Ultra-compact structures in galactic masers observed in the RadioAstron project

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RADIOASTRON MASER SURVEY: General overview and results

Title	First Space-VLBI survey of galactic H_2O masers
Targets	Galactic H_2O masers in SFRs and evolved stars
Epoch	July, 2012 – June, 2015
Aims	· Search for the most compact and bright water vapor masers. · Obtain parameters of the most compact maser spots (flux density, brightness temperature, angular size).
Instruments	Space VLBI[1]: 10-m Space Radio Telescope (SRT) + ground VLBI array. Survey design: 25 water vapor masers were observed during this program in 122 observing sessions with a typical duration of 1 hour each. One source was observed during one session.

[1] http://www.asc.rssi.ru/radioastron/index.html

OBSERVATIONS

Band	K (22 GHz); 2 x 16 MHz x 2 polarizations (RCP&LCP)
Ground radio telescopes	Effelsberg 100-m, GBT 100-m, Robledo 70-m, Sardinia 65-m, Yebes 40-m, Medicina 32-m, Noto 32-m, Torun 32-m, Onsala 20-m, Hartebeesthoek 26-m, Zelenchuk 32-m, Svetloe 32-m, Badary 32-m; Evpatoriya 70-m
Space baselines	From 0.8 up to 19.0 Earth diameters (ED)
Observed sources	· 17 masers H2O in regions of star formation (SFR). · 8 masers H2O in evolved stars including 2 water fountains.

Fringes were detected in ~25%sessions

Detected H2O masers	· 7 masers in SFR: W3 Irs5, W3 OH, Orion KL, W49N, Cepheus A, W51 E8, OH043.8* · No masers in stars were detected with RadioAstron.

** observed at space baseline less than 1 ED due to orbit orientation.*

DETECTION RESULTS

Source (Alias)	RA J2000 (h m s)	DEC J2000 (d m s)	Baselines on which the source was detected, Earth diameters (ED)	Max resolution (mas)	Max detected brightness temperature, K
W49 N	19 10 13.41	09 06 12.80	2.2-3.0; 4.5; 8.6; 9.6	23	1.4e+16
W3 Irs5	02 25 40.71	62 05 52.52	2.5-2.8; 3.5; 3.9; 5.4; 6.0	36	8.1e+15
W3 OH	02 27 04.84	61 52 24.61	3.9	56	7.1e+14
Ceph A	22 56 17.97	62 01 48.75	0.9-1.7; 1.1; 3.1-3.5	62	3.0e+14
Orion KL	05 35 14.13	-05 22 36.48	1.9; 3.4	64	6.0e+15
W51 M/S	19 23 43.87	14 30 29.45	0.4-2.3; 1.3; 1.4-1.8; 1.7	95	2.2e+14

Conclusions:

1. Very compact maser features with angular sizes of about 23 – 95 μas were observed in galactic star-forming regions. Corresponding linear sizes are ~ 5-15 million km (several solar diameters).

2. The best linear resolution was obtained for the H2O maser in Orion – 4 million km.

3. The best angular resolution for galactic masers achieved in RadioAstron mission is 23 μas for W 49 N (which is located at the distance of 11 kpc from the Sun).

4. Estimates of brightness temperatures provide the values from 10^{14} to $1.4 \cdot 10^{16}$ K. The flux density of the most compact features in W49 N detected at RadioAstron space baselines is about 0.1-0.3% of the single dish flux density.

5. Interstellar scattering does not prevent detection of the bright Galactic masers when observing with space interferometer RadioAstron.

