Coordinated observations of Sgr A*: Flaring activity in the NIR/mm

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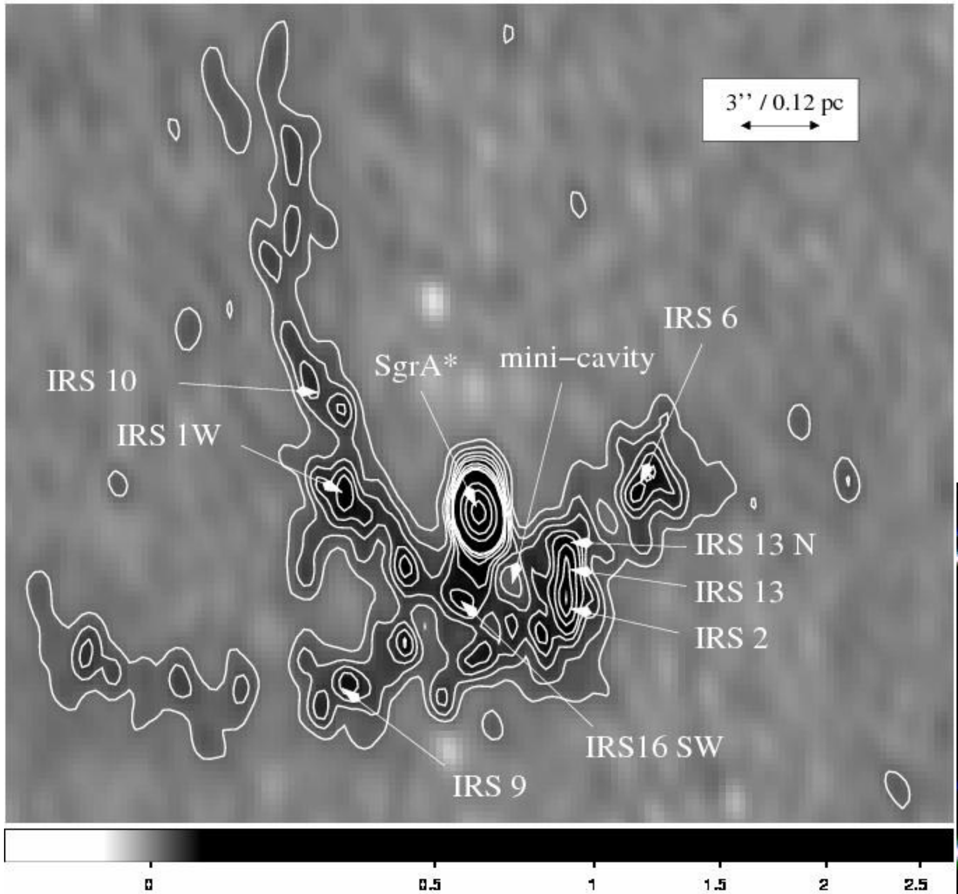
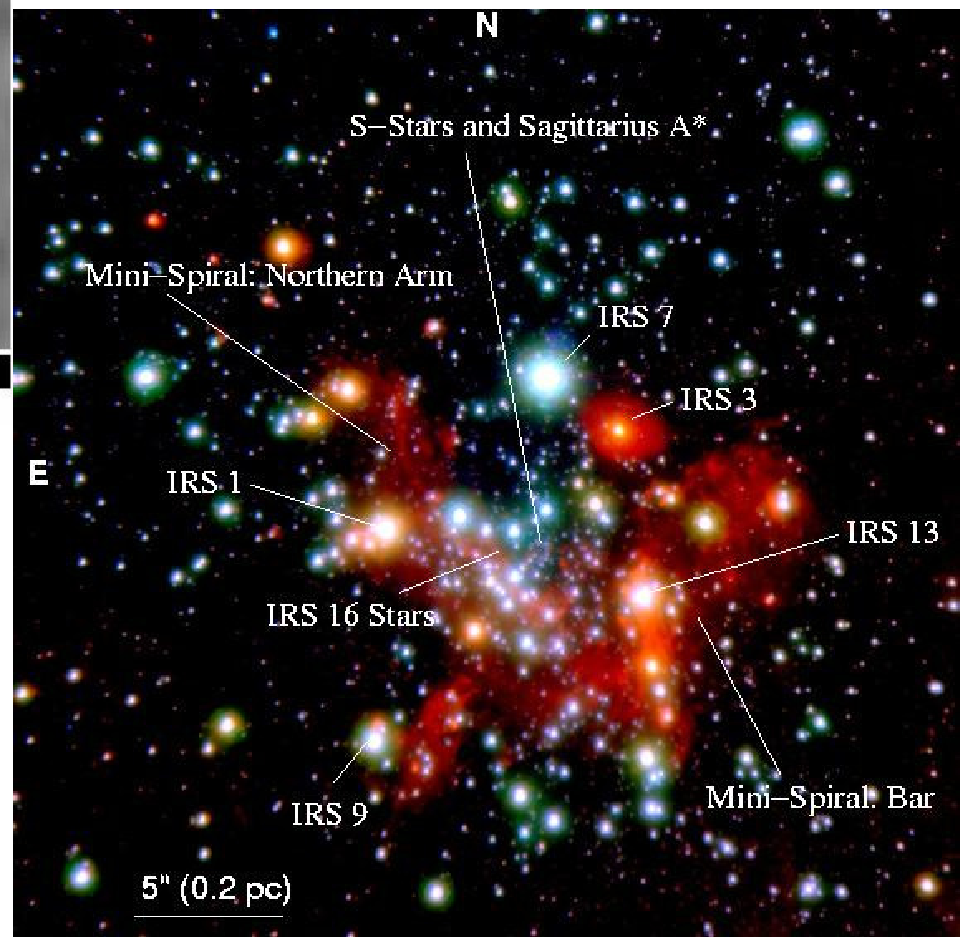


