RadioAstron space-VLBI project: studies of masers in star forming regions of our Galaxy and megamasers in external galaxies

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Cagliary 2017

Related talks:

- **W.A.Baan**
  H2O MegaMasers at High Resolution

Related posters:

- **#47 N.N.Shakhvorostova, A.V.Alakoz, A.M.Sobolev & RA maser team**
  Estimates of brightness temperatures for galactic maser sources observed byspace interferometer "RadioAstron"
- **#25 I.D.Litovchenko, S.F.Likhachev, V.I.Kostenko et al.**
  Peculiarities of maser data correlation / postcorrelation in Radioastron Mission

http://www.asc.rssi.ru/radioastron/index.html

RadioAstron

Space VLBI Mission

Russian

- Main
- News
- Organization
- Documents
- Publications
- Processing
- Meetings
- Archives
- Schedule
- Software
- AO-5

Welcome to the home page for the RadioAstron Project!

The RadioAstron is an international space VLBI project led by the Astro Space Center of Lebedev Physical Institute in Moscow, Russia.
The payload - Space Radio Telescope, is based on spacecraft Spektr-R, that have been designed by the Lavochkin Association
List of organizations which were taken part in developing of the project and now support the RadioAstron mission is presented here

What's New

- New version of the Fakerat, August 02, 2017, is available in the Software folder.
- The RadioAstron Newsletter # 32, July 27, 2017.
- RadioAstron Announcement of Opportunity - 5 for observations from July 2017 to June 2018 inclusive.
- The RadioAstron User Handbook, ver. 2.8, December 15, 2016: English version.



RadioAstron's front view

Angular resolution

is one of the main characteristics of masers as a tool which is most prominent for determination of the source structure, proper motions, parallaxes, etc.

Observations of Maser Sources in the Galaxy with high angular resolution allow:

- **Study star formation phenomena on the scales from a.u. (the Solar system) to ~ 15 kpc (the whole Galaxy)**
- **Study mass loss phenomena in evolved stars**
- **Locate new interesting objects**
- **Study nature of these sources:**
- - study structure of the sources
- - study kinematics
- - determine physical parameters in the regions where masers are formed and their vicinity, including characteristics of magnetic fields and turbulence
- measure distances to the sources by direct method of trigonometric parallax
- Study distribution of the sources in the Galaxy
- et al.

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Observations of Extragalactic Maser Sources with high angular resolution allow:

- **Measurement of the Hubble constant**
- **Study structure of accretion disks and outflows**
- **Study kinematics of the accretion disks and outflows**
- **Measure distances to the objects**
- **Measure masses of the central black holes**

- et al.

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- et al.

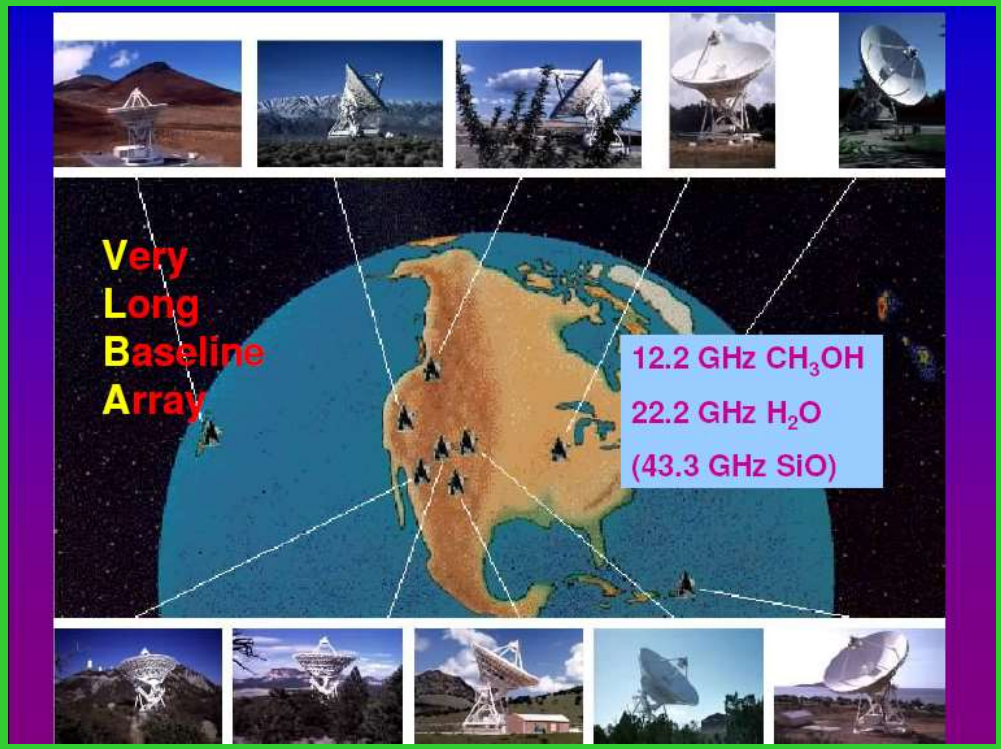
Do we want to make this instrument more precise?

Do we want to make this instrument more precise?

YES!

VLBA, EVN and some other facilities have size comparable to that of the Earth





Do we need such instrument?
Do we want to make it more precise?

Can we make a step from
Milli- to Micro-arcsecond studies
using space VLBI?

What are the main concerns?

- Maser beaming
- Scattering in the line-of-sight: dithering and scintillation
- Time variability and ultra-fine structure of the source: instabilities and turbulence

H_2O masers in the Galaxy

Most of maser spots disappear

at high angular resolution !!!

VSOP prelaunch H2O maser survey

(Migenes et al. 1999)

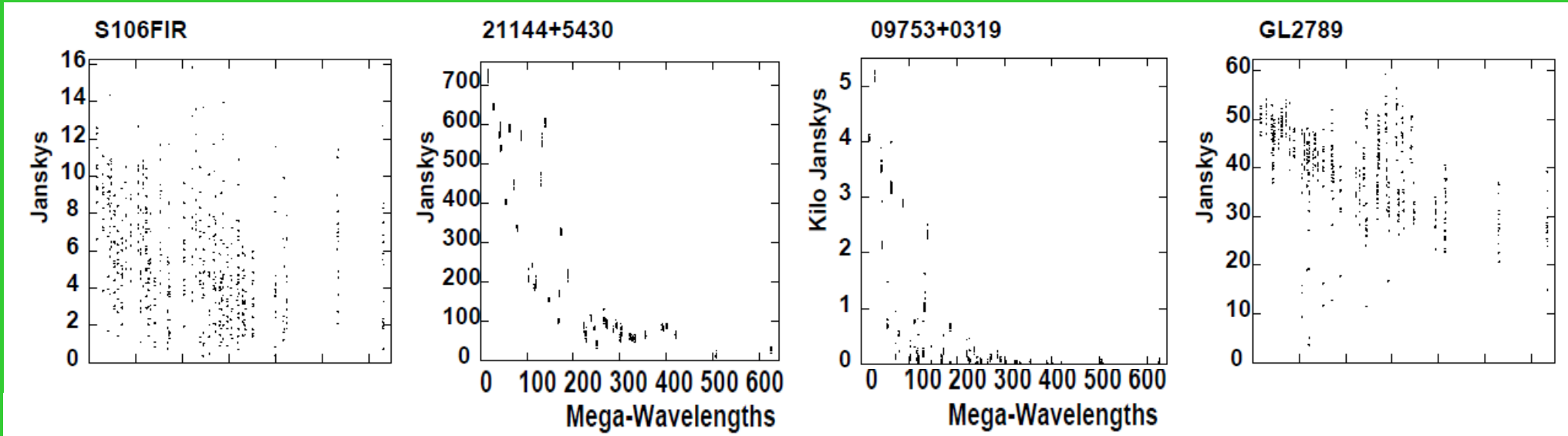
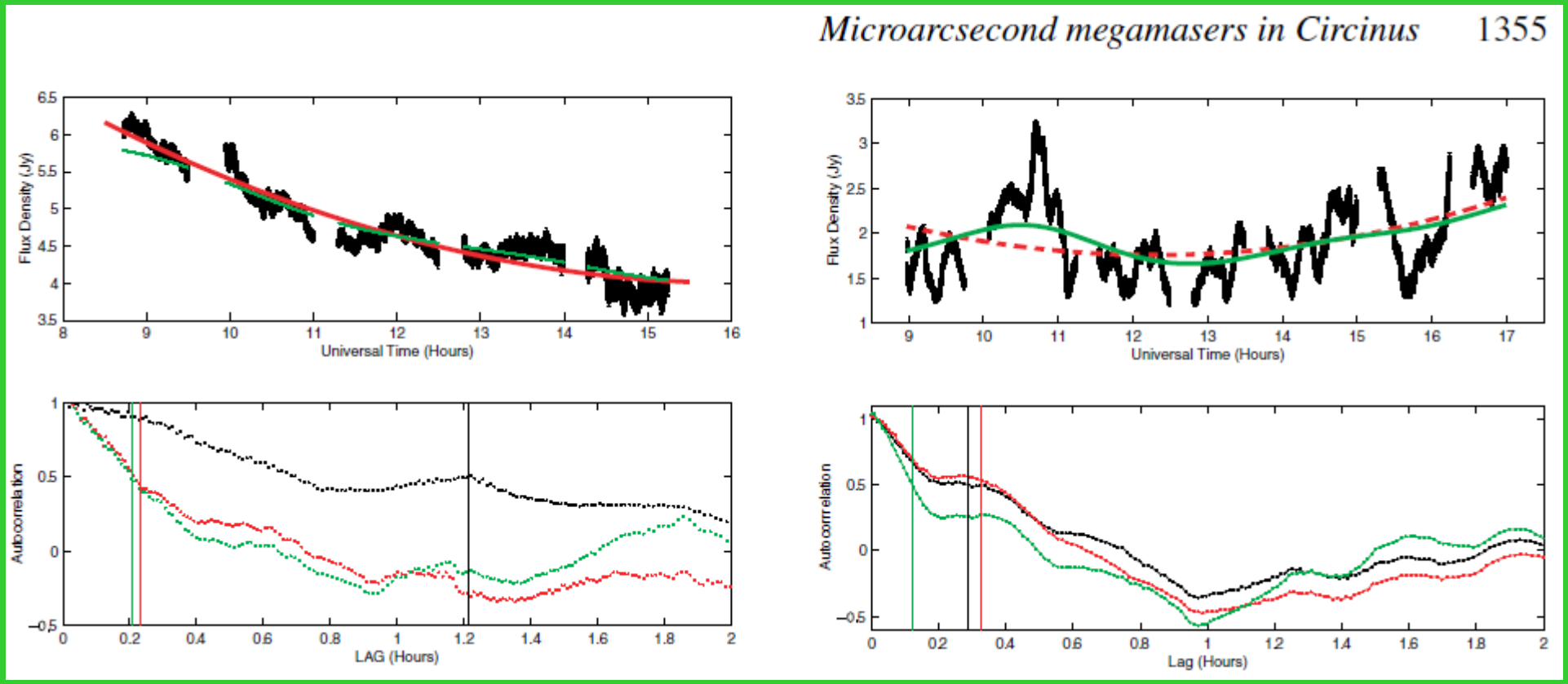


FIG. 3.—Visibility plots of the strongest maser feature for the sources not resolved with the VLBA's full resolution



McCallum et al. (2009)



Are Masers Spooks or Things ?

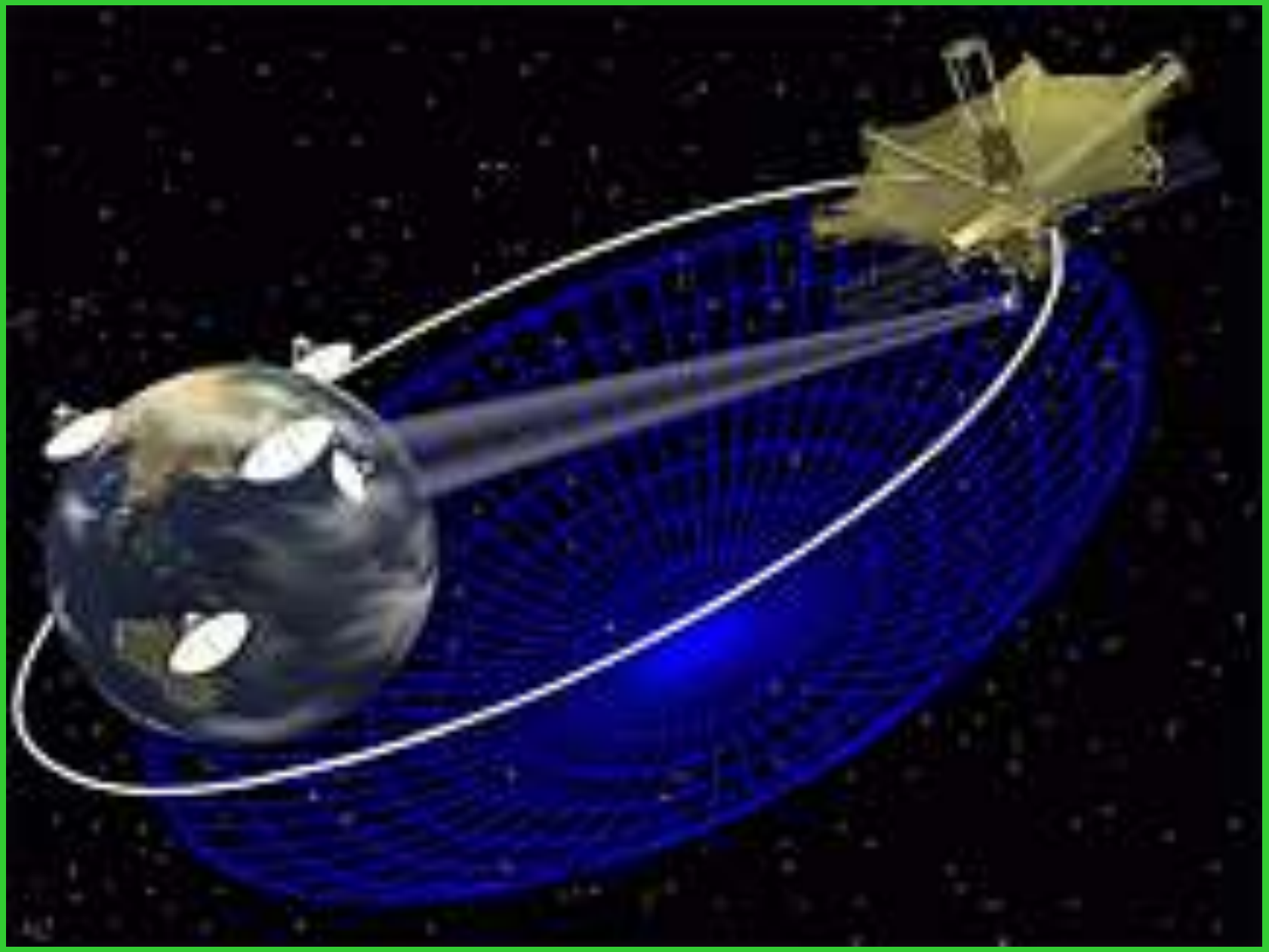






Into Space!

HALCA (VSOP) established that space VLBI instrument can be implemented



HALCA
the first cosmic radiointerferometer



Mon. Not. R. Astron. Soc. **320**, 217–223 (2001)

Space–VLBI observations of the OH maser OH 34.26+0.15: low interstellar scattering

V. I. Slysh,[1] M. A. Voronkov,[1] V. Migenes,[2★] K. M. Shibata,[3] T. Umemoto,[3] V. I. Altunin,[4] I. E. Val'tts,[1] B. Z. Kanevsky,[1] M. V. Popov,[1] A. V. Kovalenko,[1] E. B. Fomalont,[5] B. A. Poperechenko,[6] Yu. N. Gorshenkov,[6] B. R. Carlson,[7] S. M. Dougherty,[7] J. E. Reynolds,[8] D. R. Jiang,[9] A. I. Smirnov[1] and V. G. Grachev[10]

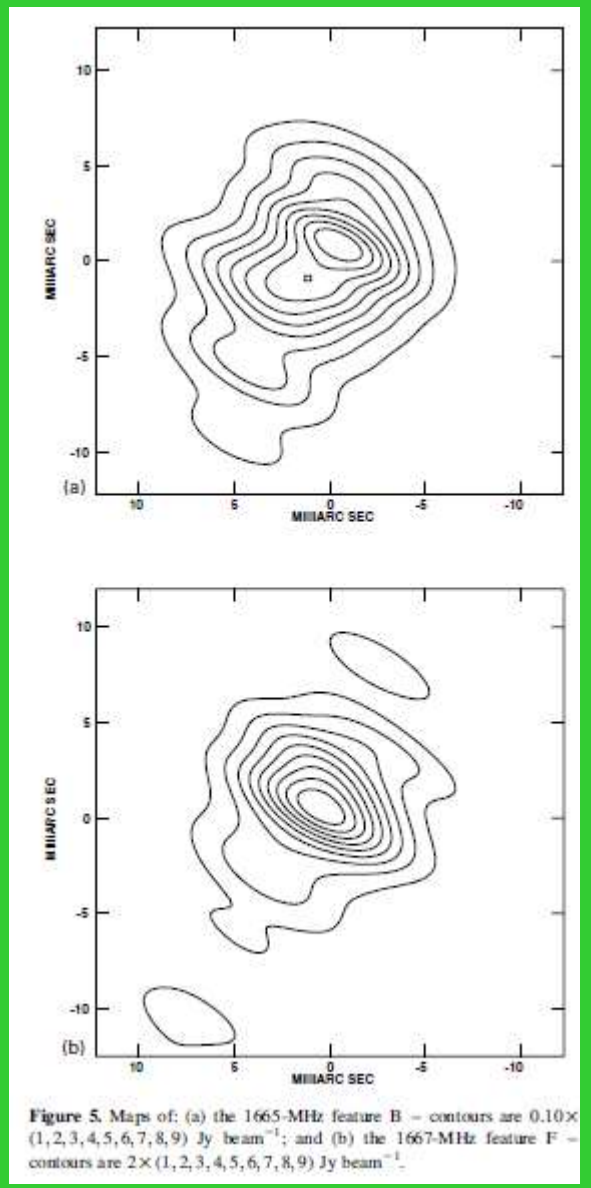


Figure 5. Maps of: (a) the 1665-MHz feature B – contours are 0.10× (1, 2, 3, 4, 5, 6, 7, 8, 9) Jy beam^{-1}; and (b) the 1667-MHz feature F – contours are 2× (1, 2, 3, 4, 5, 6, 7, 8, 9) Jy beam^{-1}.