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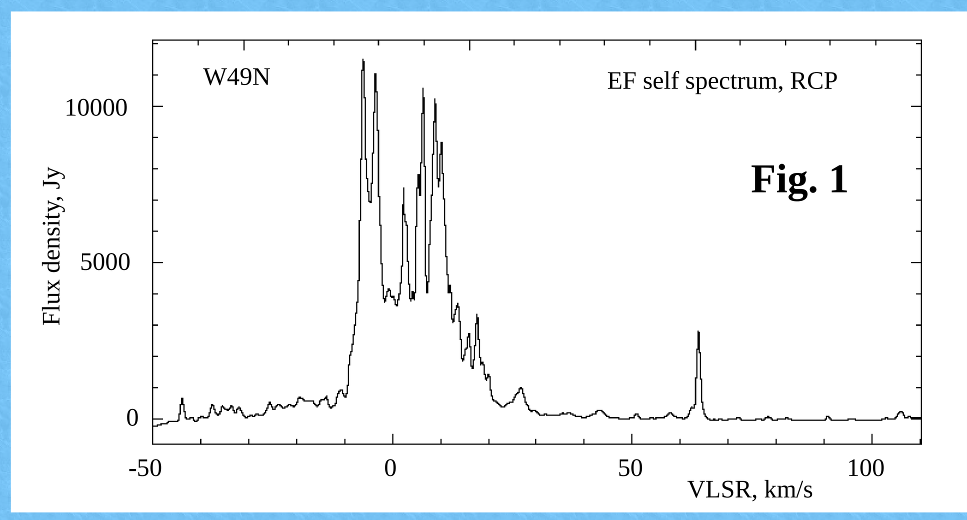
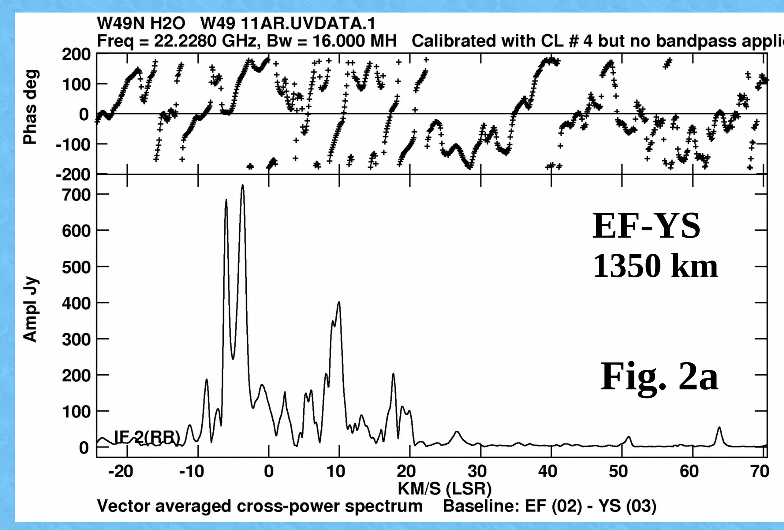
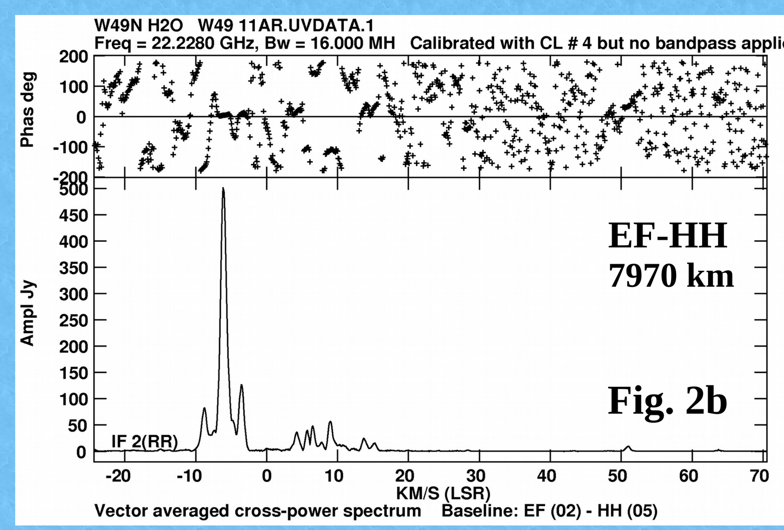
Abbreviations used in tables and figures: EF – Effelsberg 100-m radio telescope (RT), Germany; YS – Yebes 40-m RT, Spain; TR – Torun 32-m RT, Poland; HH – Hartebeeshoek 26-m RT, South Africa; GBT – Green Bank Telescope 100-m, USA; MC – Medicina 32-m RT, Italy.

