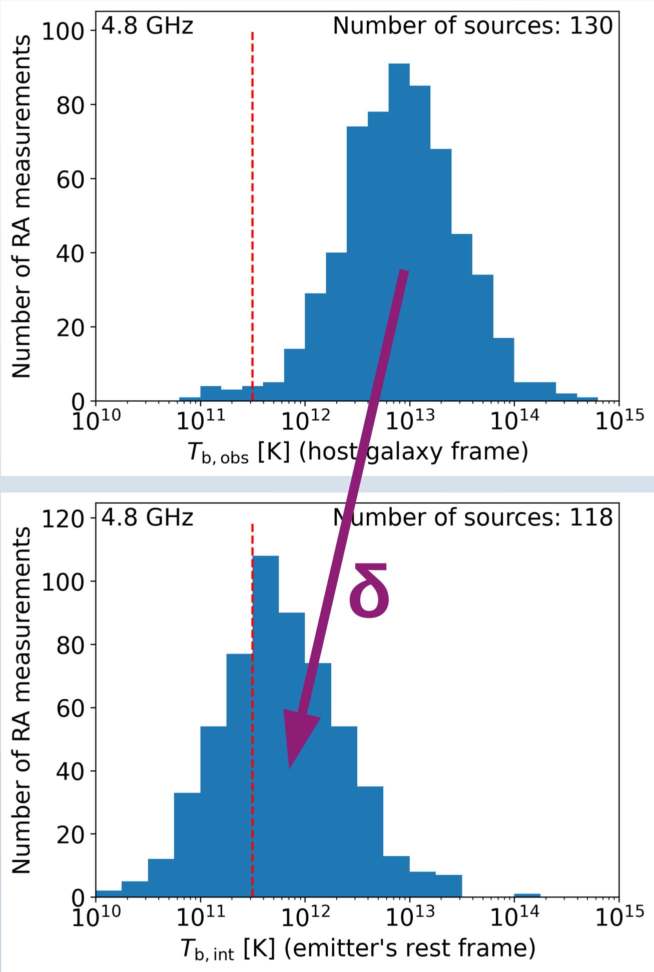
- *RadioAstron* is a space VLBI mission.
- Longest baseline: 27 Earth diameters; highest achieved resolution: 10 μas.

- AGN survey: 248 AGN observed, 167 detected.
- The goal is to study brightness temperature of AGN cores in order to better understand physics of their emission while taking interstellar scattering into consideration.
- 32 ground radio telescopes, including EVN stations. 3-4 antennas per typical observing segment.
- ASC LPI correlator.
- Frequencies: 1.7, 4.8, and 22 GHz.
- 6.5 years of observations (2012-2018).

Extreme brightness temperatures

$$T_b \equiv \frac{c^2}{2k\nu^2} I_\nu$$

- *RadioAstron* measured T_b up to $\approx 5*10^{14}$ K.
- For the incoherent synchrotron radiation of electrons, the Compton catastrophe ($L_{IC} >> L_{sync}$) occurs when $T_b > 10^{11.5}$ K (Kellermann & Pauliny-Toth, 1969; Readhead, 1994).
- Doppler boosting: $T_{b,obs} = \delta T_{b,int}$, δ – Doppler factor.
- Estimates of δ for AGN from flare modeling (Liodakis et al., 2018) and from ground-based VLBI (Homan et al., 2021) are in agreement: $\delta_{med} \approx 10$, $\delta_{max} \approx 100$.
- Doppler boosting itself does not solve the extreme T_b problem.
- **Where extremely bright regions are located? What processes cause the extreme brightness?**



Possible explanations of the extreme brightness

- Doppler factor of the jet or of its tiny spine higher than current estimates.
- Continuous re-acceleration of electrons (shock waves, magnetic reconnection):
  - in the jet's radio core (apparent base of the jet with $\tau \sim 1$ at the observing frequency)
  - in the jet, parsecs downstream from the core.
- Proton synchrotron emission.
- Synchrotron emission of electrons with mono-energetic distribution.
- Coherent emission.