RadioAstron project

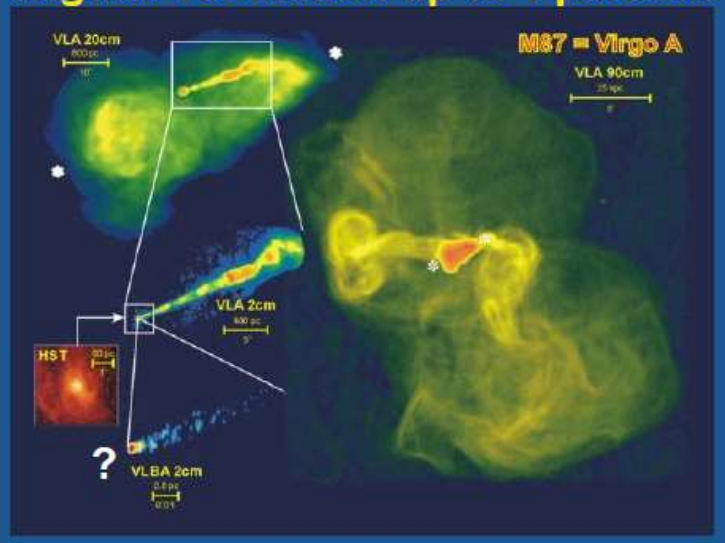
launched in July 2011

http://www.asc.rssi.ru/radioastron/index.html

Main Parameters of the RadioAstron Mission

Frequency band [GHz]	0,327	1,665	4,83	18 - 25
Bandwidth, 2-pol. [MHz]	2 x 4	2 x 32	2 x 32	2 x 32
Fringe size at 350.000 km baseline [micro arcsec]	540	106	37	7 - 10
Detection limit 1-σ [mJy] (ground radio telescope GBT, 16/4 MHz bandwidth, 300 s integration)	42	4	4	10

The unprecedented super high angular resolution up to 1 μarcsec







Pushchino, June 2012

Early Science Program maser team

TEAM

A.Alakoz , T.An, Y.Asaki, W.Baan,

A.Bartkiewicz, F.Colomer, S.Ellingsen, M.Gaylard,

J.-F.Gomez, M.Gray, C.Henkel, H.Imai, S.Kalenskii,

V.Kostenko, S.Kurtz, E.Lekht, I.Litovchenko,
L.Matveyenko, J.McCallum, K.Menten, J.Moran,

S.Parfenov, A.M.S.Richards, R.Rizzo, G.Rudnitskij,

V.Samodourov, N.Shakhvorostova, V.Strelnitski,

A.Sobolev, A.Tolmachev, H. van Langevelde,
M.Voronkov

Masers with RadioAstron:

- OH @1665 & 1667 MHz
- H_2O @ 22235.08 MHz – several bands
  (allow us to observe doppler-shifted Megamasers)
- SiO
- CH
- H_2CO
- CH_3OH
- NH_3
- HC_3N
- HCN

One of the basic RadioAstron innovations is possibility to observe H_2O masers

These masers are the strongest

Bright sources contain

numerous unresolved spots

Rather bright masers reside in external galaxies

Observing possibilities

Sensitivity

H_2O masers @22.235 GHz:
dV=0.1 km/s, t_{coher}=100 s, SEFD Eff=90Jy, SEFD RA=30.000 Jy
Smin=15 Jy (for GBT + wider lines Smin is down to 3-4 Jy)

OH masers @1.665 GHz:
dV=0.1 km/s, t_{coher}=600 s, SEFD Eff=20 Jy, SEFD RA=3.400 Jy
Smin=3.5 Jy

Observing possibilities

Angular & linear resolution

H_2O masers @22 GHz ang. resolution is up to ~0.007 mas
(equivalent to linear size of 0.007 ae @ 1 kpc = 70 ae @ 10 Mpc)

OH masers @1.6 GHz resolution is up to 0.1 mas
(equivalent to linear size of 0.1 ae @ 1 kpc)

Summary of RadioAstron unsuccessful observations of evolved stars in the Galaxy

Source name	Line	Number of sessions	Projected baselines (approx. ED range)	Note
S Persei	H_2O (22 GHz)	7	2,3,4,7,10,20	
VY CMa	H_2O (22 GHz)	7	3,4,5,7,10	1 session RA form. error
VY CMa	OH (1.665/1.667 GHz)	3	2.5,5	
U Her	H_2O (22 GHz)	1	2.5	
VX SGR	H_2O (22 GHz)	1	2.0	RA pointing error!
NML Cyg	H_2O (22 GHz)	1	1.7	

Extragalactic water masers

- **W.A.Baan**

H2O MegaMasers at High Resolution

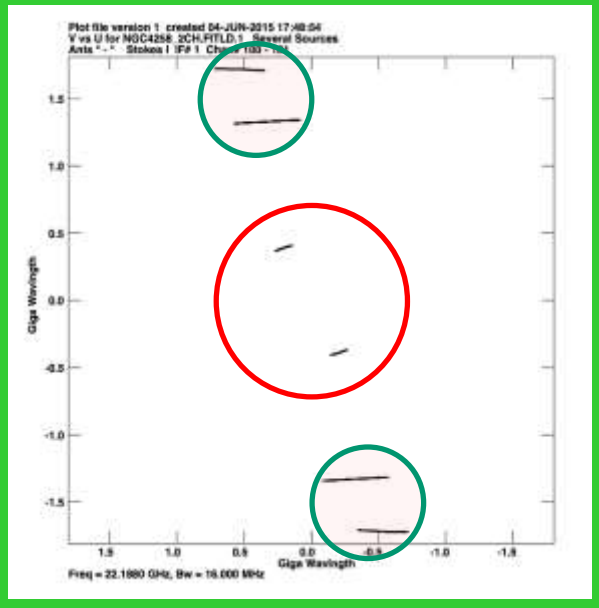
Name RA,Dec(2000)	type	flux (Jy)	Distance (Mpc)	Approximate masing region size (milliarcsec)	Velocity range (km/s)	reference
Circinus $14^h13^m09.95^s$ $-65°20'21''$	disk-megamaser, jet-megamaser, outflow-megamaser	5 - 100 strong variability Rich spectrum	4.2	100	250, 650	McCallum et al. (2009): Microarcsec structure, scintillations
NGC3079 $10^h01^m57.80^s$ $55o40'47''$	flared disk megamaser	2 - 5	**16**	30	900, 1400	Vlemmings et al. (2007): 12 microarcsec sizes for the most saturated maser features
NGC4945 $13^h05^m27.48^s$ $-49°28'05''$	disk-megamaser	10	3.7	40	410, 720	Greenhill et al. (1997)
NGC4258 $12^h18^m58^s$ $47°18'15''$	disk-megamaser	0.6 - 2	7.2	300	-500, 1500	Humphreys et al. (2008): spiral structure signs
N113 $05^h13^m23.1^s$ $-69°227'34''$	Star formation LMC	70			250, 260	Oliveira et al.(2006)
M33 (IC133) $01^h30^m27.3^s$ $+30°37'28''$	star formation, local	2 - 5			250, -200	Greenhill et al. (1990)

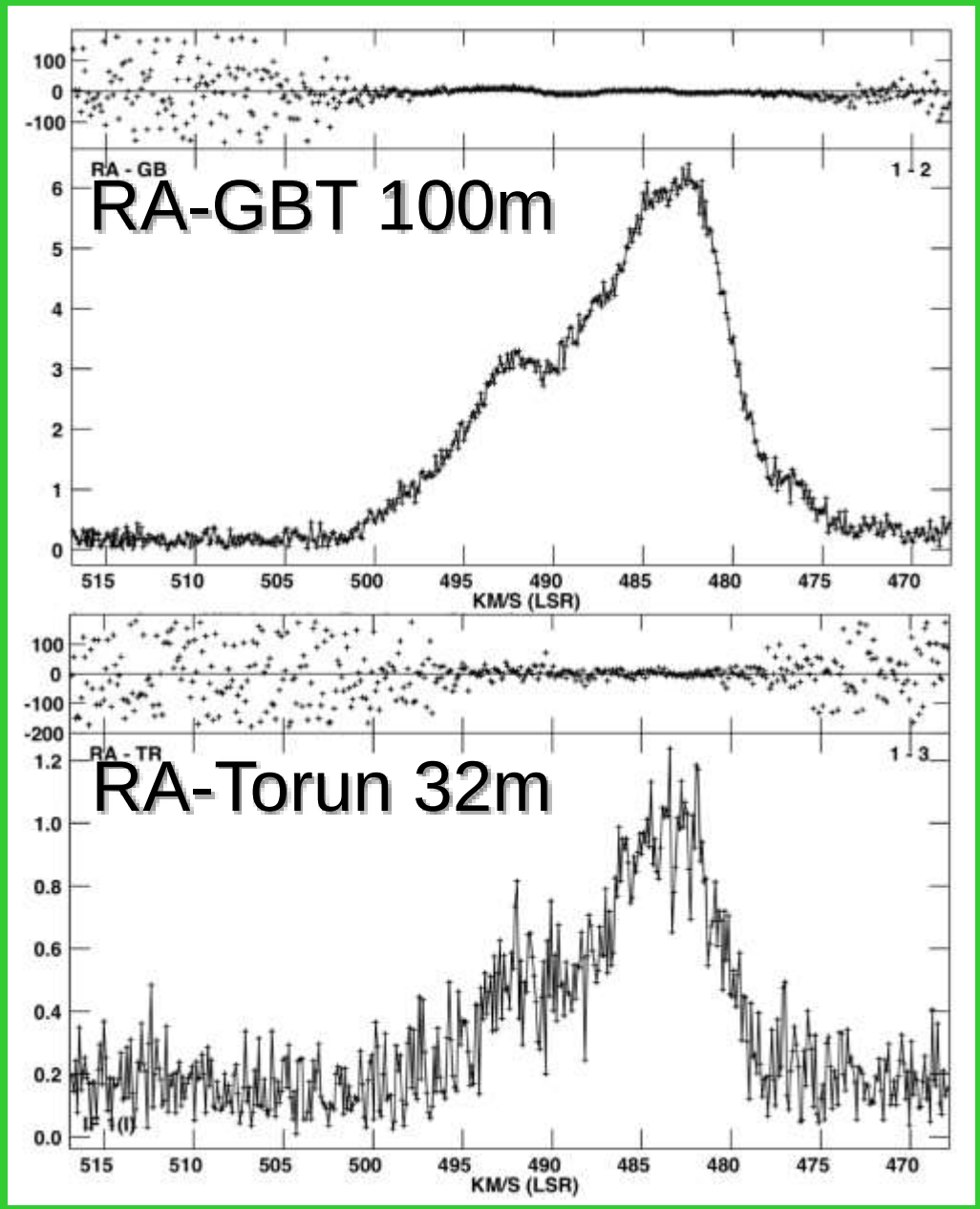
April 2015 (observation 18.12.2014)
Detection of NGC 4258 Megamaser!

Baseline 2 ED

110 μas

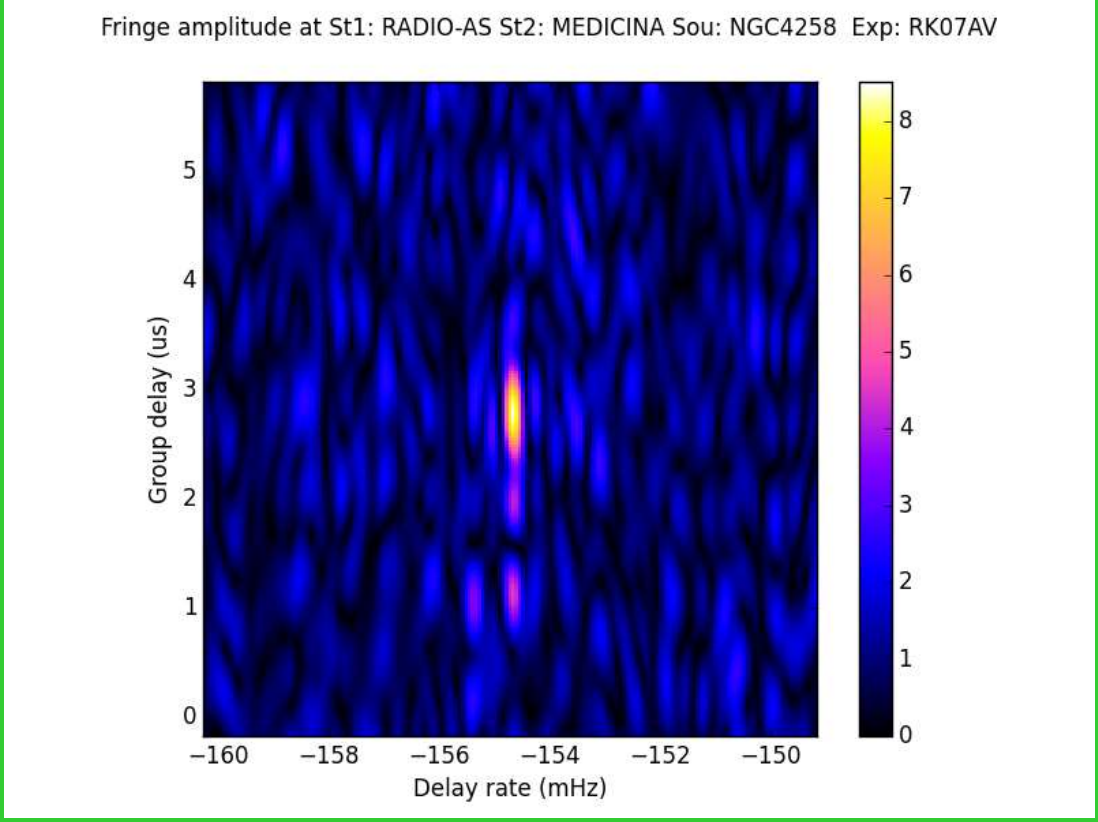
800 a.u. at 7.2 Mpc





raks07av | NGC4258 | 12:18:57.504600 | 47:18:14.30300 J2000
start date /UT time 2014-02-10 05:00:00
stop date /UT time 2014-02-10 06:00:00
fringes between RA and MEDICINA have been detected at

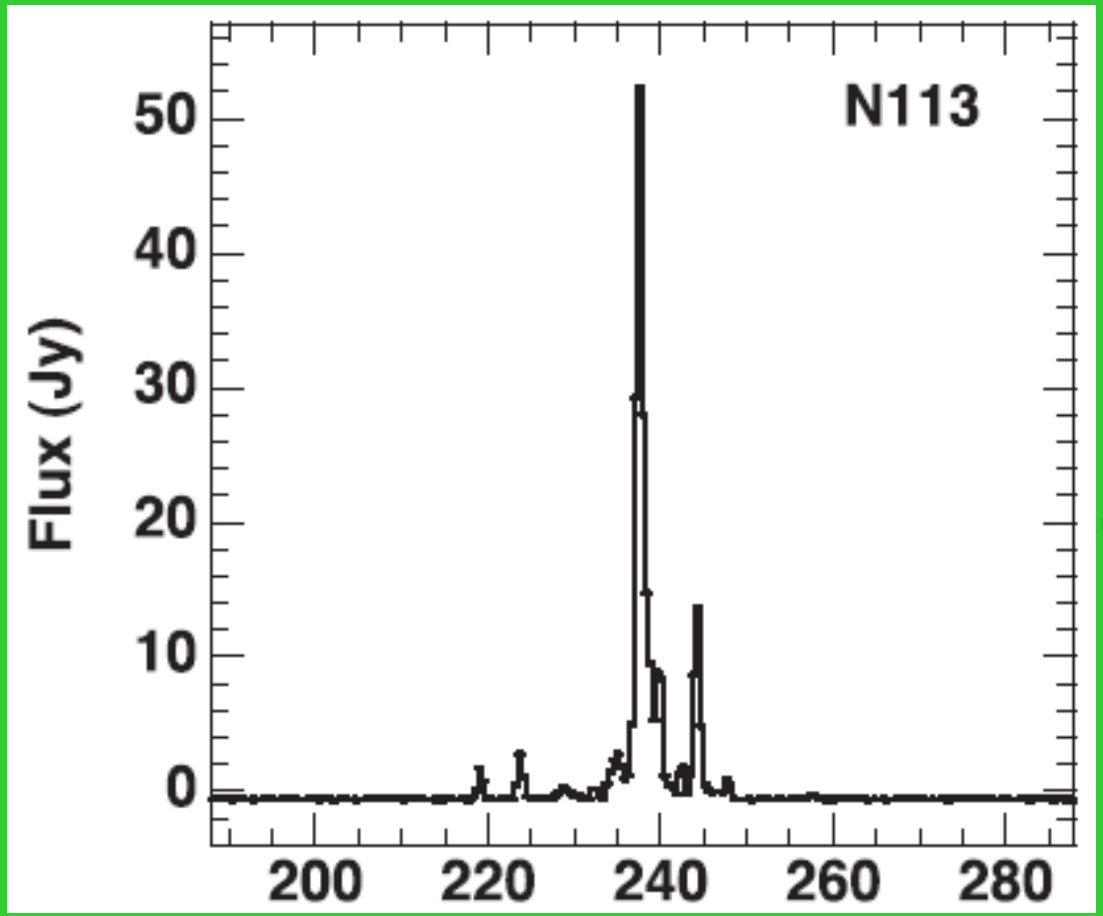
Absolute Record!!! 26.5 Earth Diameters (~8 microarcsec resolution)

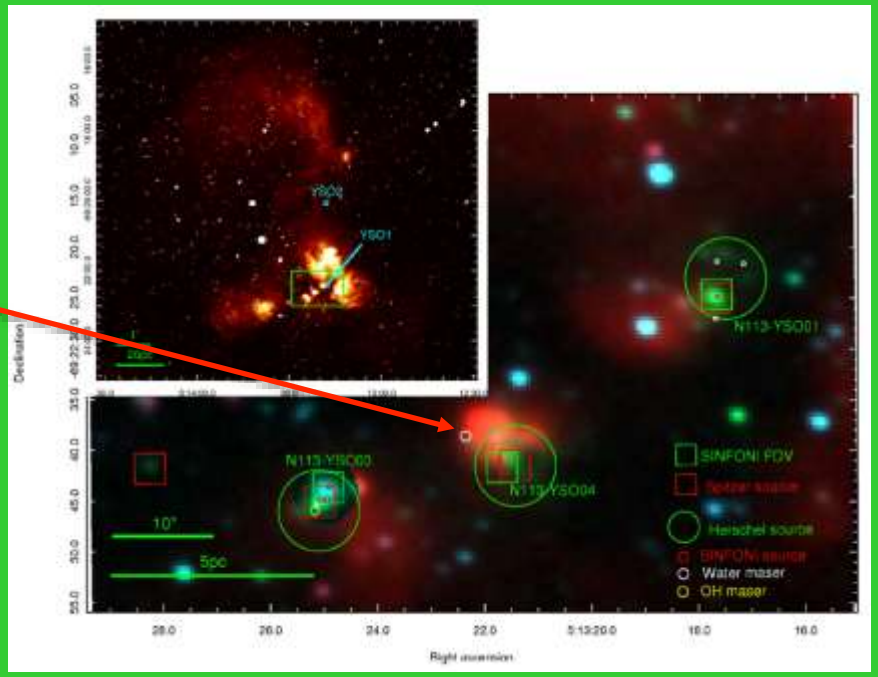


Sobolev et al. (2017ASPC..510...27S)

N113 in LMC

50 kpc = 0.5 a.u. with 10 microarcsec beam





Extragalactic water masers with RadioAstron: statistics and records

Source	Molecule	Baseline (ED)	Max Resolution (mas)
NGC4258*	H2O	1.3; 1.7; 6.5; 9.5; 11.6; 11.8; 12.2; 19.2; 19.5; 26.5	8
NGC3079*	H2O	1.9; 1.9	115