RADIOASTRON MASER SURVEY: Observations of star formation region W49 N

Epoch	Ground array	Band	Observing time	Baseline length	Angular resolution
2015 April 27	Ef, Ys, Tr, Hh *(for details see the box in the left bottom corner)*	K (22 GHz)	1 hour	9.6 ED ~122 000 km	23 μas







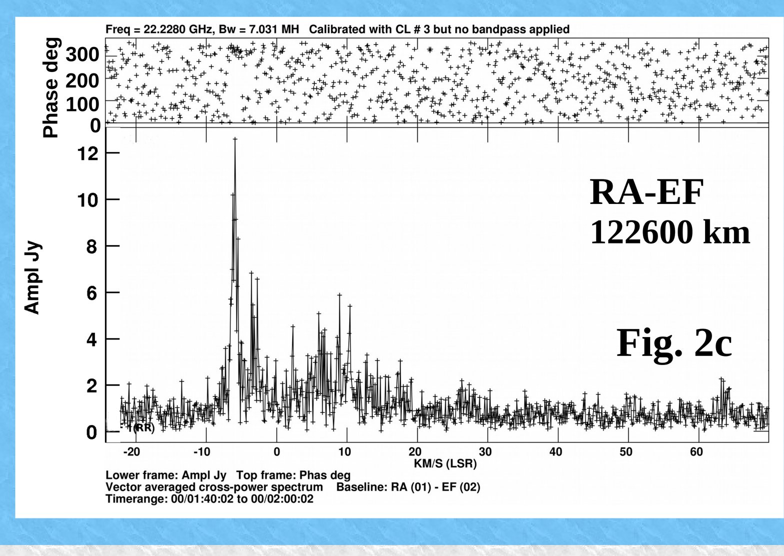


Figure 1. Autocorrelation spectrum of the W49 N (right circular polarization) obtained at Effelsberg 100-m RT.

Figure 2. Cross correlation spectra of the W49 N obtained at baselines Effelsberg – Yebes (**a**); Effelsberg – Hartrao (**b**); RadioAstron – Effelsberg (**c**).

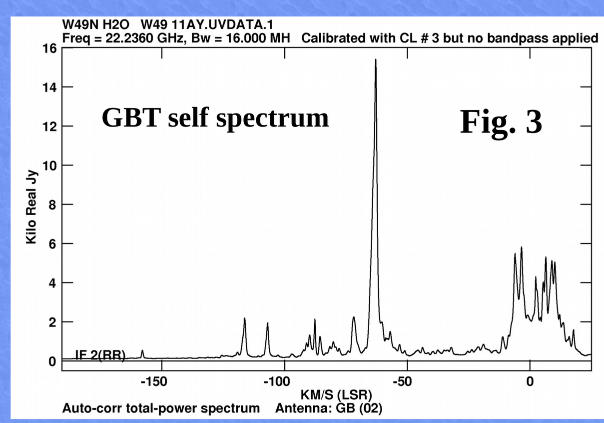
The duration of typical RadioAstron survey observation is 1 hour, and we have only a few baselines (typically ~3-6). In this case, we can assume the shape of brightness distribution as a circular Gaussian and estimate brightness temperature T_b of a source (1), where B is baseline length, V_0 and V_q – visibility amplitude at single spatial frequency q=B/λ (see Lobanov, 2015)*.