The Galactic Centre

-Compact NIR, radio and X-ray source

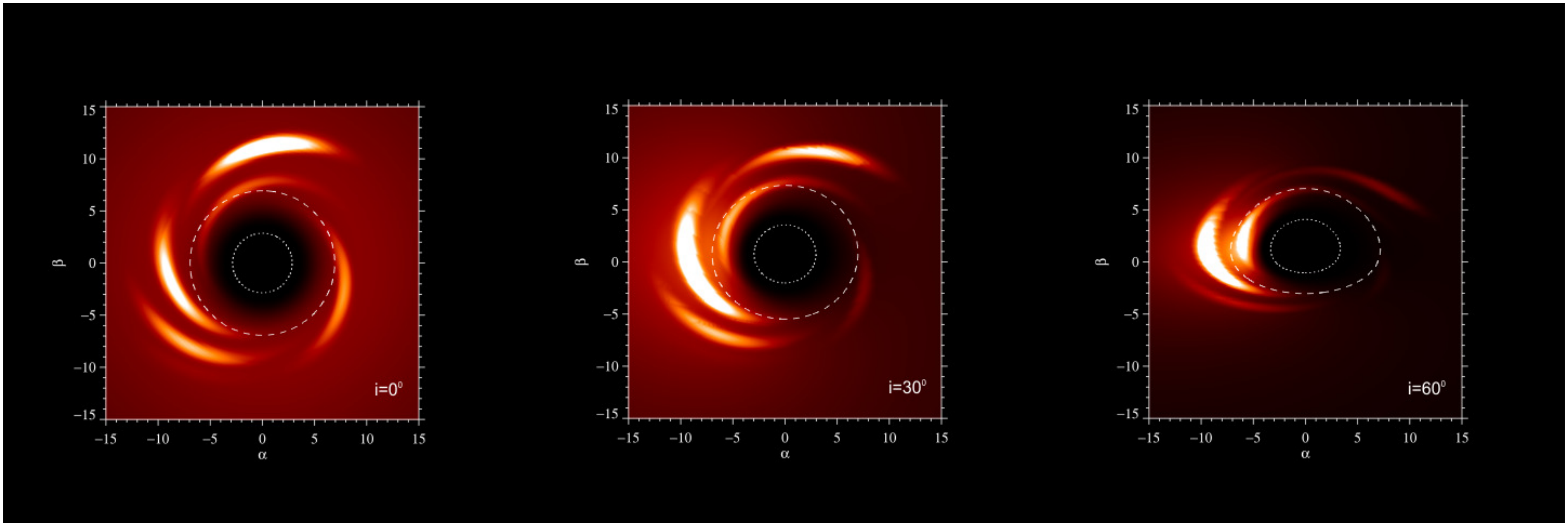
-~8 kpc away from us

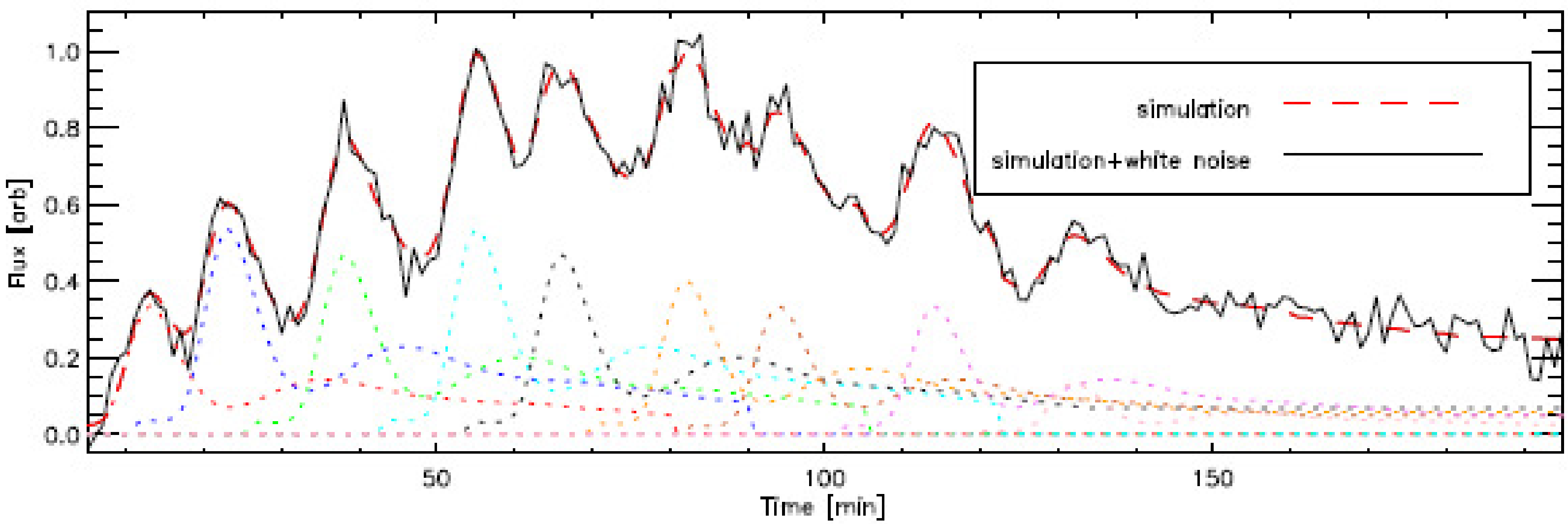


-SMBH of mass ~ 4 x 10^6 M_{sun}

-Highly variable in NIR, X-ray and radio wavelengths

Multi-component spot/disk model





Zamaninasab et al. 2010, Eckart et al. 2009

Adiabatic Expansion Model

An expanding blob of relativistic electrons with energy spectrum