Summary (basic statements)

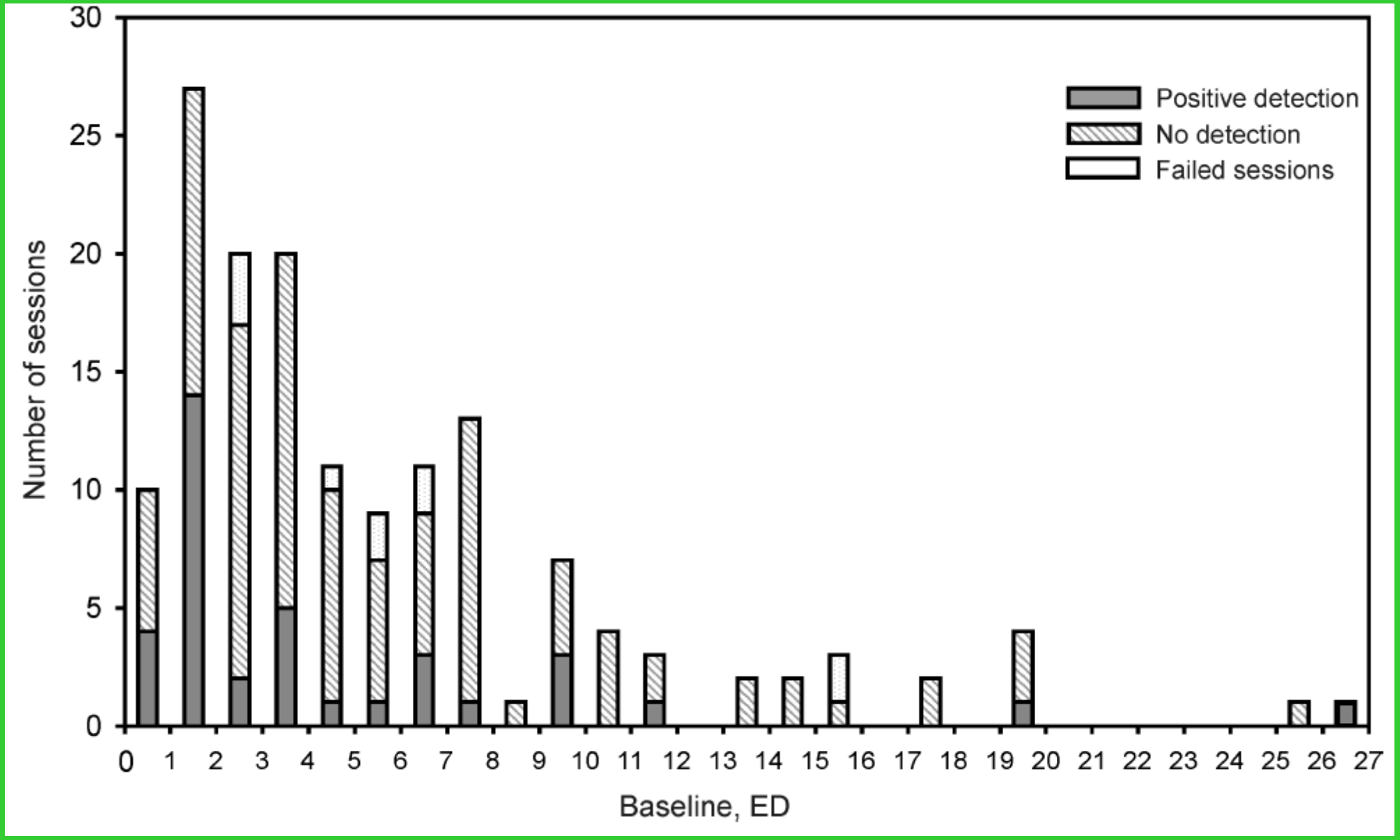
- ✓ Scattering does not prevent observations of the bright extragalactic H2O masers with the space-ground interferometer.
- ✓ Considerable number of maser features become resolved (bigger size or beaming effect) at 10-20 microarcsec
- ✓ No strong polarization is detected at ultimate angular resolutions
- ✓ future: observation of other extragalactic sources, study influence of the scintillation effects (characteristic times, changes in positions and dithering radii).

Galactic water masers

Source	Molecule	Baseline (ED)	Max Resolution (mas)
W3 Irs5	H2O	2.5-2.8; 3.5; 3.9; 5.4; 6.0; 6.0-10.0	22
W49 N	H2O	2.2-3.0; 4.5; 7.9; 9.4	23
W3 OH	H2O	3.9	56
Cepheus A	H2O	0.9-1.7; 1.1; 3.1-3.5	62
Orion KL	H2O	1.9; 3.4	64
W51 M/S	H2O	0.4-2.3; 1.3; 1.4-1.8; 1.7	95
G43.8-0.13	H2O	1.2; 1.2	182

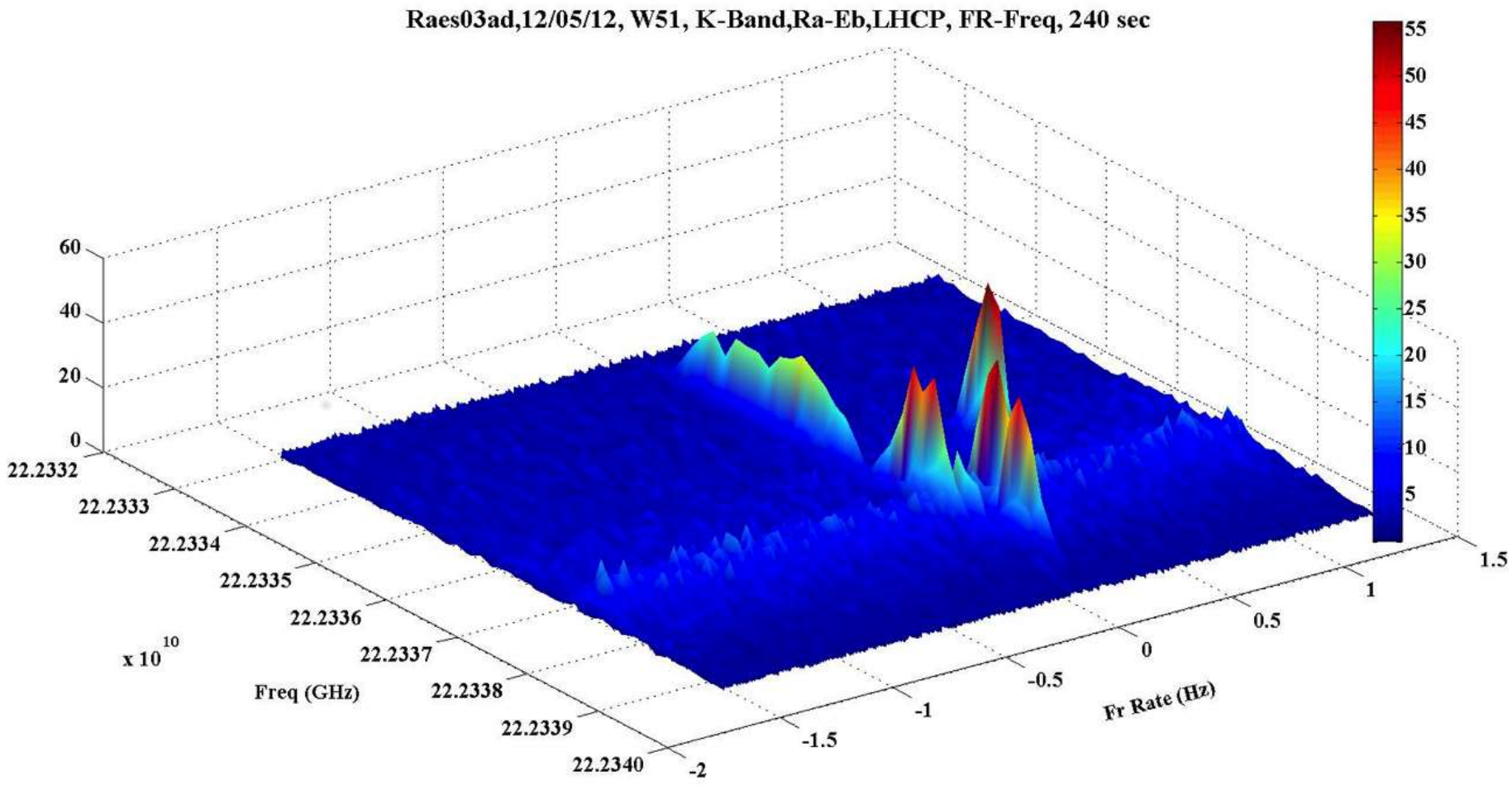
Galactic hydroxyl masers

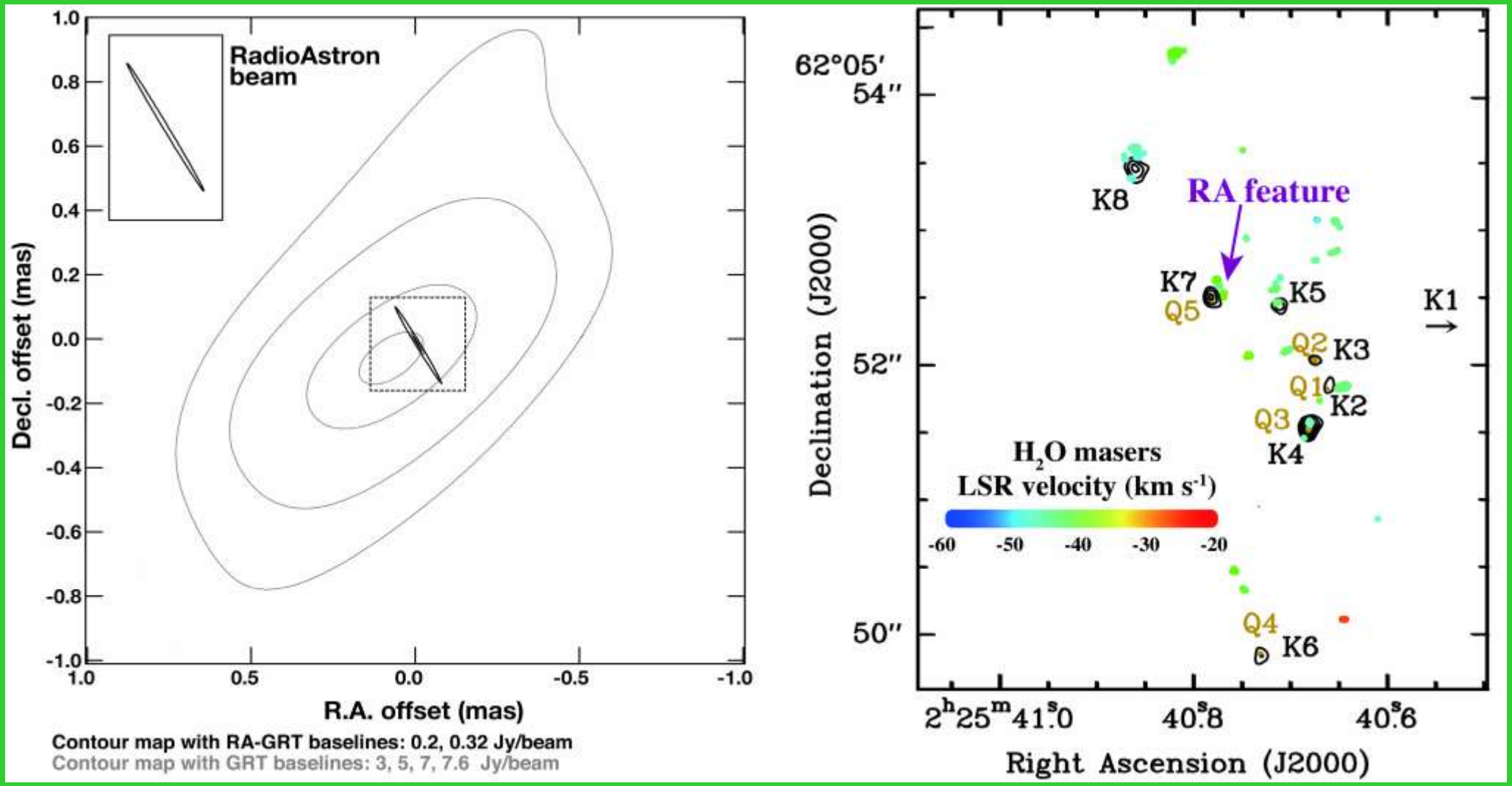
Onsala 1	OH	0.2-0.7; 1.0-1.9	1540
W75 N	OH	0.1-0.3; 0.1-0.8	3660


Positive detection
No detection
Failed sessions
Number of sessions
0
5
10
15
20
25
30
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
Baseline, ED

Galactic water masers

W51M , first fringes at 22GHz
(H_2O maser line RA-Eff, 1.14 Earth D.)
Now- fringes at 2 Earth D.




RadioAstron
beam
Decl. offset (mas)
R.A. offset (mas)
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
1.0
0.5
0.0
-0.5
-1.0
Contour map with RA-GRT baselines: 0.2, 0.32 Jy/beam
Contour map with GRT baselines: 3, 5, 7, 7.6 Jy/beam
62°05′
54″
52″
50″
Declination (J2000)
K8
RA feature
K7
Q5
K5
K1
Q2
K3
Q1
K2
Q3
K4
H2O masers
LSR velocity (km s-1)
-60
-50
-40
-30
-20
Q4
K6
2h25m41s.0
40s.8
40s.6
Right Ascension (J2000)

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

$$T_{b,min} = \frac{\pi e}{2k} B^2 V_q \approx 3.09 \left(\frac{B}{km}\right)^2 \left(\frac{V_q}{mJy}\right) [K].$$

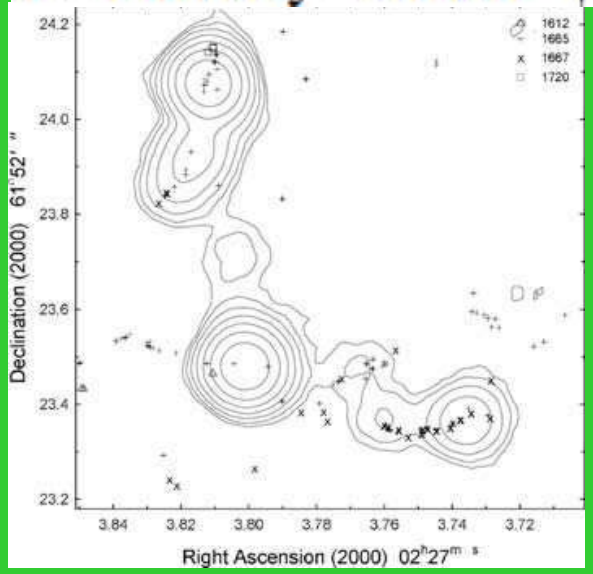
Source	RA J2000 (hh:mm:ss.ss)	DEC J2000 (dd:mm:ss.ss)	Baseline (ED)	Resolusion (μas)	Tb,min (K)	Tb (K)
Orion KL	05:35:14.13	-05:22:36.48	3.3	66	$1.2 \cdot 10^{15}$	$6 \cdot 10^{15}$
Cepheus A	22:56:17.97	62:01:48.75	3.4	64	$1.2 \cdot 10^{14}$	$3 \cdot 10^{14}$
W3 OH	02:27:04.84	61:52:24.61	3.8	58	$2.1 \cdot 10^{14}$	$7 \cdot 10^{14}$
W3 Irs5	02:25:40.71	62:05:52.52	5.4	40	$1.5 \cdot 10^{15}$	$8 \cdot 10^{15}$
W 49N	19:10:13.41	09:06:12.80	9.6	23	$4.5 \cdot 10^{14}$	$3 \cdot 10^{15}$

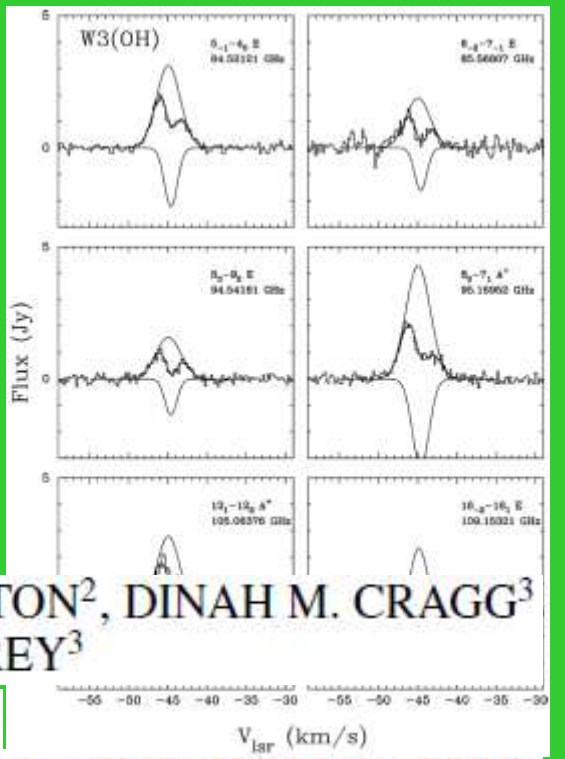
Poster #47 by N.N.Shakhvorostova, A.V.Alakoz, A.M.Sobolev & RA maser team

Mon. Not. R. Astron. Soc. 371, 1550–1558 (2006)

Discovery of large-scale methanol and hydroxyl maser filaments in W3(OH)

L. Harvey-Smith★† and R. J. Cohen





ANDREI M. SOBOLEV[1], EDMUND C. SUTTON[2], DINAH M. CRAGG[3] and PETER D. GODFREY[3]

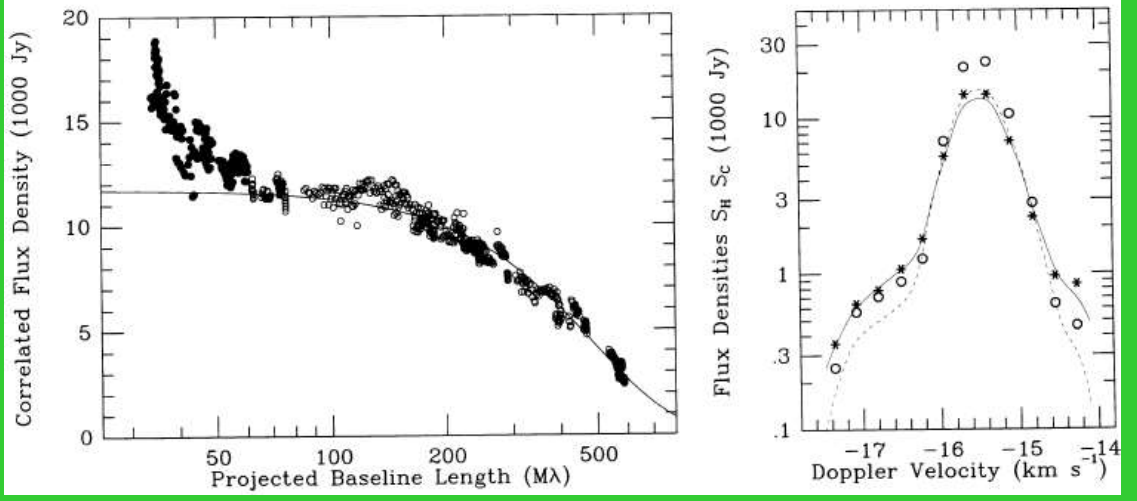
MODEL OF THE W3(OH) ENVIRONMENT BASED ON DATA FOR BOTH MASER AND "QUASI-THERMAL" METHANOL LINES

Astrophysics and Space Science **295:** 189–196, 2004.