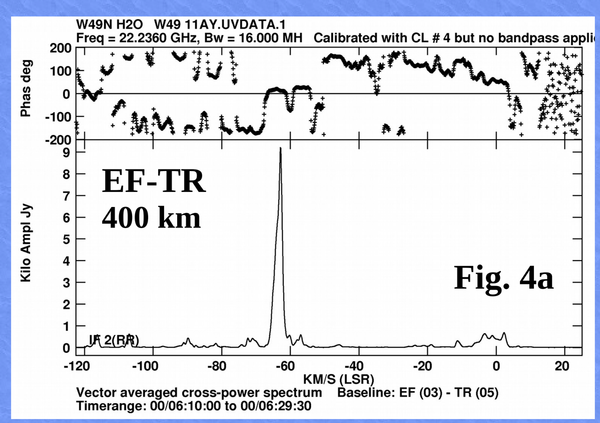
$$T_b = \frac{\pi}{2k}\frac{B^2 V_0}{\ln(V_0/V_q)} \quad (1)$$

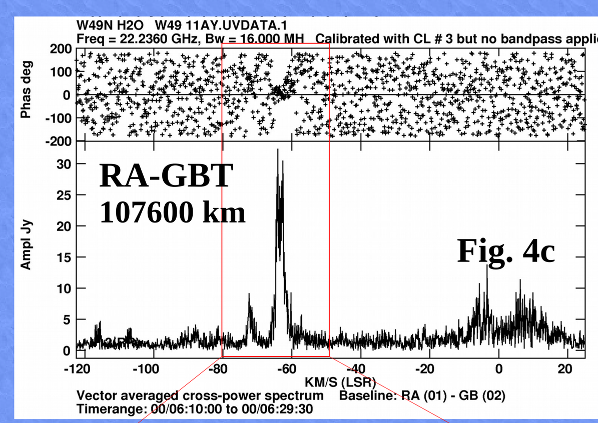
*A. Lobanov, Astron. & Astrophys. 574, A84 (2015)

The brightest feature at the velocity V_{LSR} ~ –6 km/s is unresolved at space-ground baseline. The brightness temperature Tb ~ 2.3e+15 K with the size estimate equal to angular resolution ~ 23 μas. Correlated flux density at the space-ground baseline RadioAstron – Effelsberg is ~ 12.6 Jy, which is ~ 0.1% of the single dish flux density.

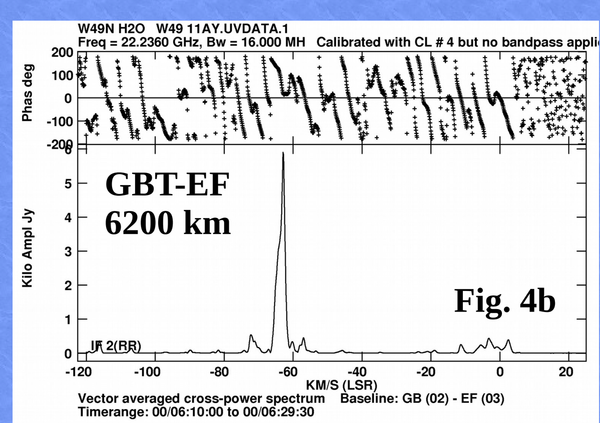
Epoch	Ground array	Band	Observing time	Baseline length	Angular resolution
2015 May 22	Ef, GBT, Mc, Tr *(for details see the box in the left bottom corner)*	K (22 GHz)	50 min	8.6 ED ~110 000 km	26 μas







The brightness temperature of the most bright feature at V_{LSR} ~ –63 km/s Tb ~ 1.4e+16 K with the size estimate equal to ~ 31 μas. Correlated flux density at the space baseline RadioAstron – GBT is ~ 32 Jy, what is ~ 0.2% of the single dish flux density.