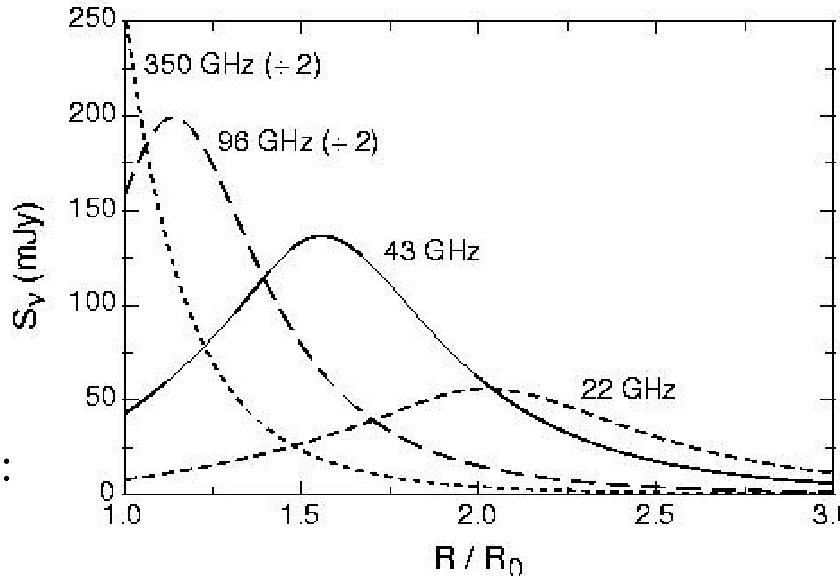
$$N(\gamma) = \begin{cases} N_0 \gamma^{-p} & \gamma \le \gamma_c \\ 0 & \gamma > \gamma_c \end{cases}$$

Synchrotron optical depth at frequency ν scales as:

$$\tau_\nu = \tau_0 \left(\frac{\nu}{\nu_0}\right)^{-(p+4)/2} \left(\frac{R}{R_0}\right)^{-(2p+3)}$$

And flux density scales as:

$$S_\nu = S_0 \left(\frac{\nu}{\nu_0}\right)^{5/2} \left(\frac{R}{R_0}\right)^3 \frac{1 - \exp(-\tau_\nu)}{1 - \exp(-\tau_0)} .$$