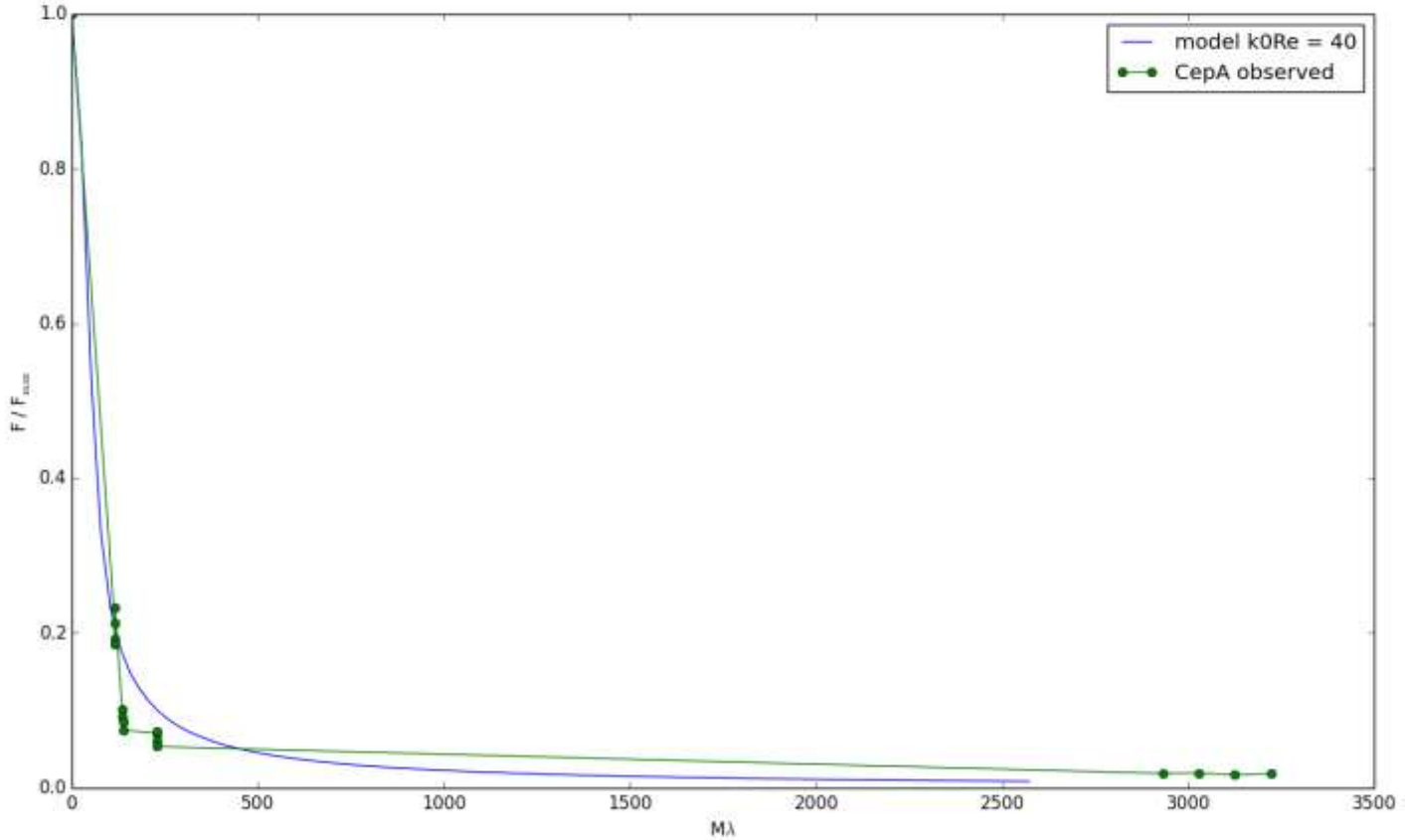
THE ASTROPHYSICAL JOURNAL, 431:L123–L126, 1994 August 20

SCATTERED HALOS AROUND H_2O MASERS

C. R. GWINN

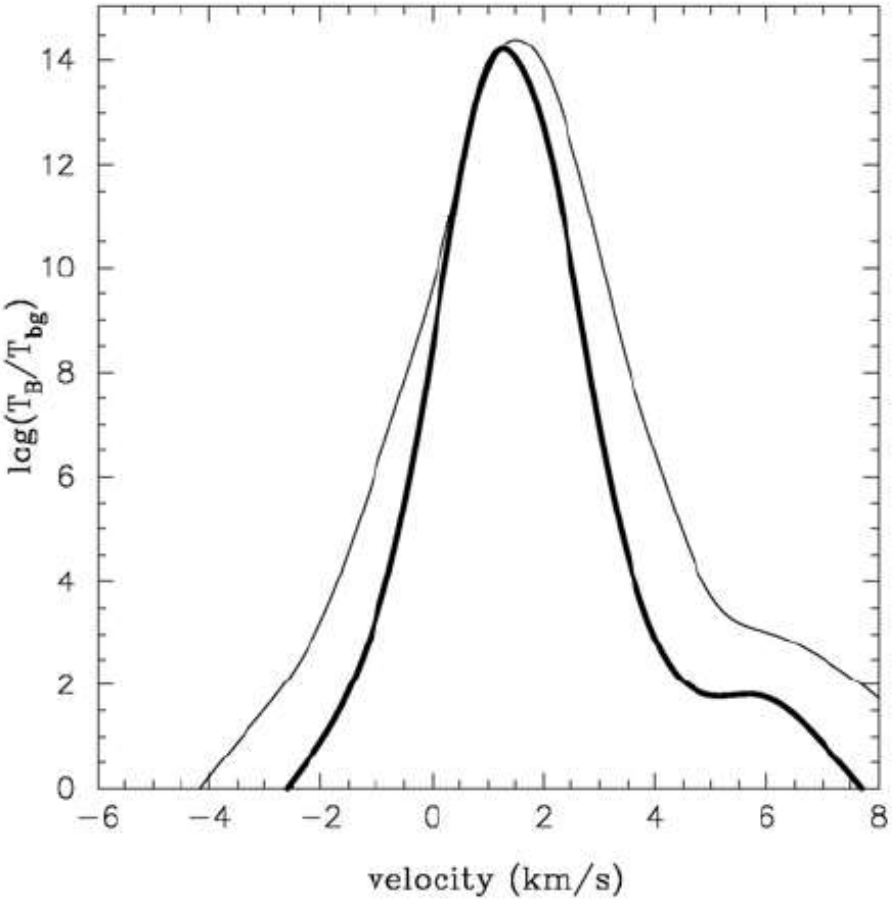


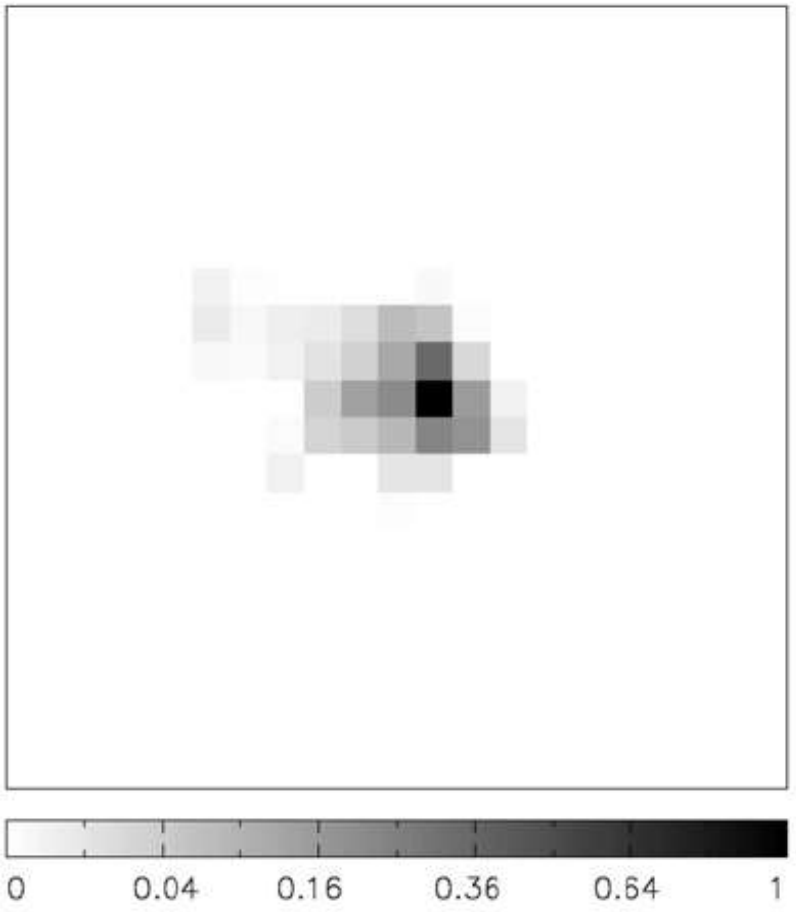
Change of the size due to saturation



Model of **W.D.Watson & H.W.Wyld (2003)**
Apparent Sizes and Spectral Line Profiles for Spherical and Disk Masers: Solutions to the Full Equations

Correlation paths in the turbulent medium





Model of the turbulent layer by
A.M.Sobolev, E.C.Sutton, W.D.Watson et al. (2008)
Sizes of Masing Parts of Massive Star Forming Regions

Summary 1
(brightness temperatures and lost flux)

Space-ground interferometer proved working in the spectral regime :

7 water maser sources (W51, W3IRS5, Cep A, W3(H2O), W49N, etc.) were detected in the 22 GHz water maser line with projected baselines up to 9.6 Earth diameters.

2 OH maser sources (W75N and ON1) were detected with projected baselines 0.75 and 1.8 Earth diameters.

Model of the correlation paths in the turbulent medium has potential to account for the lost flux.

Summary 2 (basic statements)

✓Interstellar scattering (both on the way to the object and in the object itself) does not prevent observations of the bright galactic H_2O and OH masers with the space-ground interferometer. (see also VSOP observations of OH masers in G34.26 , W48, and Cep A)

➢ future: study influence of the interstellar scattering (characteristic times, changes in positions and dithering radii, difference of scattering in different directions).

✓It has been shown that the maser spots with very small sizes are numerous, at least in Cep A, W51, W49N and W3IRS5 several maser features show up and contain very small spots each, spots of small sizes are connected to highly variable features showing strong velocity gradient

➢ future: prove this statement for the other sources, mapping with RA, several epochs with VERA to establish stability of the source presence, follow up with ALMA to establish nature of associated sources: discs or turbulent eddies

Cepheus A

Related talk:

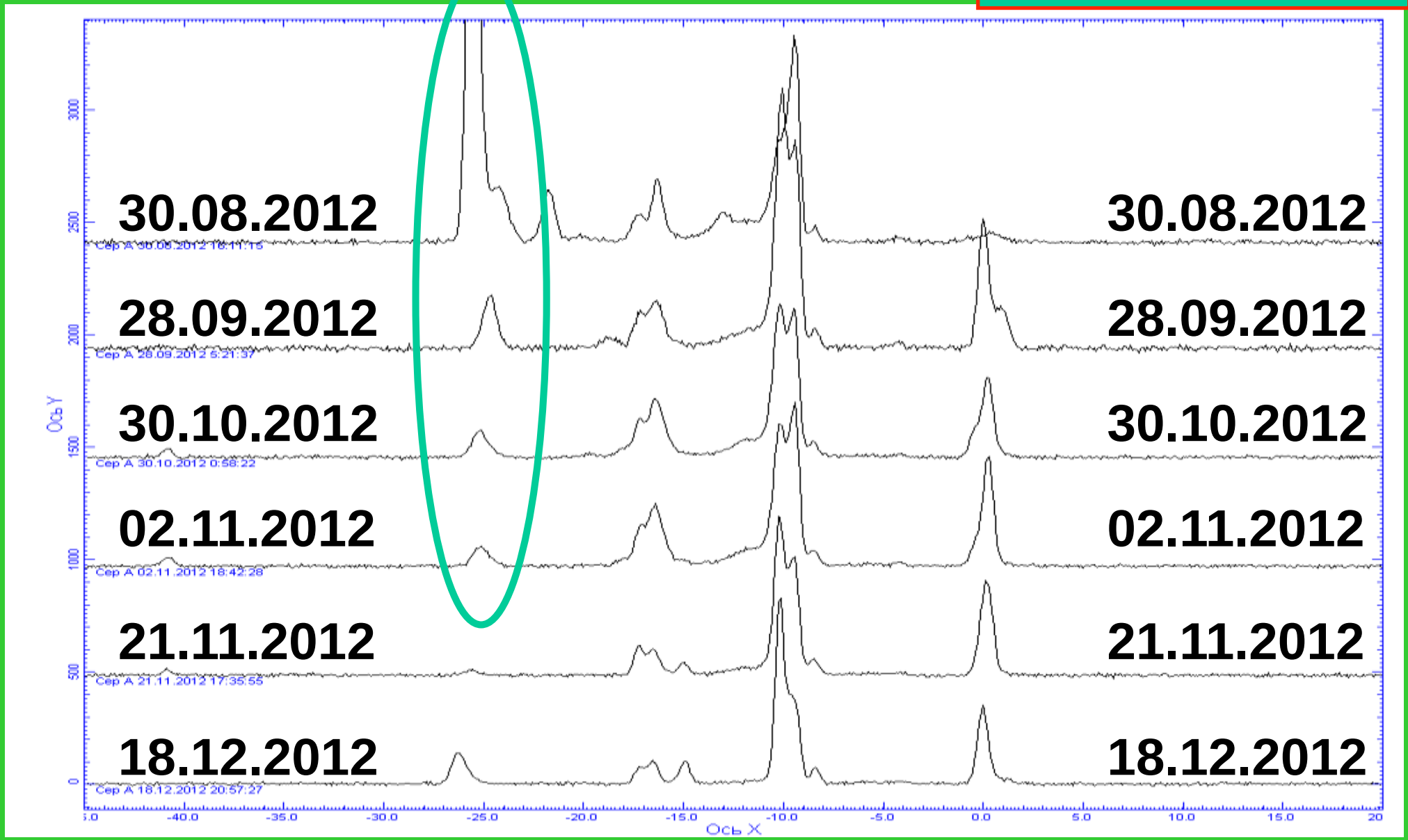
- **A.Sanna**
  The CepHeus-A Star formation and proper Motions (CHASM) Survey – Where is the mass reservoir of massive young stars?

Related poster:

- **#30 Jeoung-Sook KIM et al.**
  New water maser source near HW3d in the massive star-forming region Cepheus A

Cepheus A

RA observations
18.11.2012



Cep A water maser

Experiment code raes02q

Date: 18 Nov 12:00-12:40 UTC

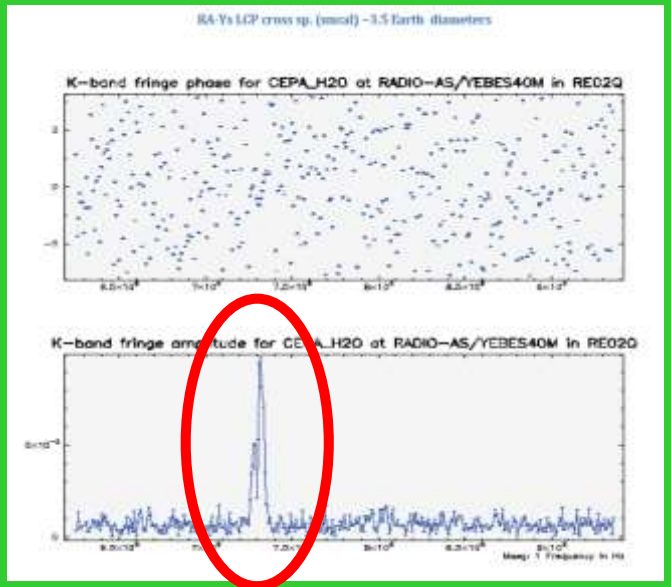
Stations in experiment :Zelenchuk, Noto, Yebes

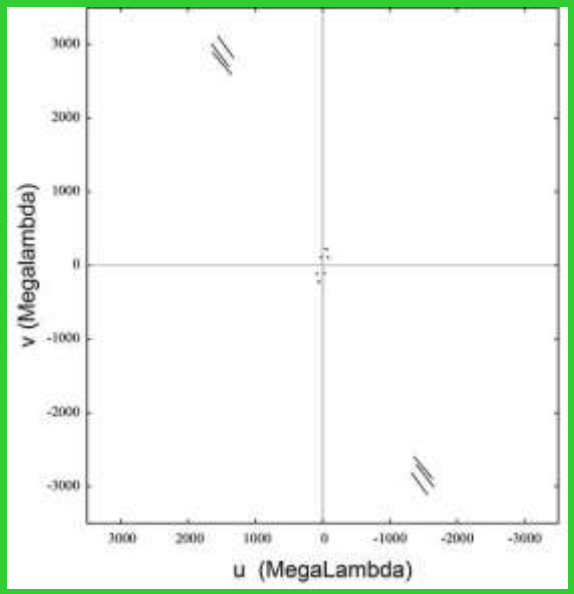
Space- earth projections : ~3.5 Earth diameters

Data were correlated with DiFX corr.