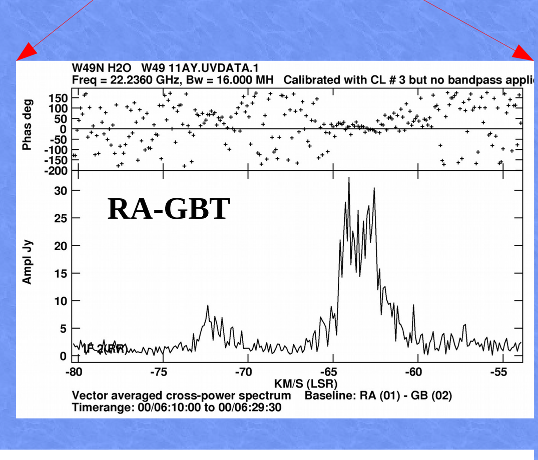
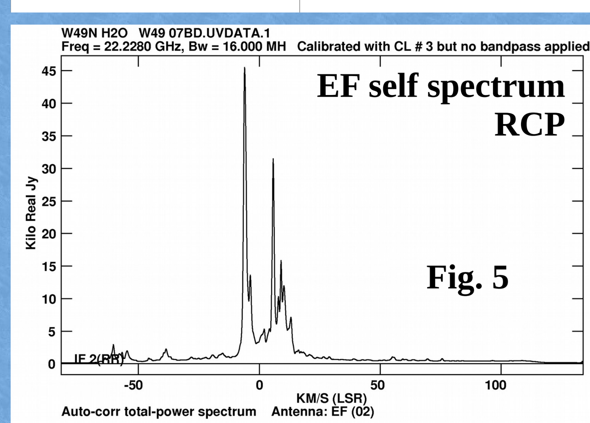
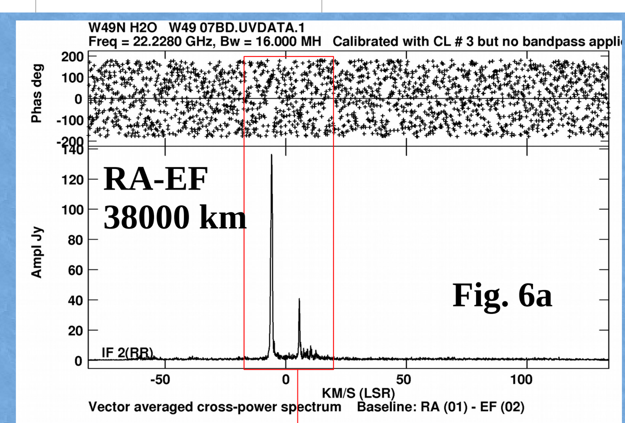
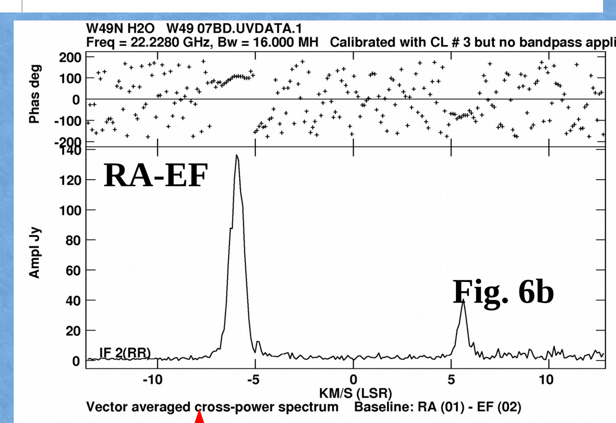


Figure 3. Autocorrelation spectrum of the W49 N (right circular polarization) obtained at Green Bank 100-m RT (GBT).
Figure 4. Cross correlation spectra of the W49 N obtained at baselines Effelsberg – Torun (**a**); GBT – Effelsberg (**b**); RadioAstron – GBT (**c**).

Epoch	Ground array	Band	Observing time	Baseline length	Angular resolution
2014 May 18	Ef *(for details see the box in the left bottom corner)*	K (22 GHz)	1 hour	3.0 ED ~38 000 km	74 μas







Lack of the intermediate length baselines does not allow to explore the structure of the spot and we cannot separate the contribution from different components. With available angular resolution we can obtain only a lower limit of the brightness temperature, Tb ~ 1.1e+15 K, and an upper limit of the size of the feature at V_{LSR} ~ –6 km/s -- 93 μas. Correlated flux density at the space baseline RadioAstron – GBT is ~137 Jy, which is ~0.3% of the single dish flux density.

Figure 5. Autocorrelation spectrum of the W49 N (right circular polarization) obtained at Effelsberg 100-m RT.
Figure 6(a,b). Cross correlation spectrum of the W49 N obtained at baseline RadioAstron – Effelsberg.



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