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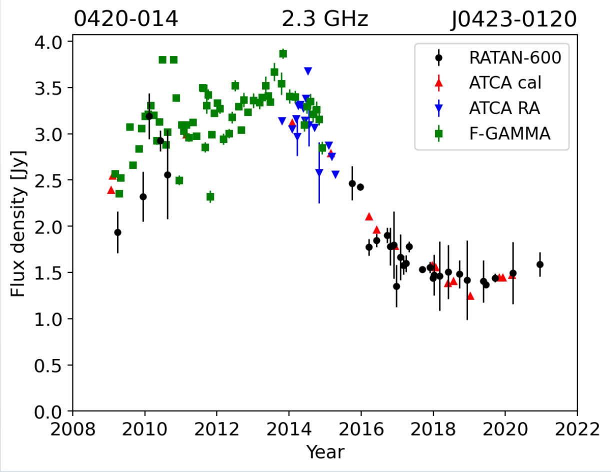
In some models, the extreme brightness is generated in the jet's radio core and is connected to the major flares, in other models it is not.

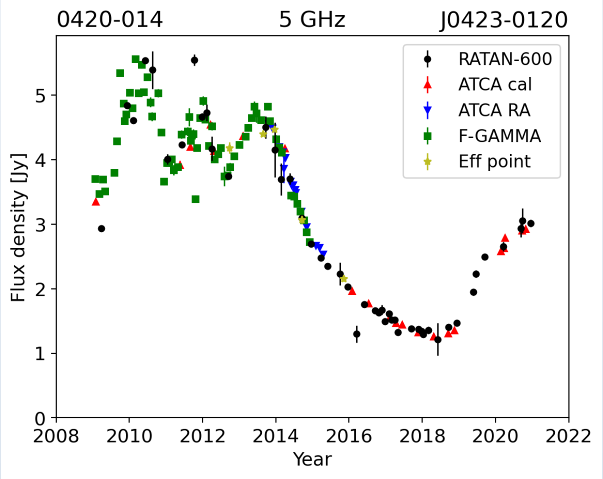
Our goal: to test the relation between the extreme brightness and radio flares => to constrain physical processes causing extreme brightness.

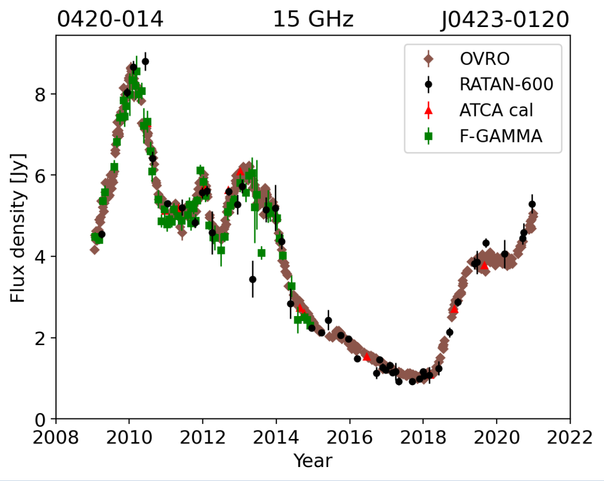
Long-term variability data

- Multi-frequency monitoring programs at RATAN-600, ATCA, OVRO 40m, Effelsberg 100m, as well as published F-GAMMA data (Angelakis et al. 2019). Reduced to a common flux density scale.
- Frequencies: 2.3, 5, 8, 11, 15, and 22 GHz.