Postcorrelation: PIMA

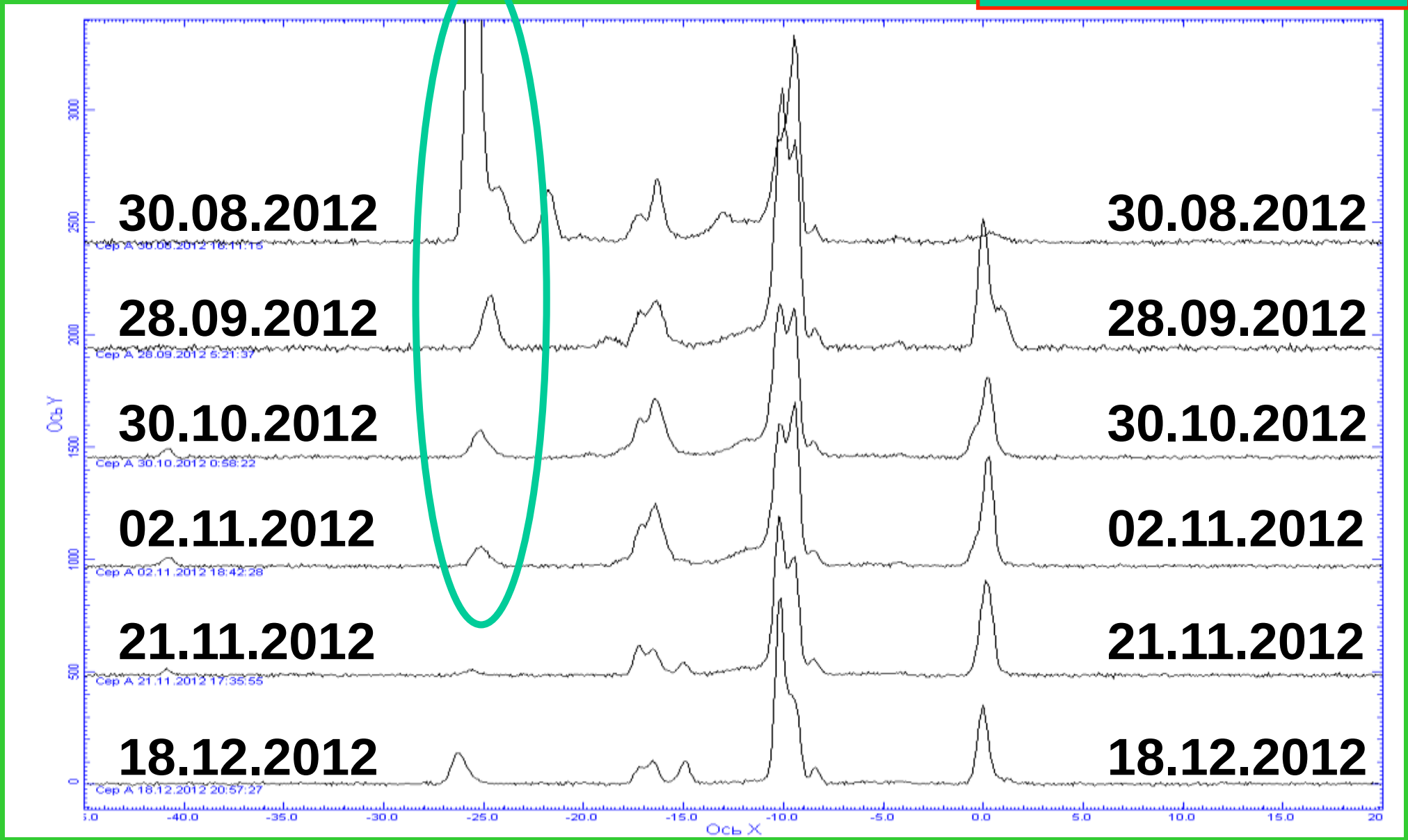
(http://astrogeo.org/pima/)





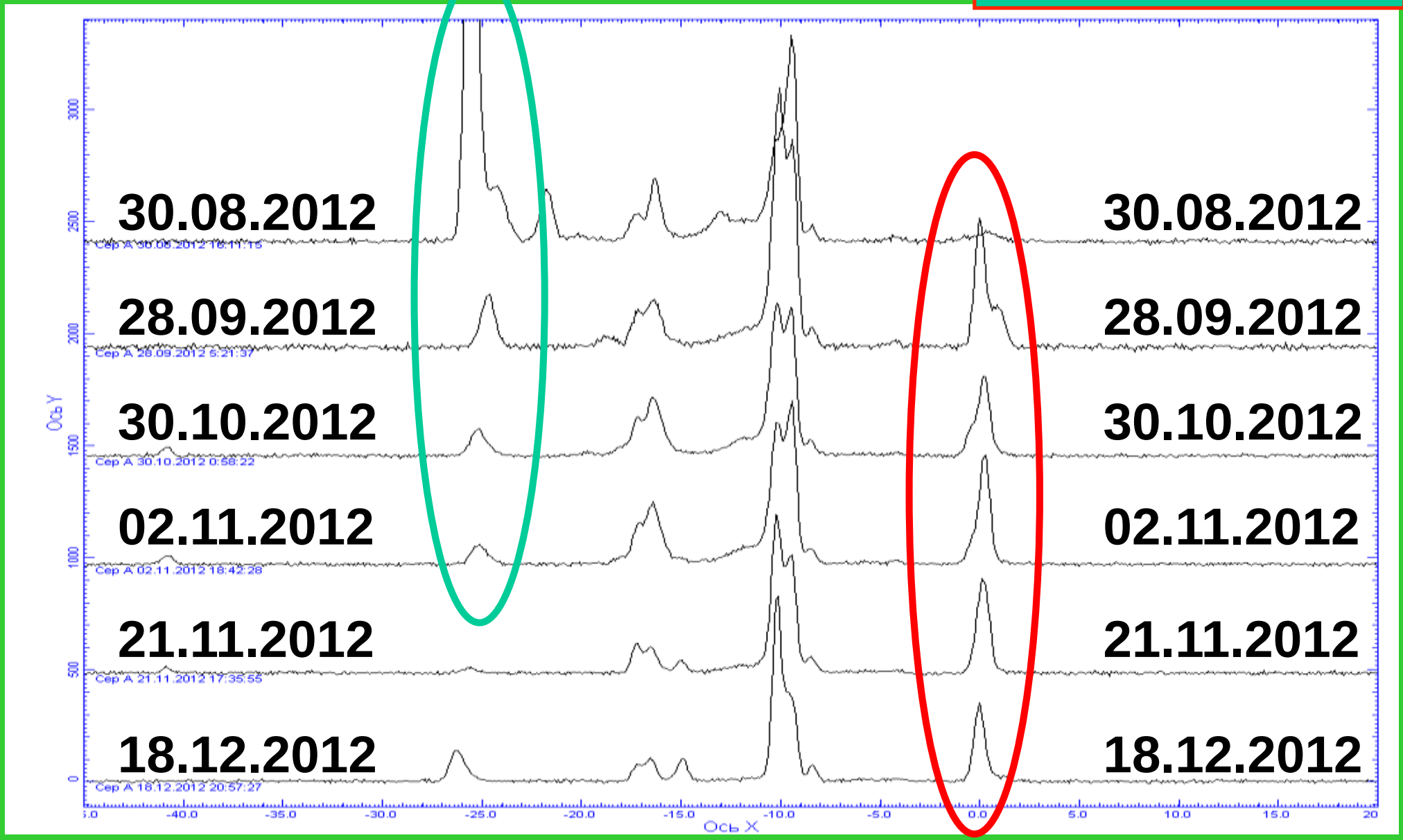
Cepheus A

RA observations
18.11.2012



Cepheus A

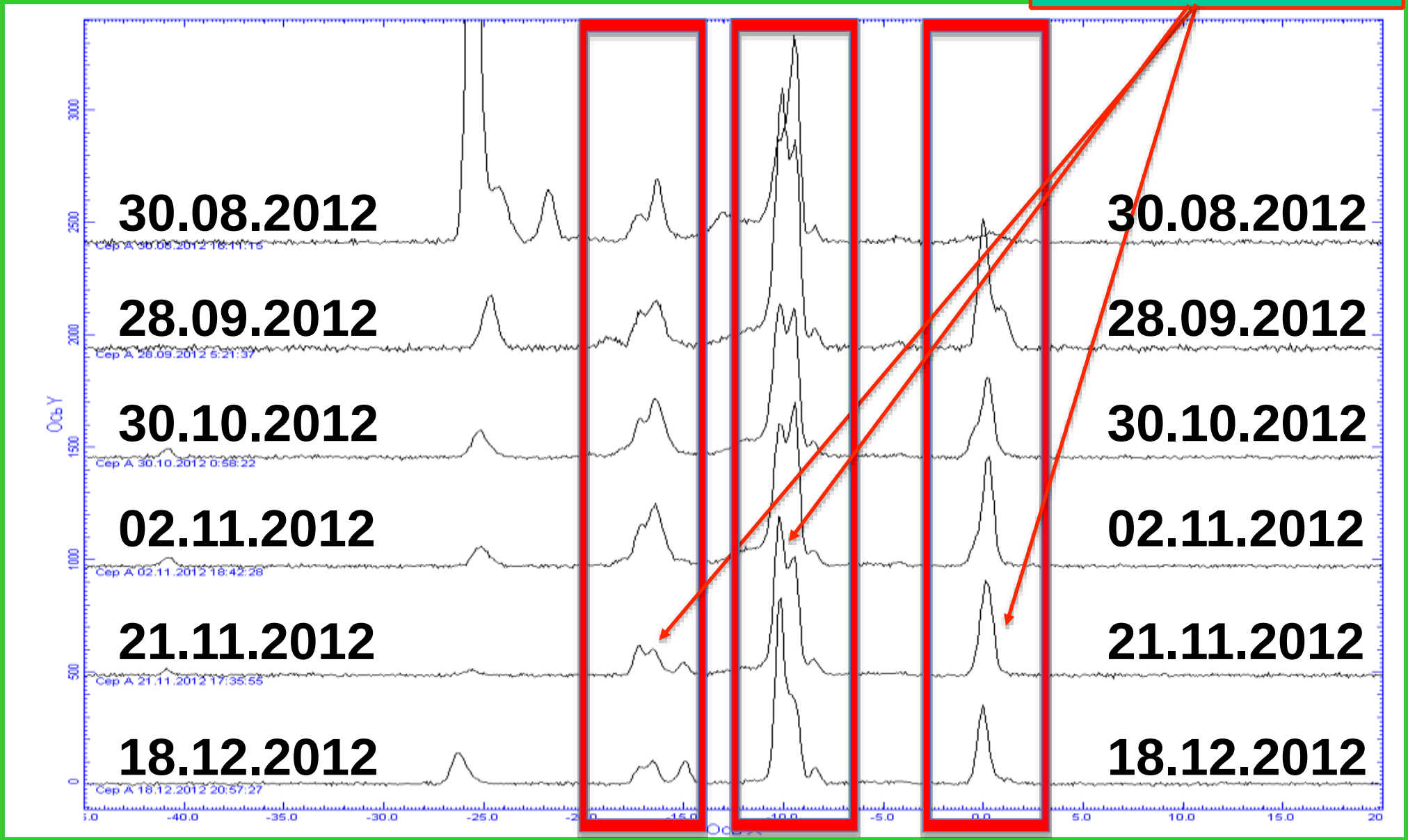
RA observations
18.11.2012

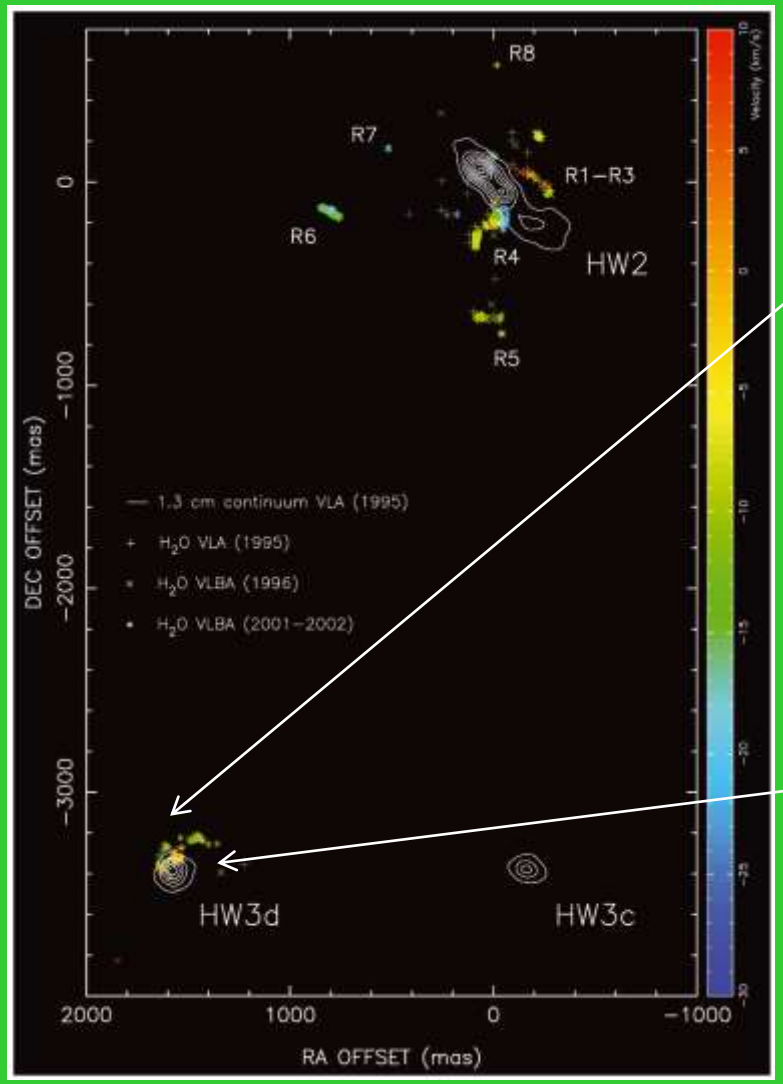


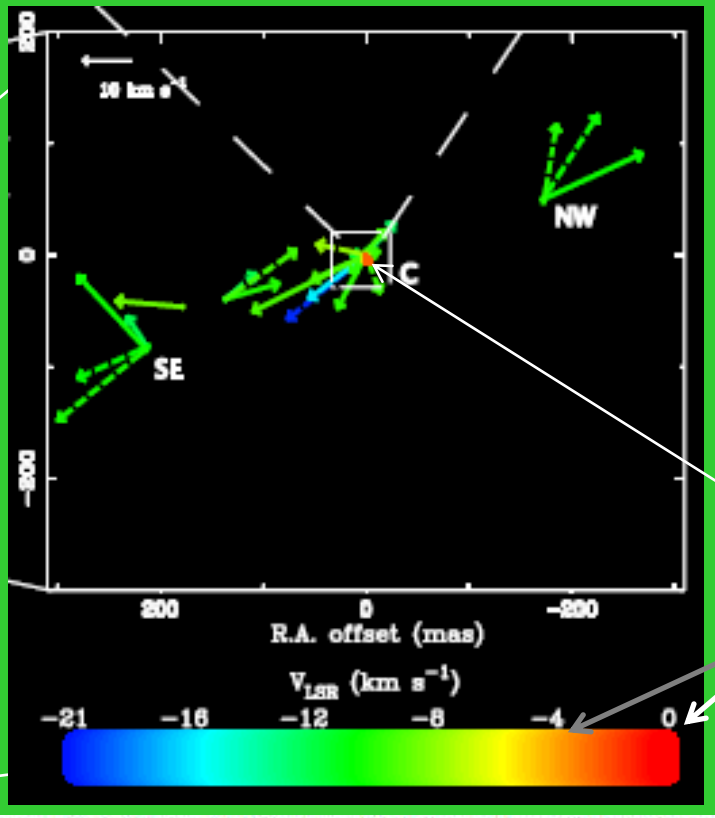
PRAO LPI
RT-22 monitoring

Cepheus A

RA detections
18.11.2012







V_{RA}

A HIGHLY COLLIMATED WATER MASER BIPOLAR OUTFLOW IN THE CEPHEUS A HW3d MASSIVE YOUNG STELLAR OBJECT

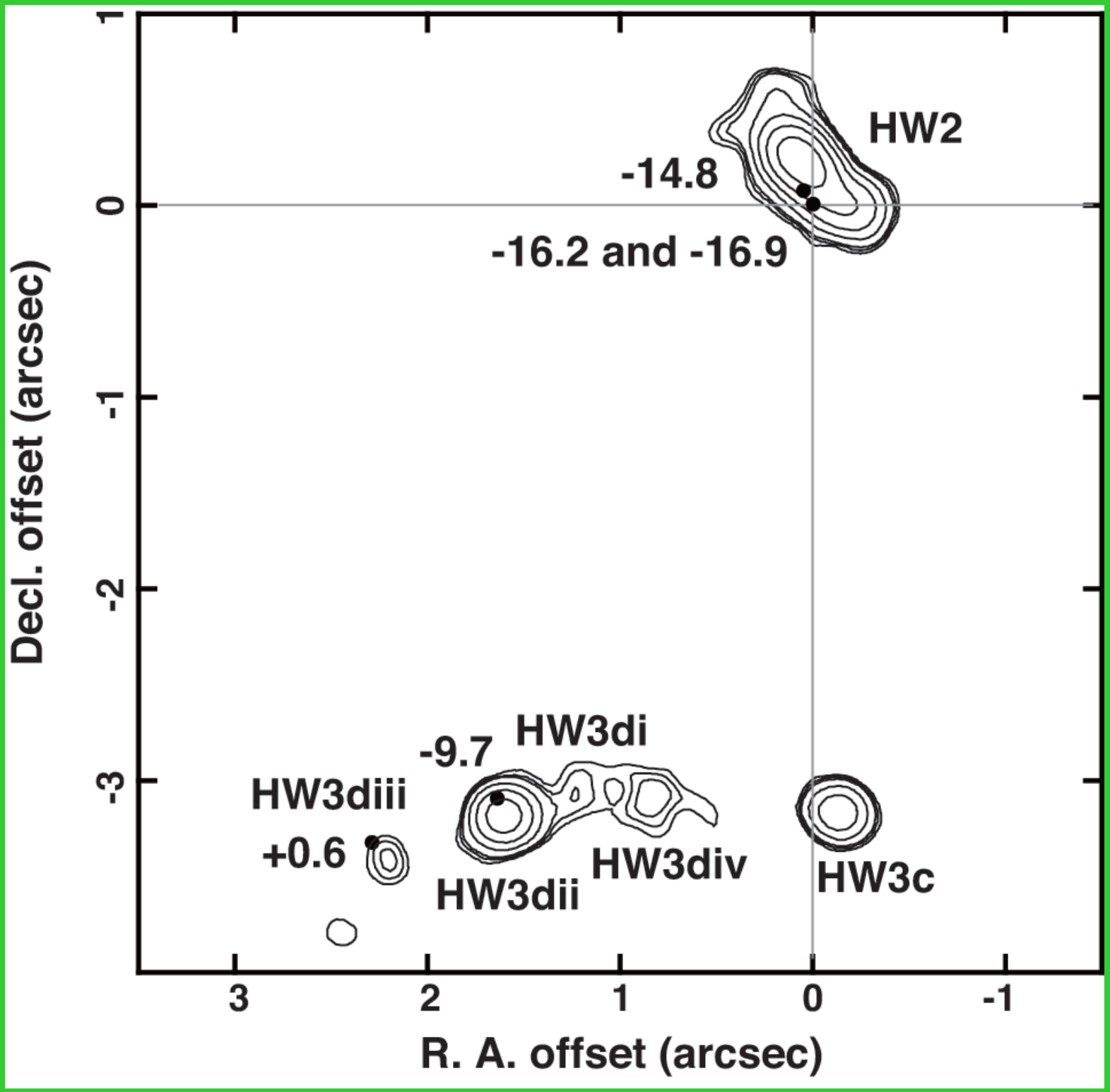
James O. Chibueze[1,2], Hiroshi Imai[1], Daniel Tafoya[1], Toshihiro Omodaka[1], Osamu Kameya[3], Tomoya Hirota[3], Sze-Ning Chong[1], and José M. Torrelles[4]