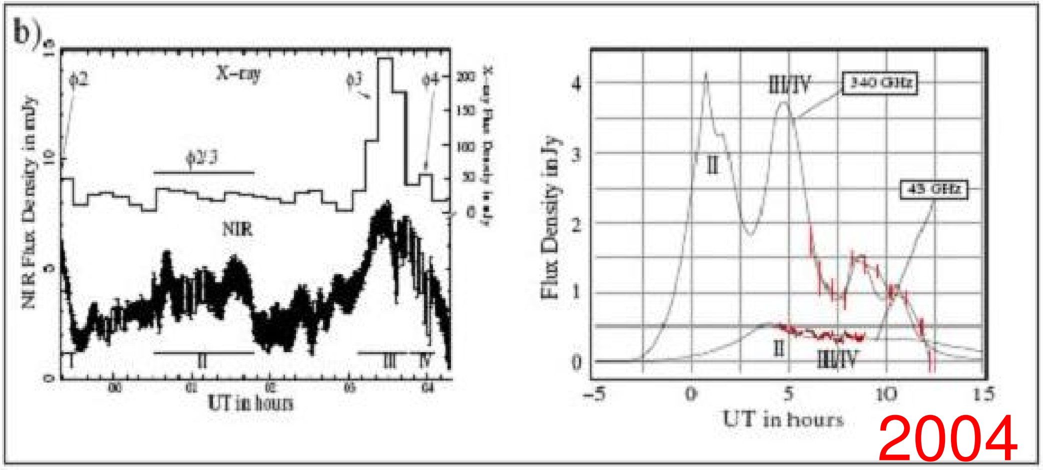


Yusef-Zadeh et al. 2006
Van der Laan Nature 1966

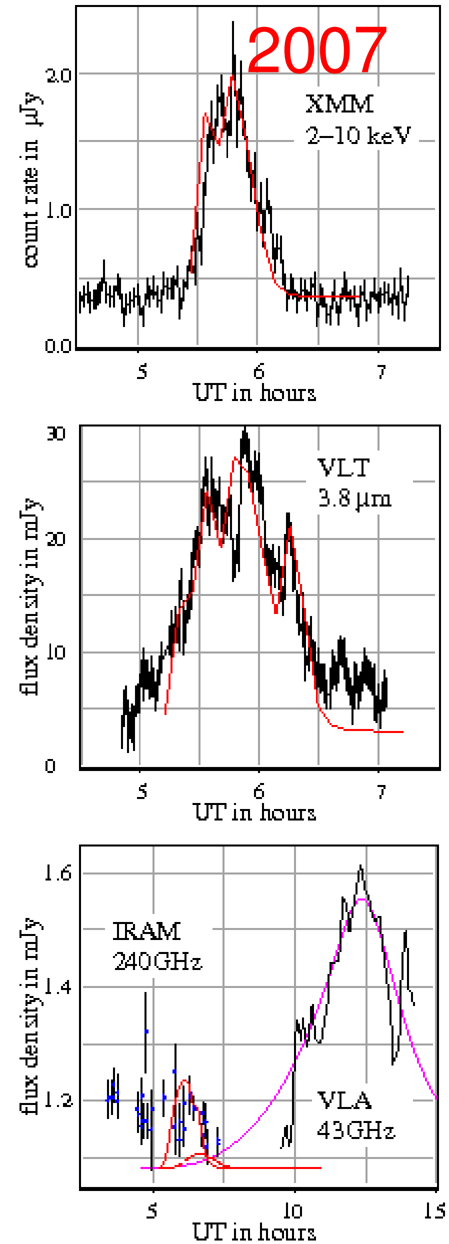
At a constant expansion speed V_{exp},

$$R - R_0 = v_{\rm exp} (t - t_0)$$

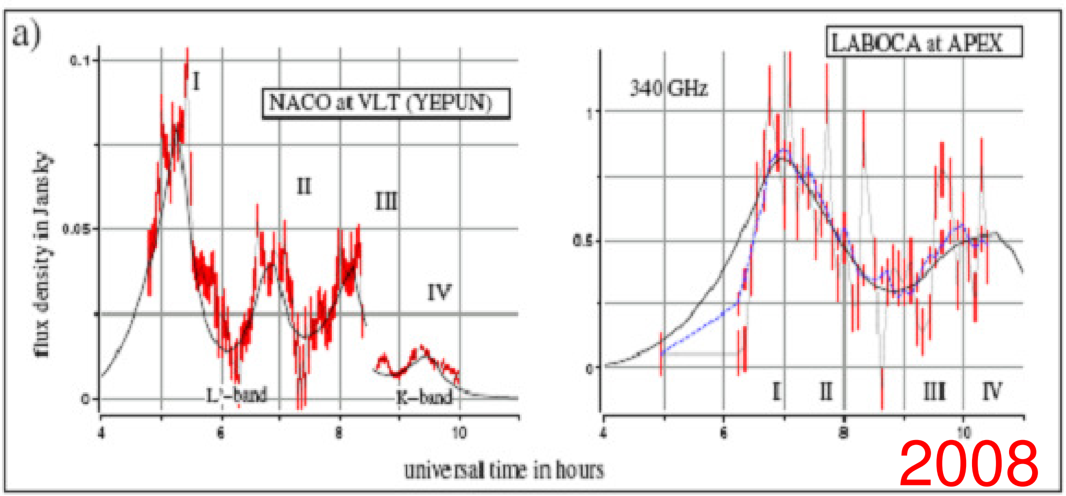