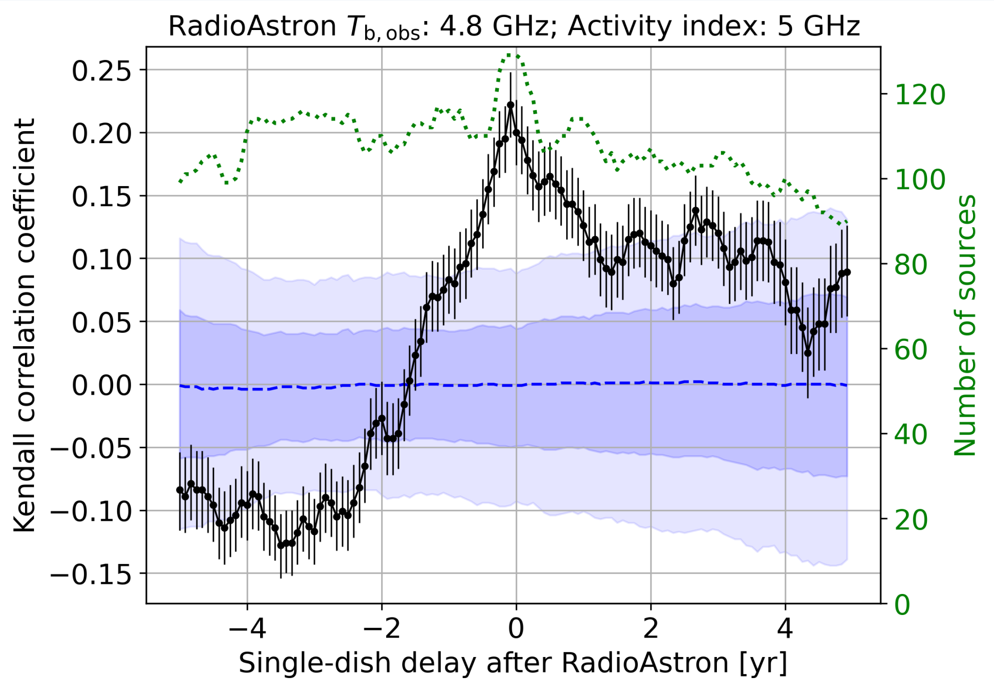






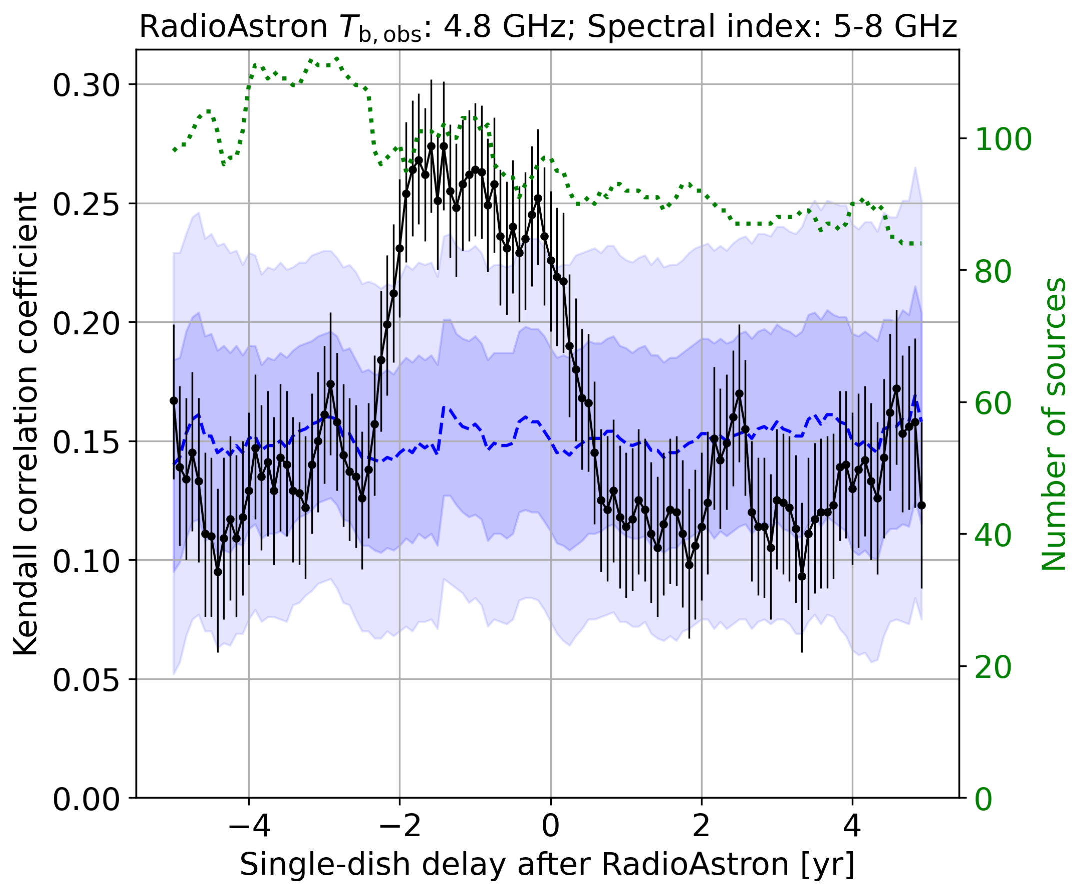
Correlation of T_b and single-dish activity index