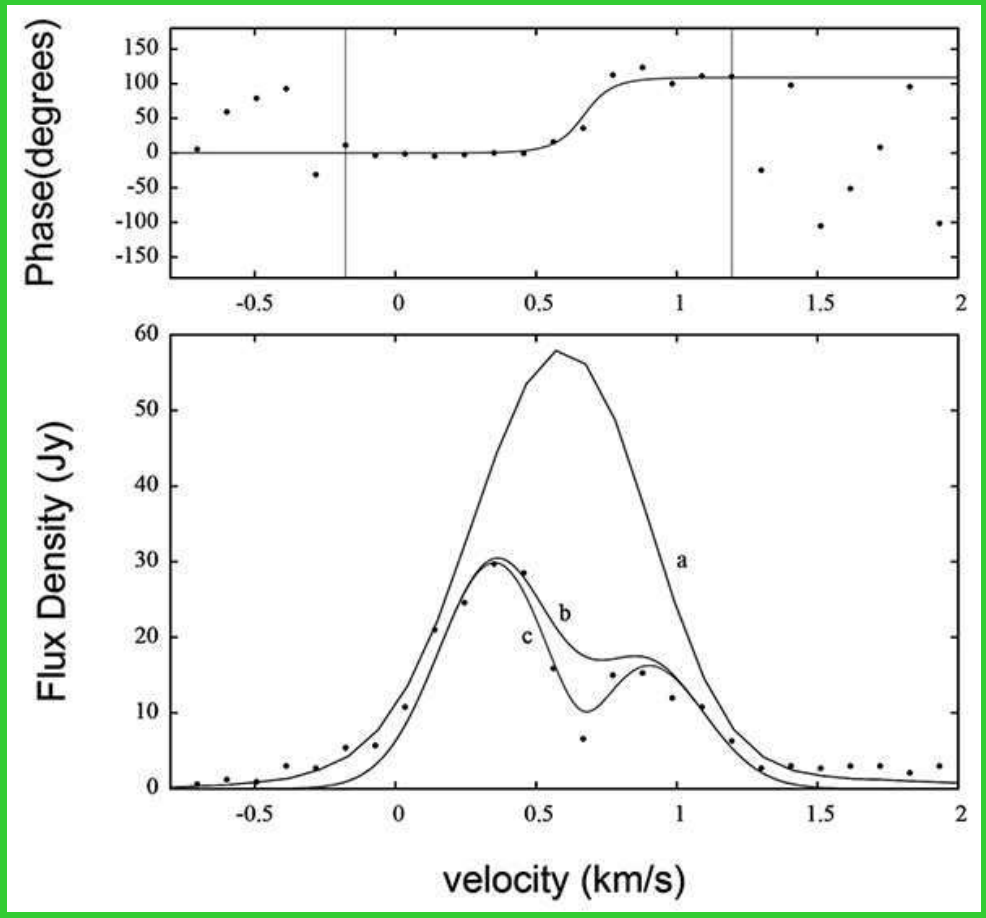
The Astrophysical Journal, 748:146 (11pp), 2012 April 1

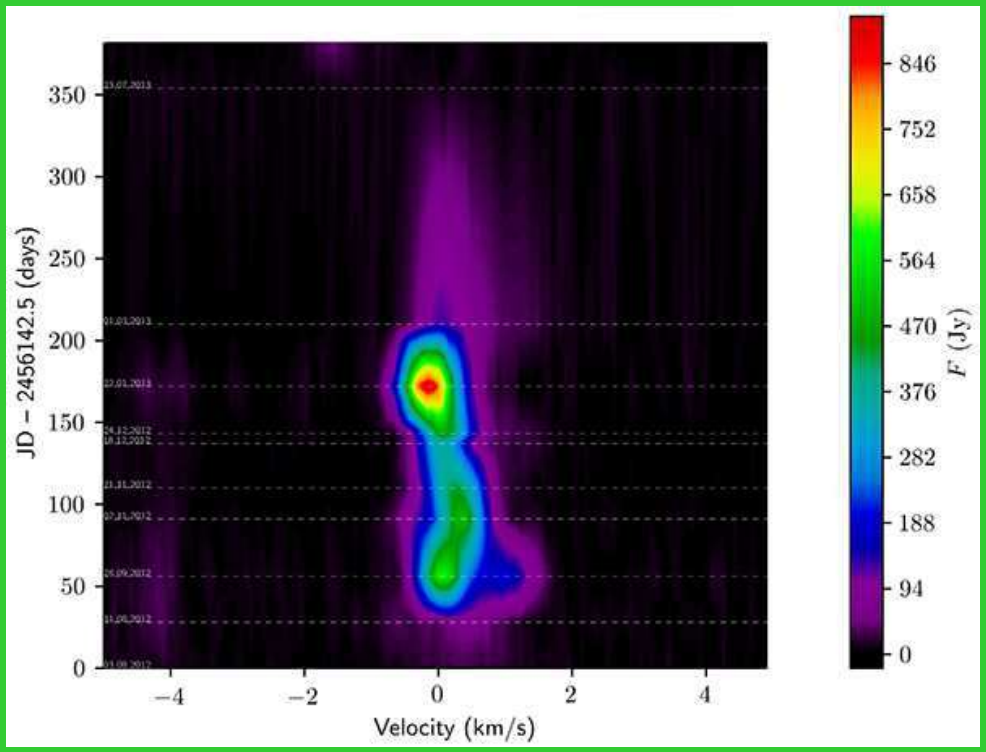
A wide-angle outflow with the simultaneous presence of a high-velocity jet in the high-mass Cepheus A HW2 system

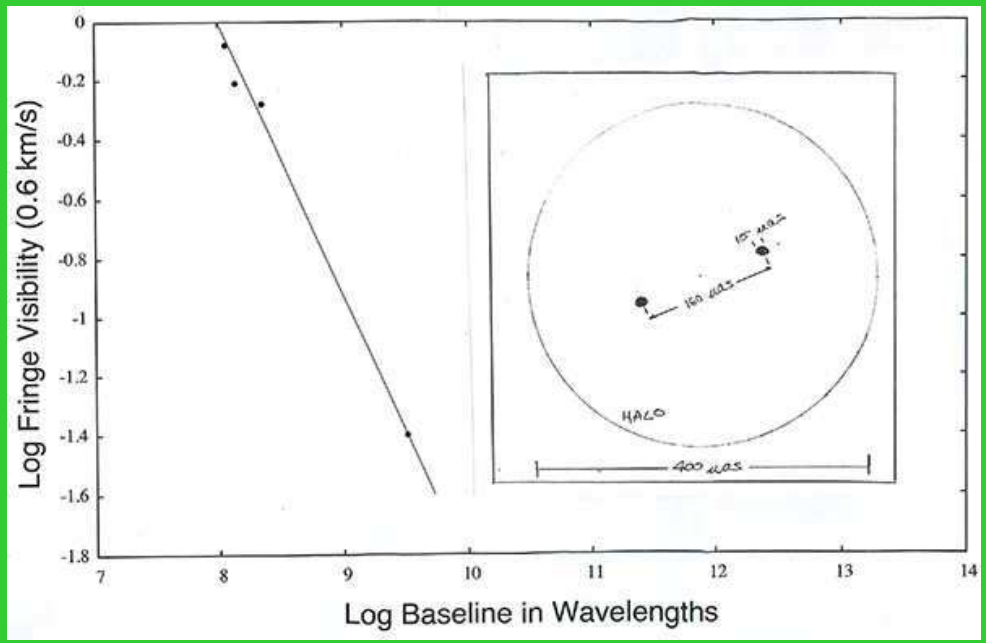
J. M. Torrelles,[1⋆] N. A. Patel,[2⋆] S. Curiel,[3⋆] R. Estalella,[4⋆] J. F. Gómez,[5⋆]
L. F. Rodríguez,[6⋆] J. Cantó,[3] G. Anglada,[5⋆] W. Vlemmings,[7⋆] G. Garay,[8⋆]
A. C. Raga[9⋆] and P. T. P. Ho[10,2⋆]

Mon. Not. R. Astron. Soc. **410,** 627–640 (2011)

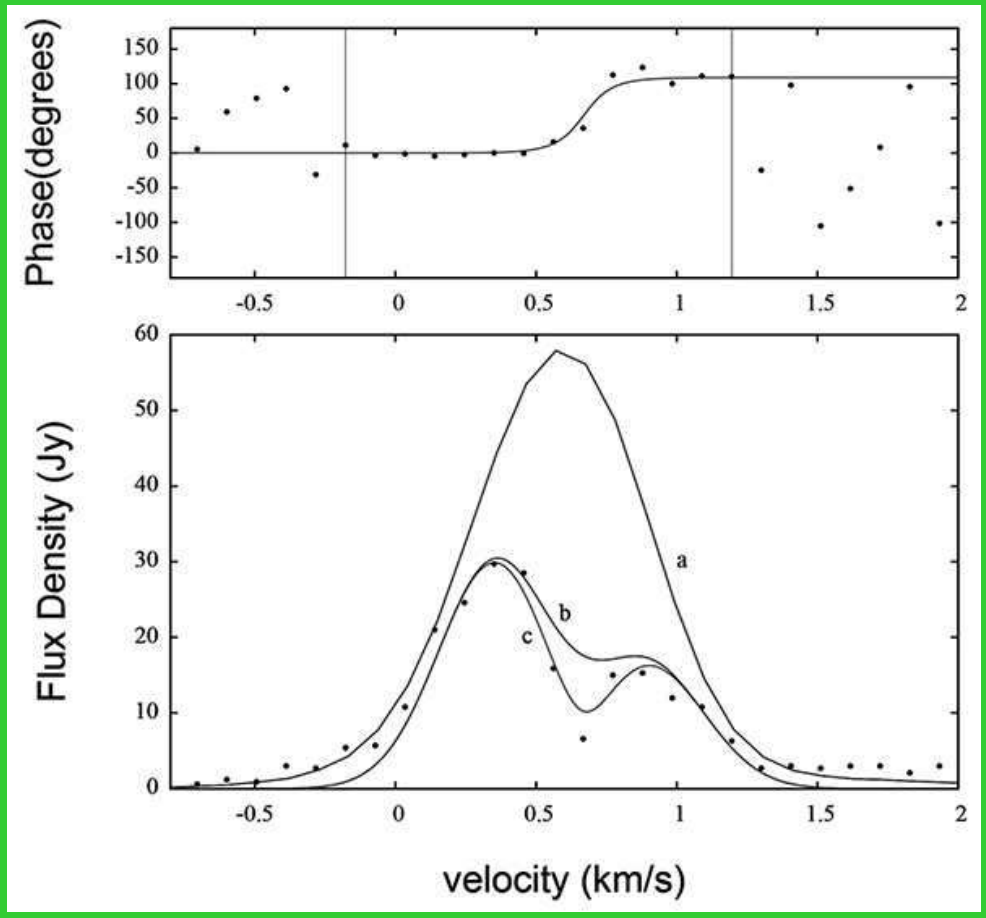

HW2
-14.8
-16.2 and -16.9
HW3di
-9.7
HW3diii
+0.6
HW3dii
HW3div
HW3c
Decl. offset (arcsec)
R. A. offset (arcsec)
1
0
-1
-2
-3
3
2
1
0
-1

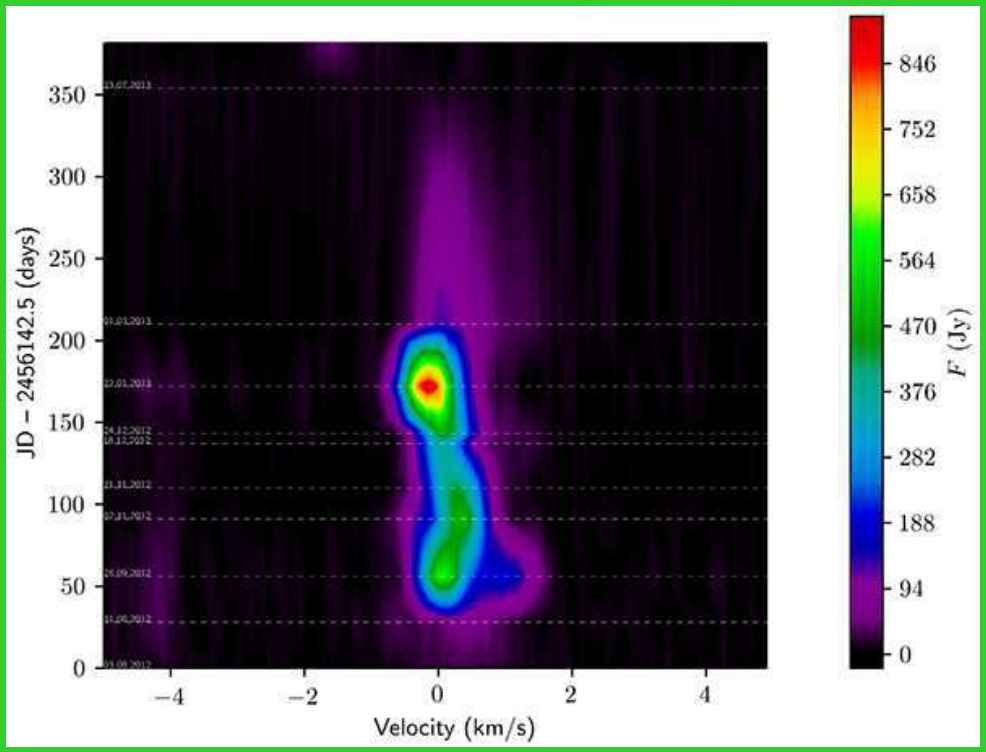


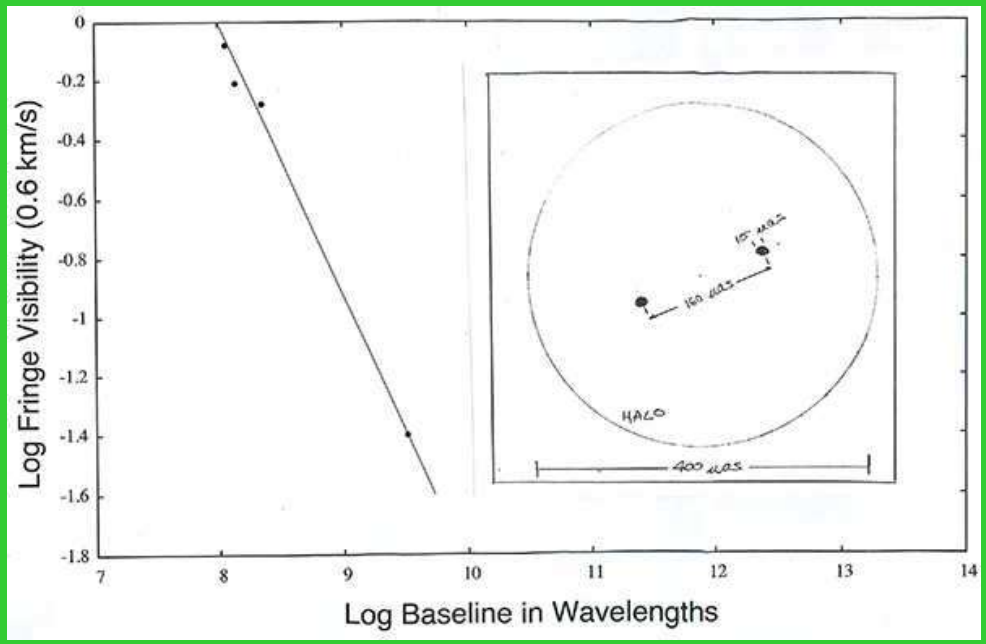




1) doublet structure at space–ground baselines
2) non-systemic radial velocity
3) strong variability with velocity drift







maser structures of about Sun size are observed!

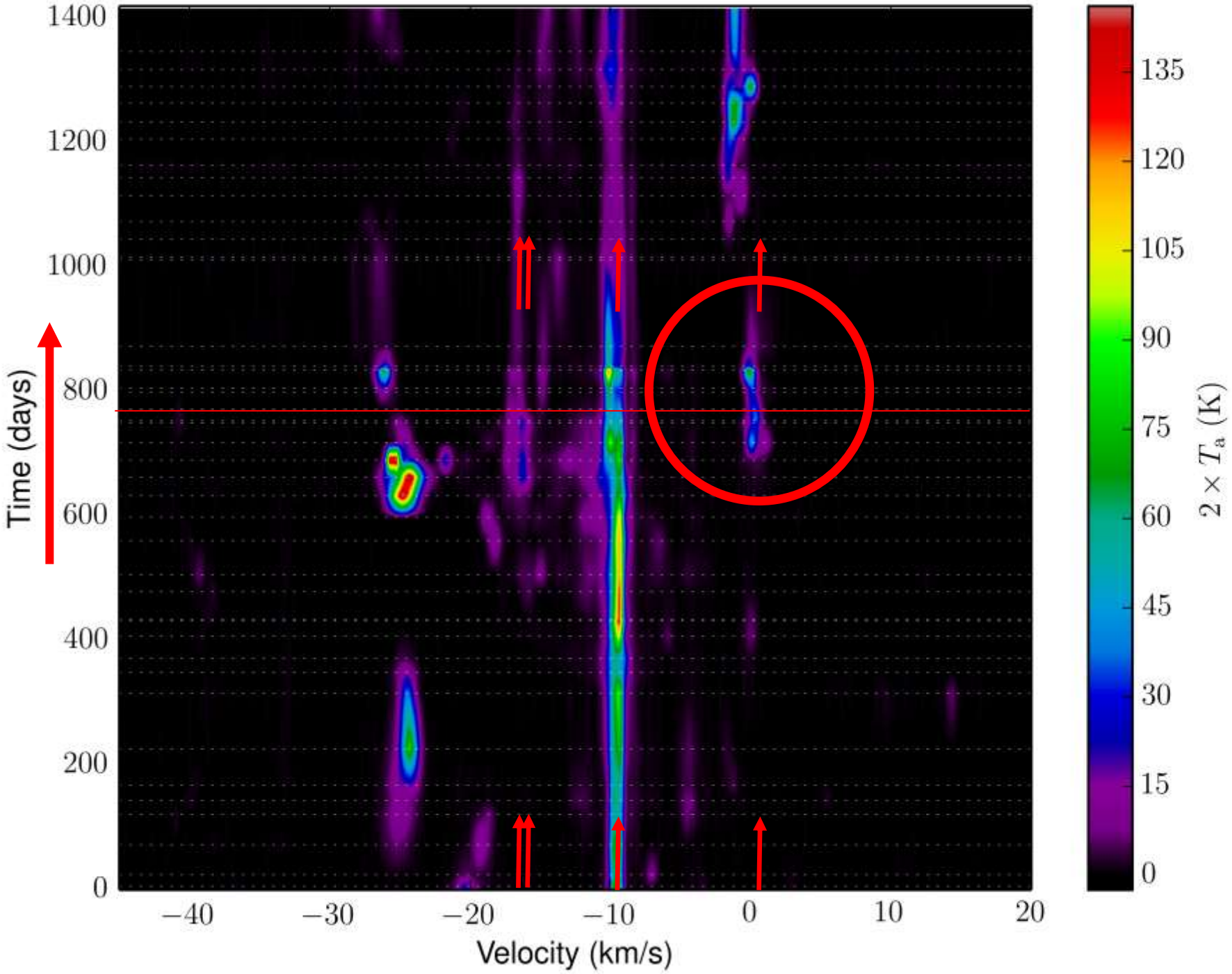
Keplerian rotation around central object

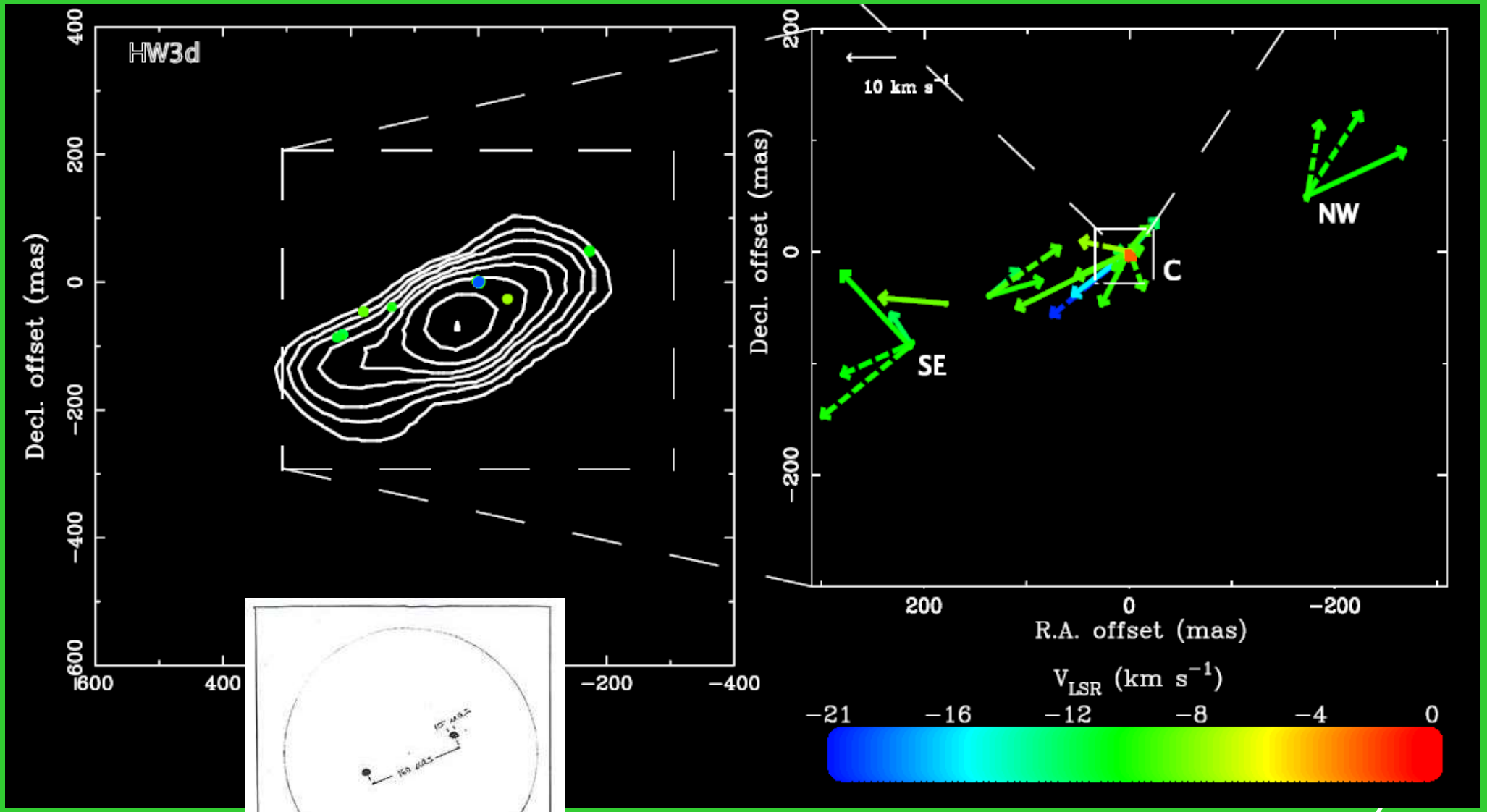
$$M = rv^2/G = 6.6\times10^{24}\ \mathrm{kg}$$
$$= 1.1\ \text{Earth masses}$$

Fails to explain

- Difference from systemic velocity
- Variability pattern of single-dish monitoring

PRAO LPI RT-22 monitoring



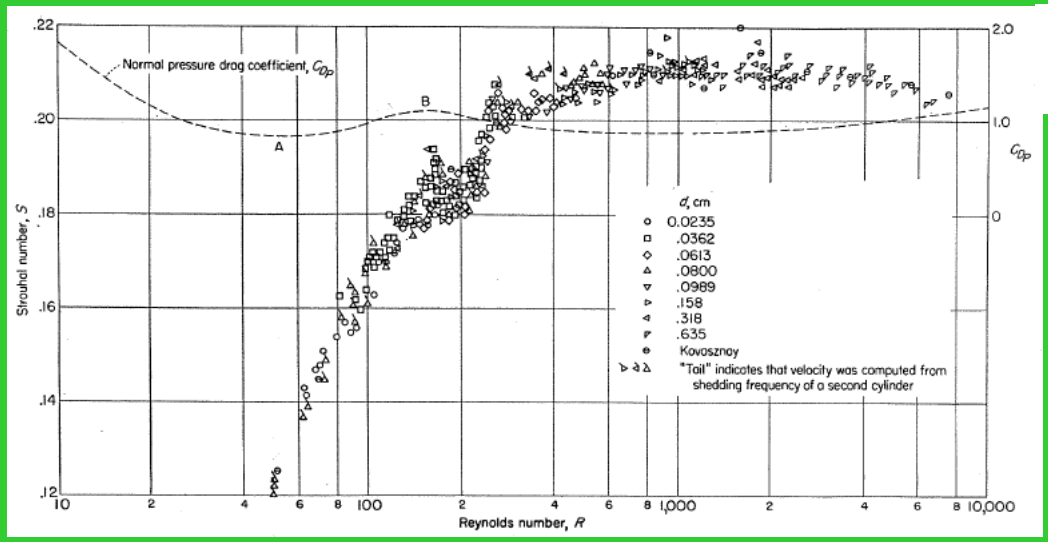


Chibueze et al. (2012)

V_{RA}

Strouhal number (criterion)

$$St = R/(\tau v) = 56.8\, R_{AU}/(\tau_m v_{kms})$$



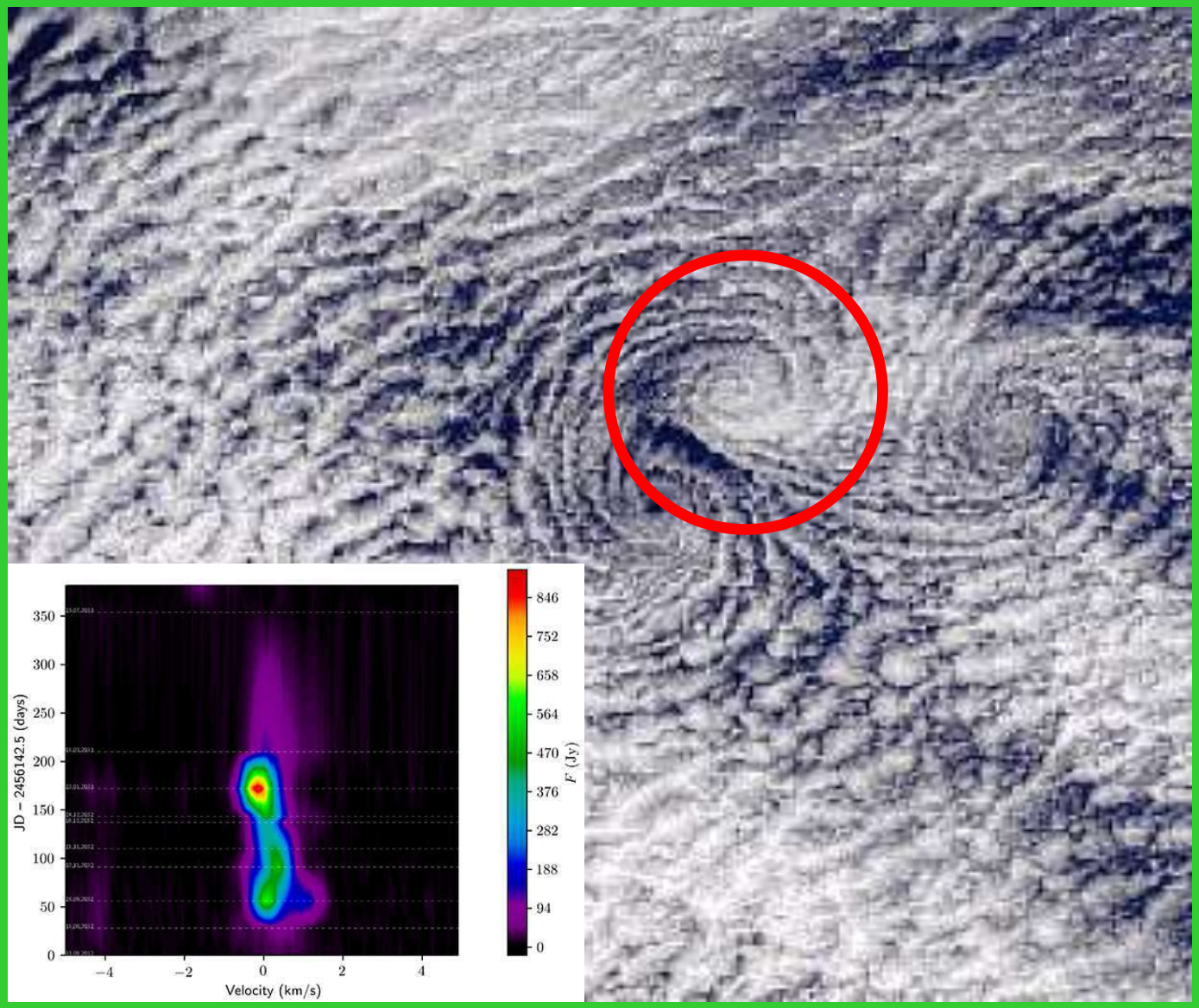
Roshko (1954)

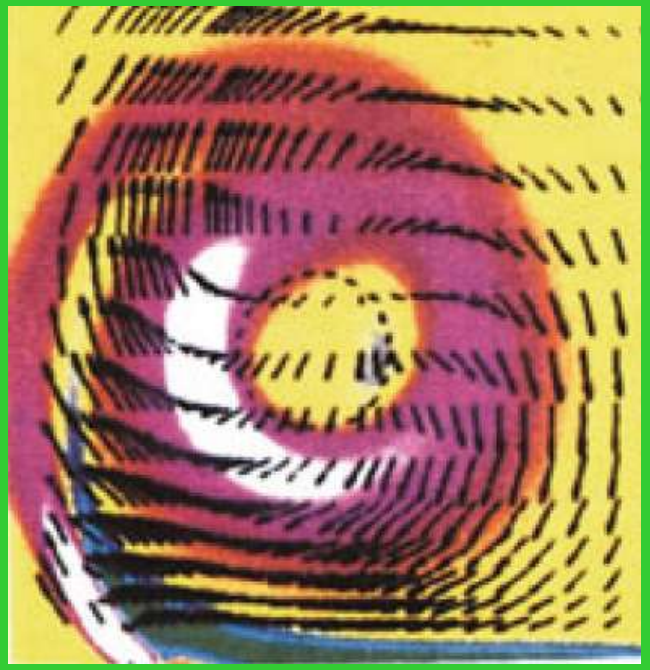


wikipedia

Turbulent vortex

Fluid vortices 1995
edited by Sheldon I. Green





R=0.112 a.u.

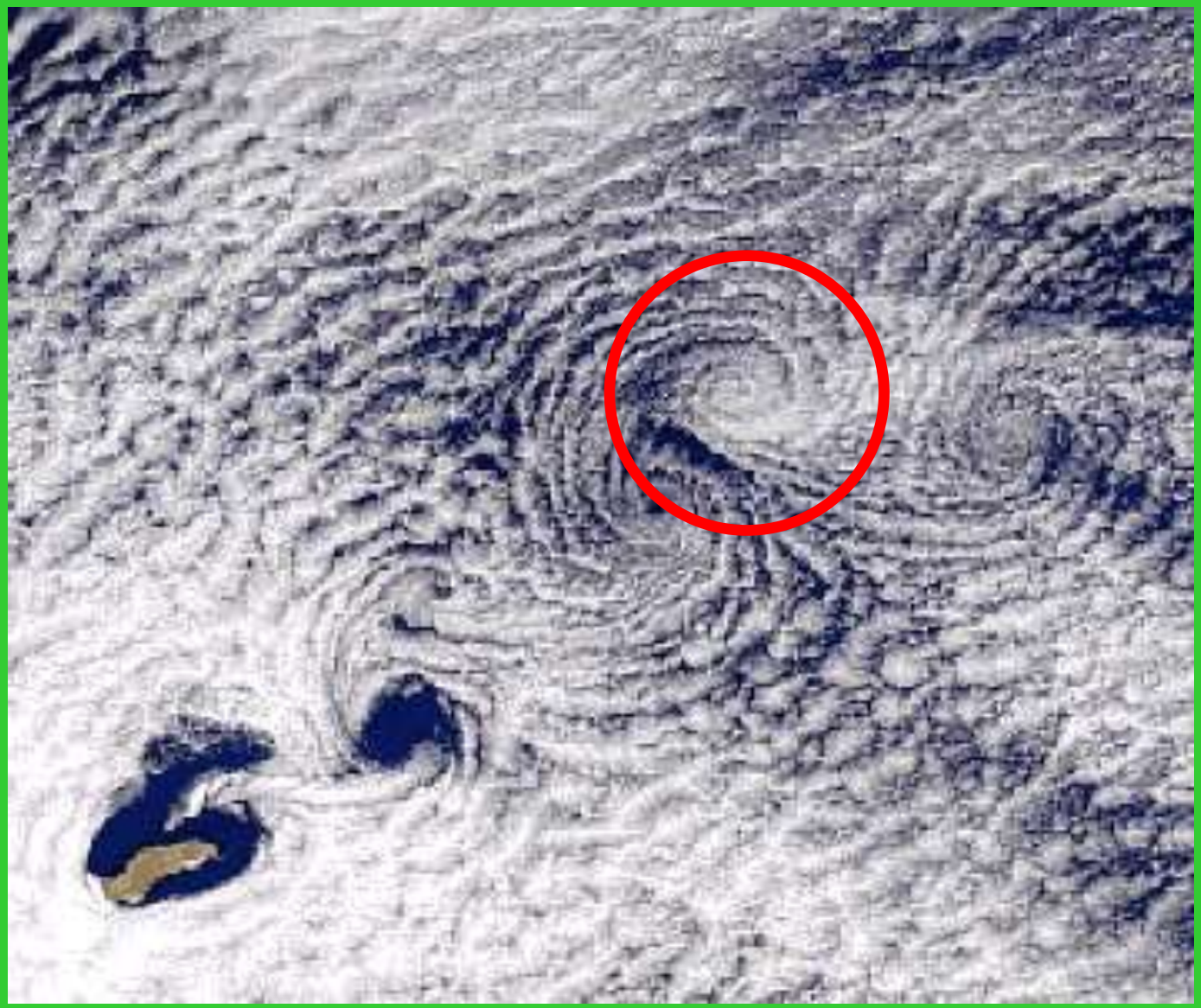
τ= 2*4 months

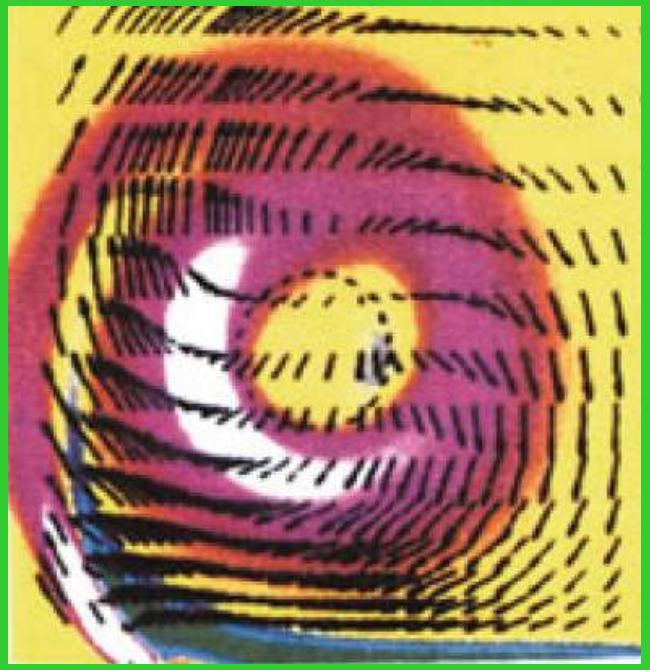
V=0.54/2 km/s

St = 2.95

Turbulent vortex

Fluid vortices 1995
edited by Sheldon I. Green





R=0.112 a.u.