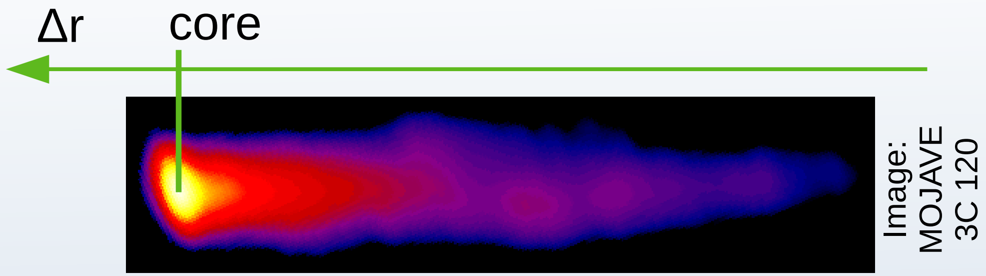
- Activity index = (flux density) / (median flux density)
- Correlation at the delays about zero is statistically significant at all three RadioAstron bands: 1.7, 4.8, 22 GHz.
- Therefore, T_b is higher when the single-dish flux density is higher.
- **The extreme T_b appears during major flares.**

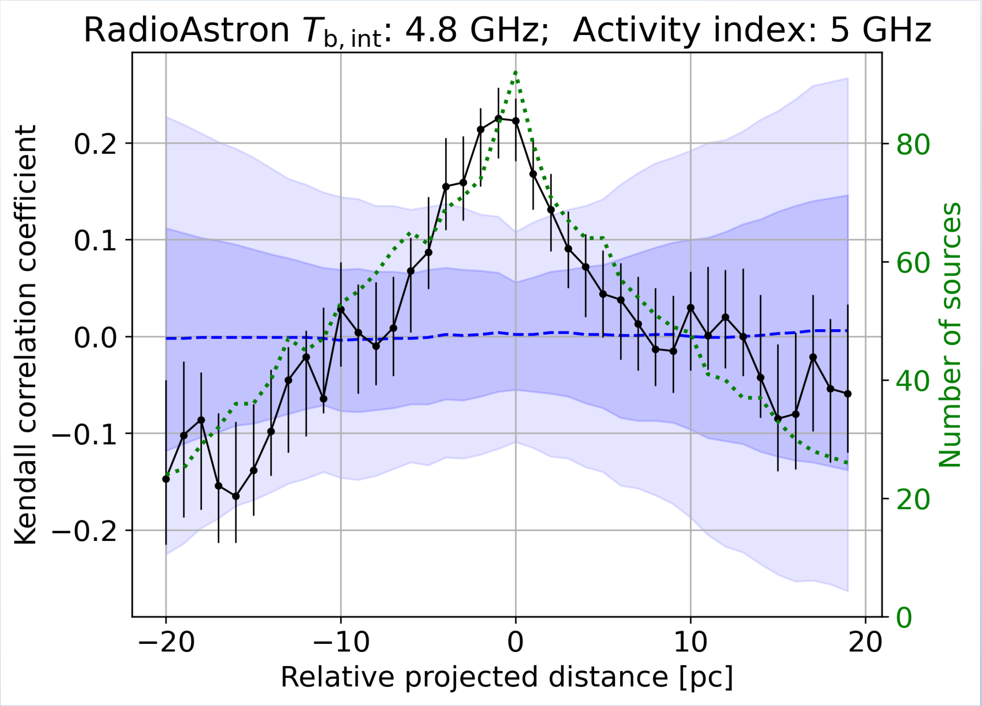
Correlation of T_b and single-dish spectral index

- Spectral index α: $S \sim \nu^{+\alpha}$.
- Increase of α is an indicator of a beginning flare.
- Statistically significant peaks of the correlation with the spectral index for T_b at 1.7 and 4.8 GHz => **another signature of the connection between T_b and flares.**
- Correlation is non-zero at all delays => T_b and α are connected in a quiescent state too.
- Confirmation from the RadioAstron detection statistics: spectral index of the sources detected at long baselines is significantly higher than of non-detected.



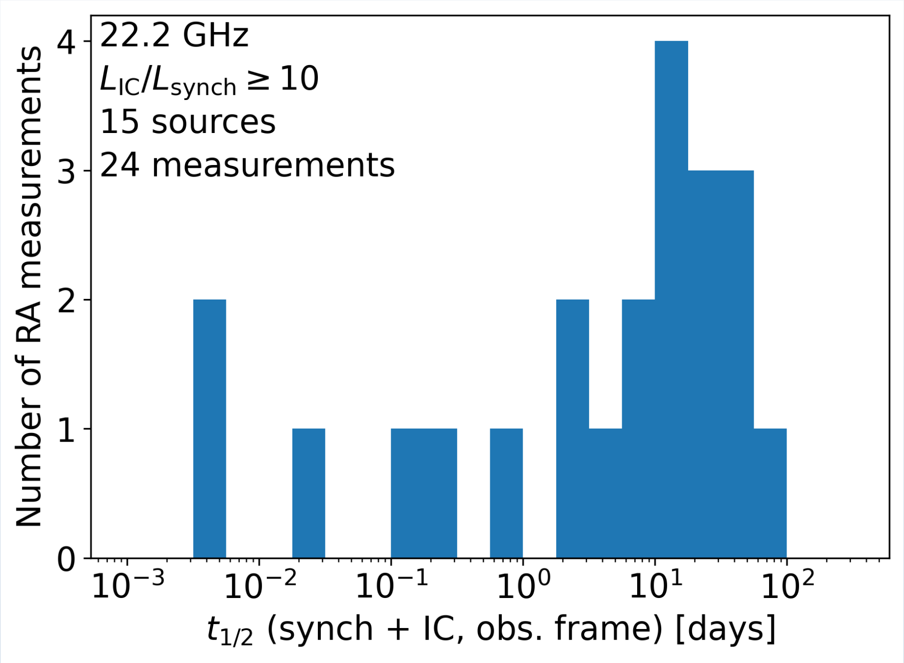
Localization of extremely bright regions





- We assume that the total flux density is maximal when the perturbation moves through the core.
- Time delay between RadioAstron and single dish is translated to the distance between the extremely bright region and the core, using apparent velocities of the jets from the MOJAVE project (Lister et al., 2021).
- Maximum correlation at Δr ~ –1 pc.
- Characteristic core size at 5 GHz is about 3 pc (Koryukova et al., 2022).
- **=> Extremely bright regions are located in the radio core or near it.**

Extreme brightness — during Compton catastrophes?



- May all the observations of the extreme T_b coincide by chance with inverse-Compton cooling periods after flares?
- We estimated synchrotron + IC cooling timescales according to Readhead (1994), using T_b measured by the *RadioAstron*: ~10 days in the observer's frame for 22 GHz.
- Monte-Carlo simulation for the *RadioAstron*-detected sources: up to thousands (typically ~100) flares per year needed to explain the RadioAstron extreme brightness measurements at 22 GHz by a chance coincidence.

Summary

- Extreme brightness temperatures of AGN were observed by the *RadioAstron* preferably near the the moments of their radio flares.
- Extremely bright areas appear in the jet's radio core or close to it.
- Constraints on the mechanisms of the extreme brightness generation:
  - ✔ core activity related to major radio flares — supported (proton synchrotron? standing shocks?);
  - ✗ processes in the jet not connected to flares or operating far away from the core (magnetic reconnection, shock waves) — not supported.