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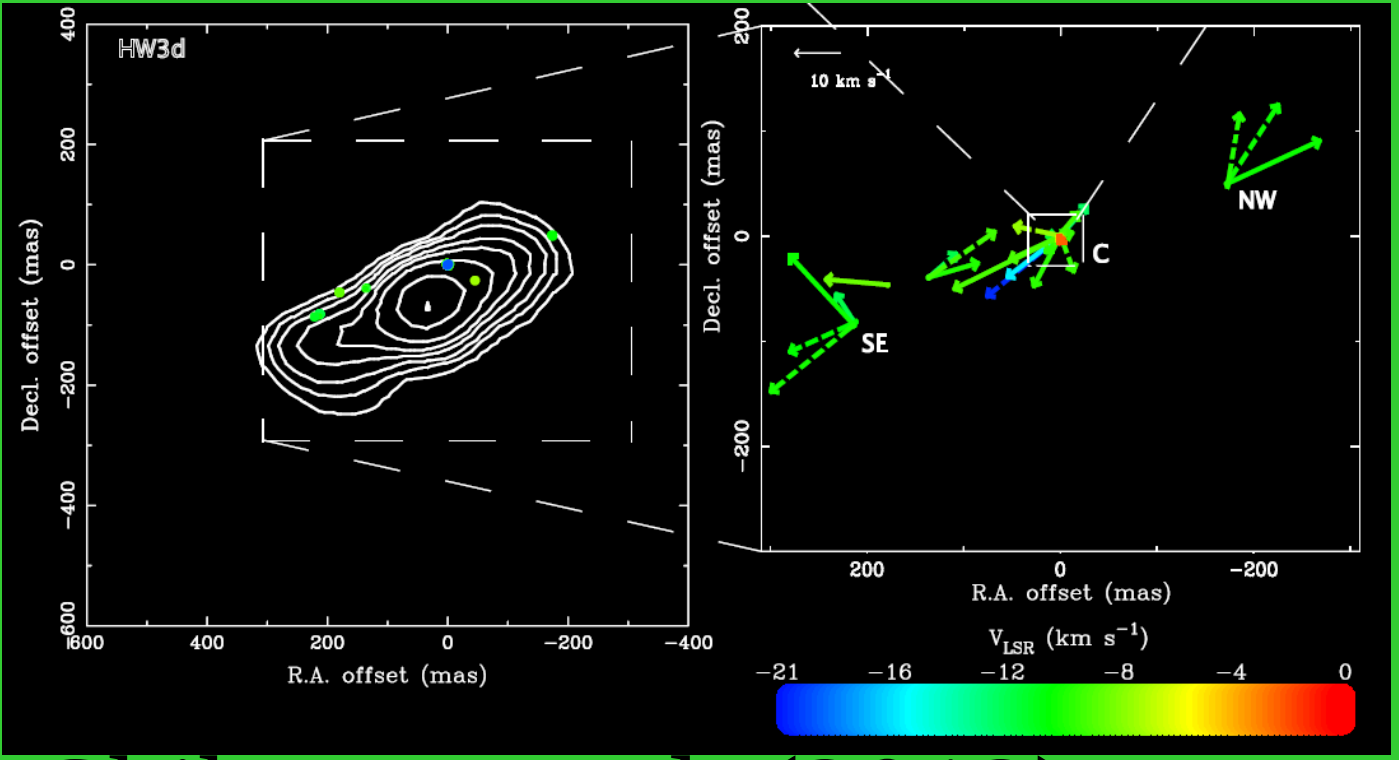
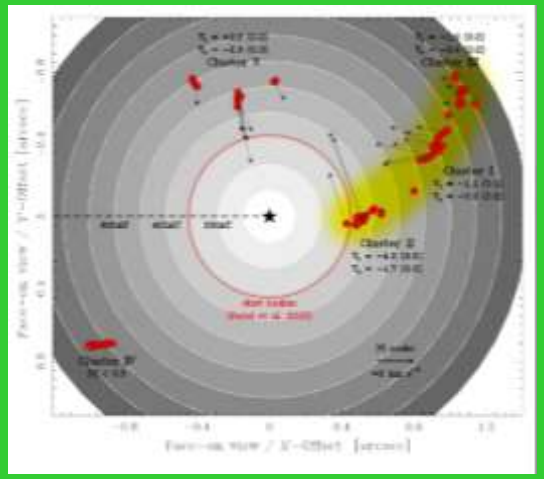
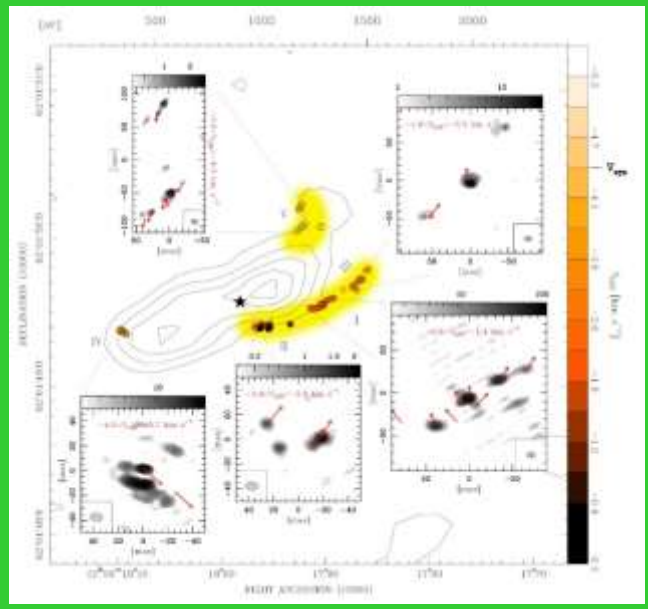


Chibueze et al. (2012)



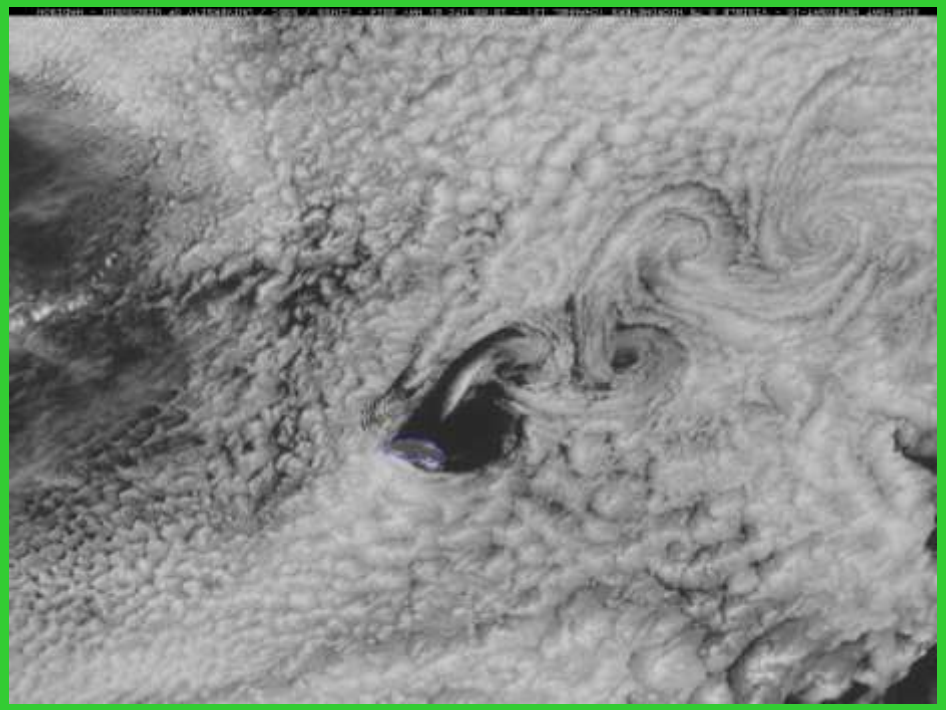


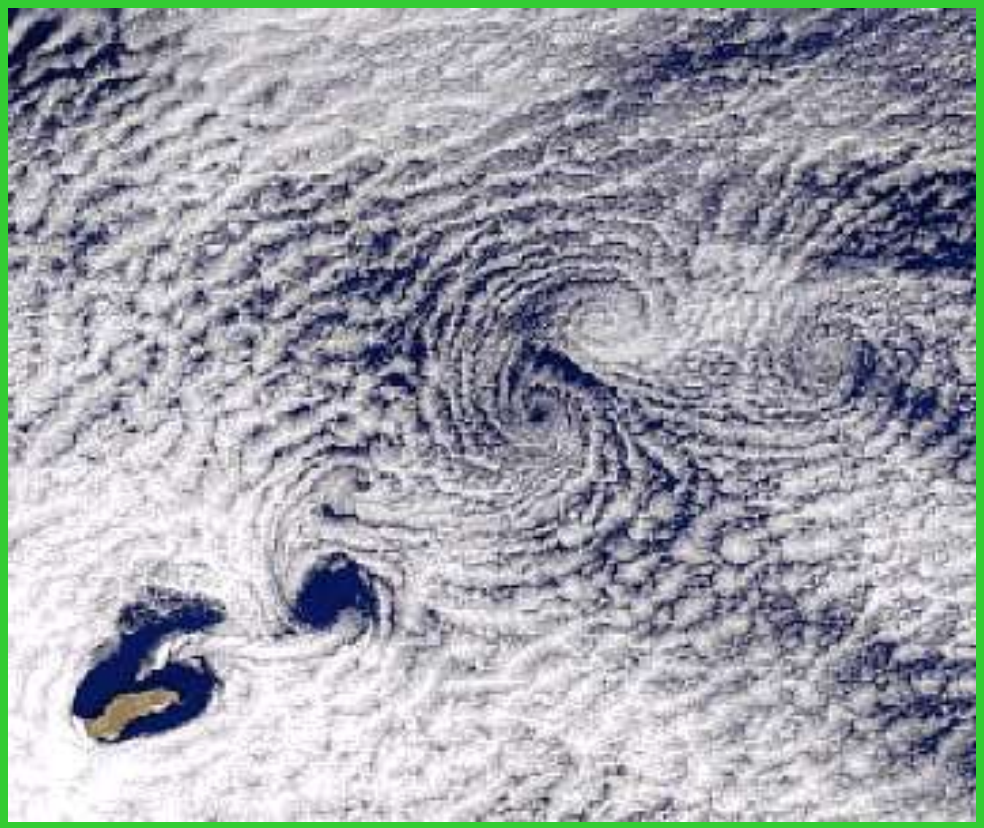
Sanna et al. (2017)

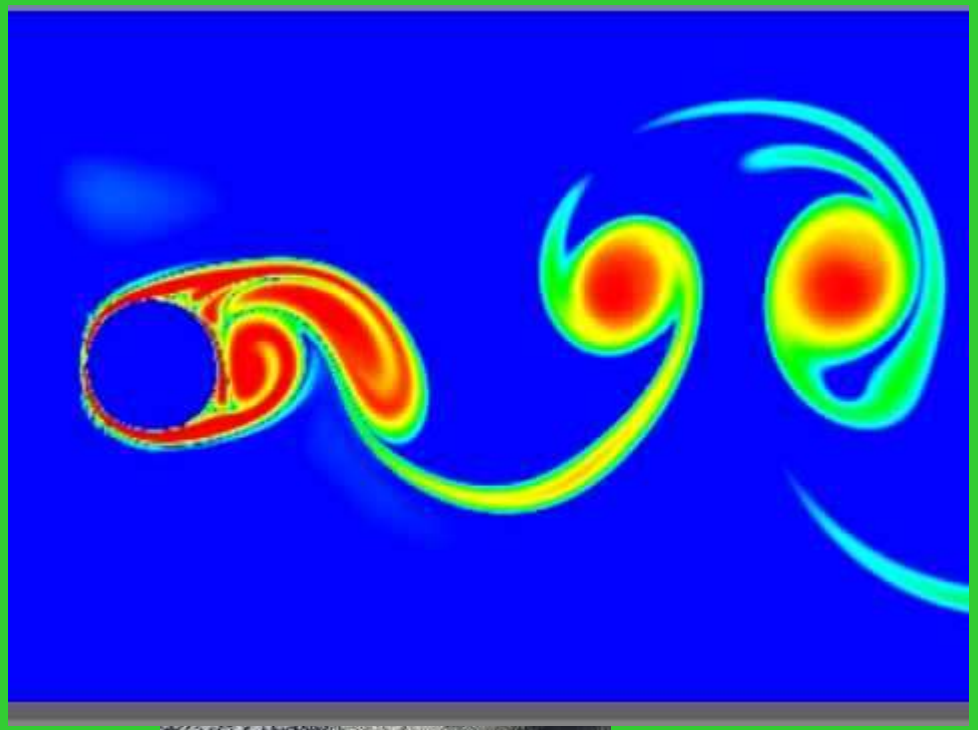
Planar infall of CH_3OH gas around Cepheus A HW2

Von Karman vortex street





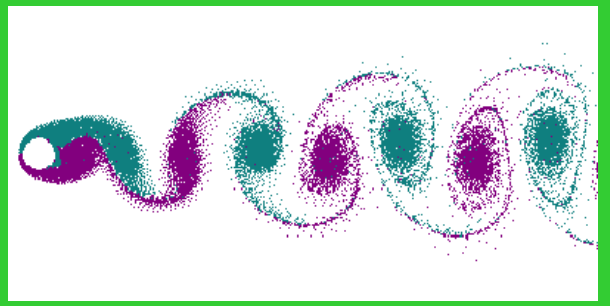


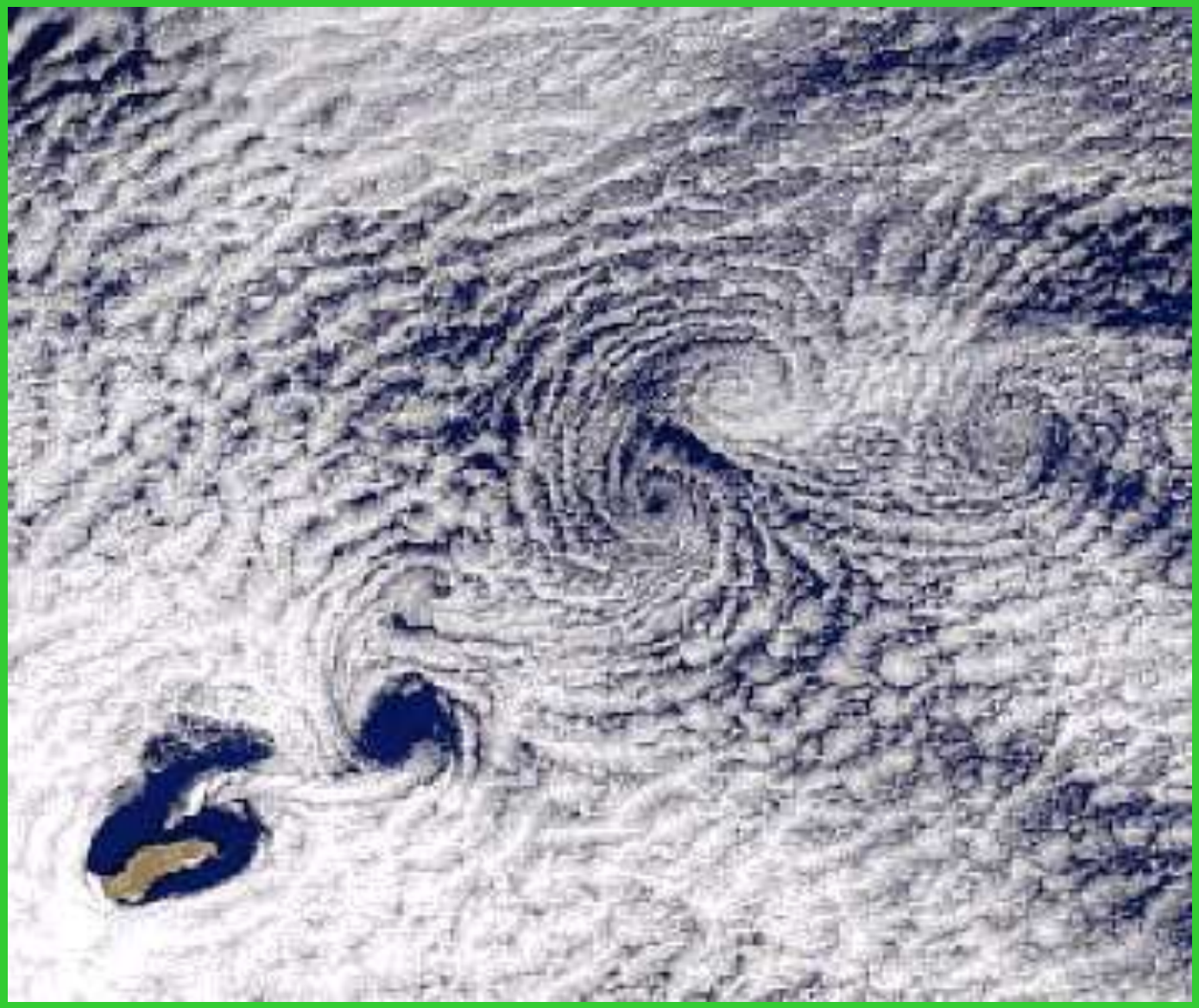


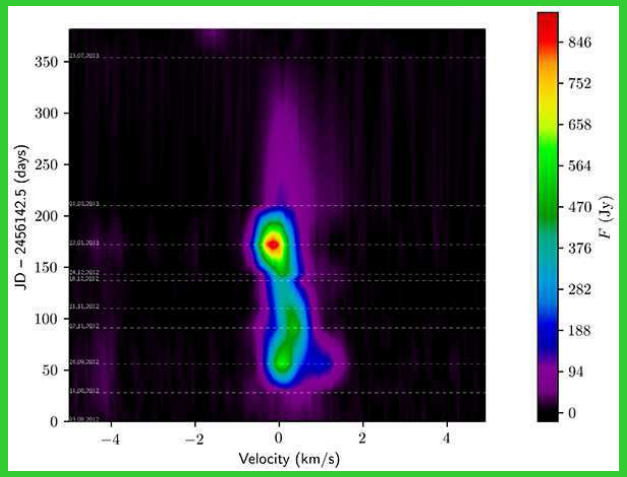




Von Karman vortex street







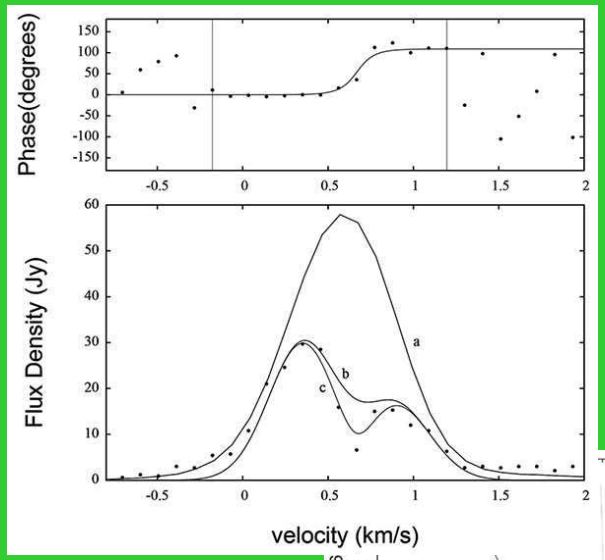
R=0.112 a.u.

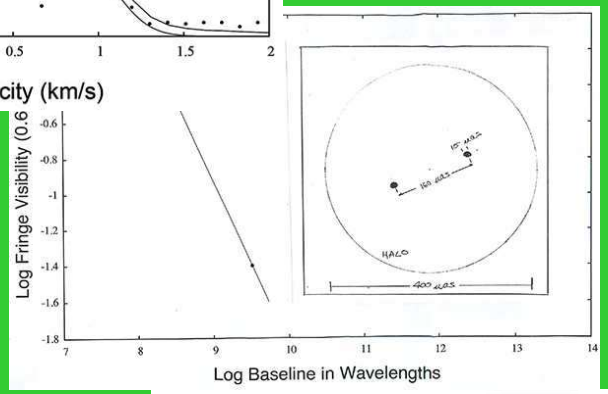
τ= 4/2 month

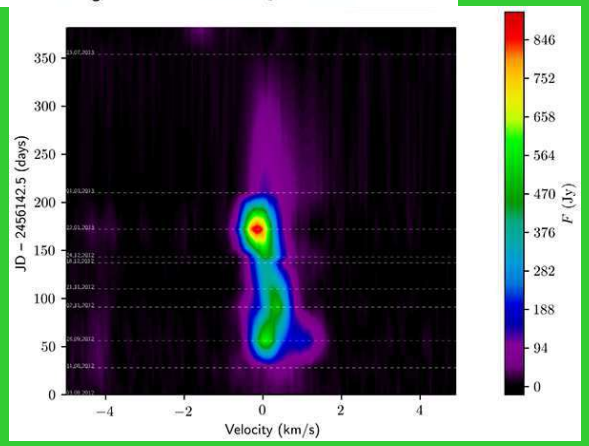
V=10 km/s

St = 0.3

Summary (Cep A)







3 features are detected, in total

This feature at 0.6 km/s is single-peaked in the single dish observations and ground-ground baselines . On the space- ground baseline the feature shows 2 pronounced peaks.

The data can be fitted by a model of a spot consisting of 2 hotspots of approximately Sun size with surrounding halo .

Remarkably high velocity gradient: More than order of magnitude higher than previously detected.

The results can be explained in the model of turbulent vortices shed by the outflow from the obstacle on the disc surface

Grazie!

Thank you very much!

Спасибо!