Eckart et al. 2006, 2009



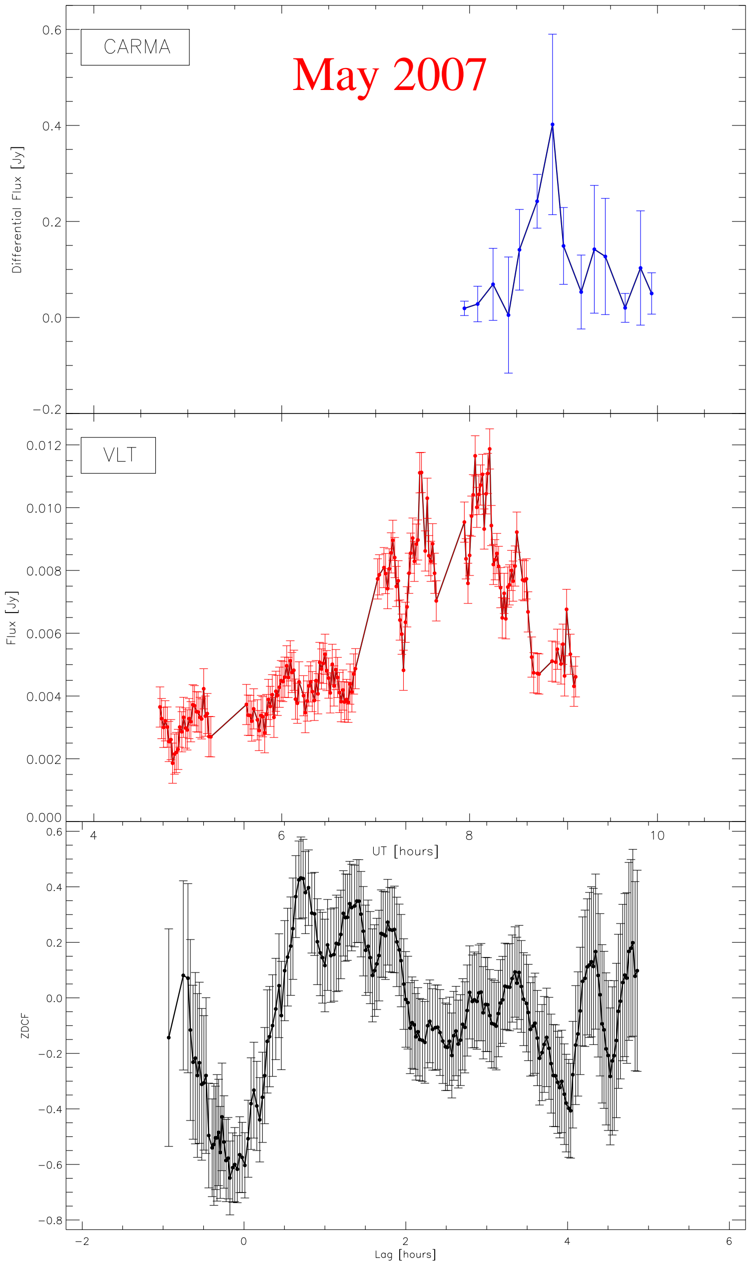
Sabha et al. 2009



Eckart et al. 2008



Also Yusef-Zadeh et al. 2007, 2008, Marrone 2008



Kunneriath et al. 2010

Flare analysis results

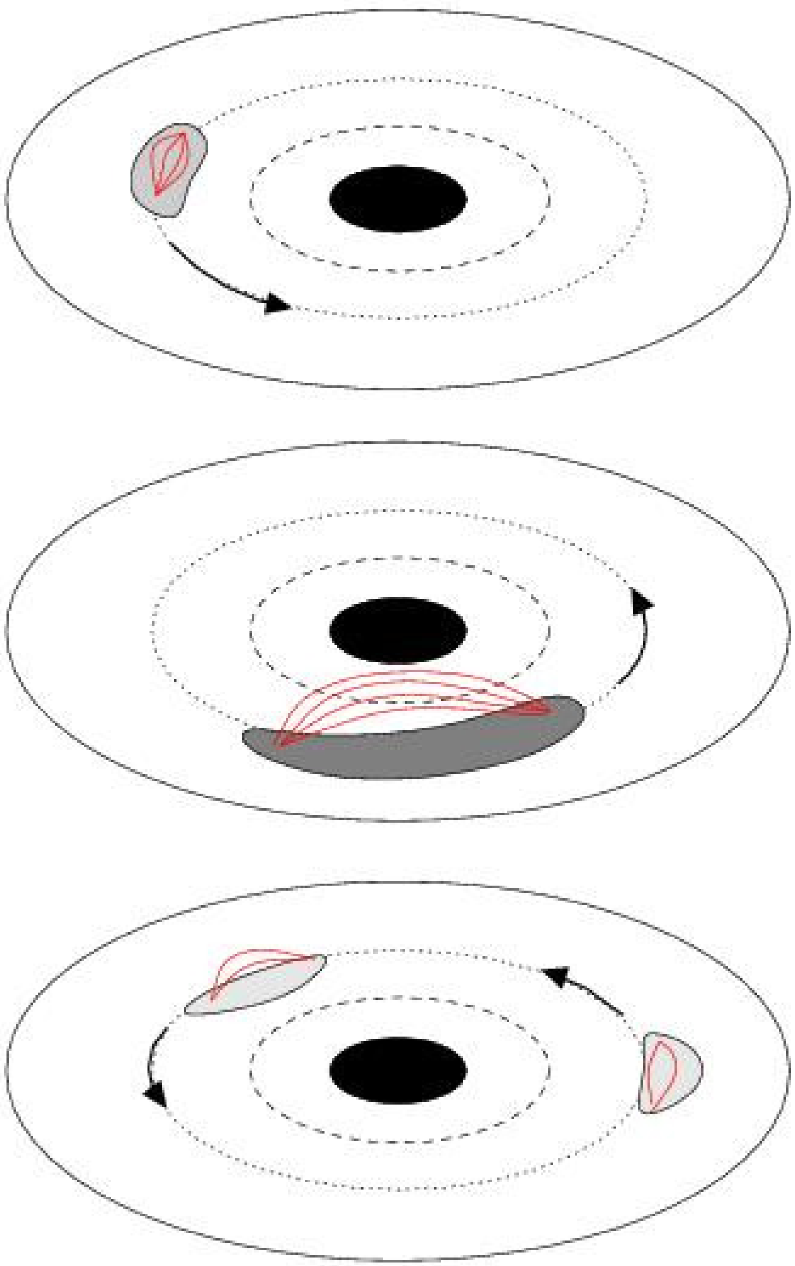
Low expansion speeds ~ 0.005c - 0.017c

Spectral indices ~0.6-1.3

Time delay between NIR and mm flares ~ 1.5 ± 0.5 hours

Source sizes ~ 1 R_s

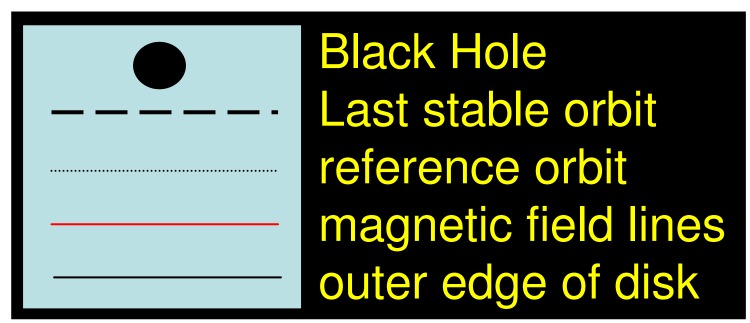
(in agreement with Yusef-Zadeh et al. 2007, 2008, Marrone 2008)



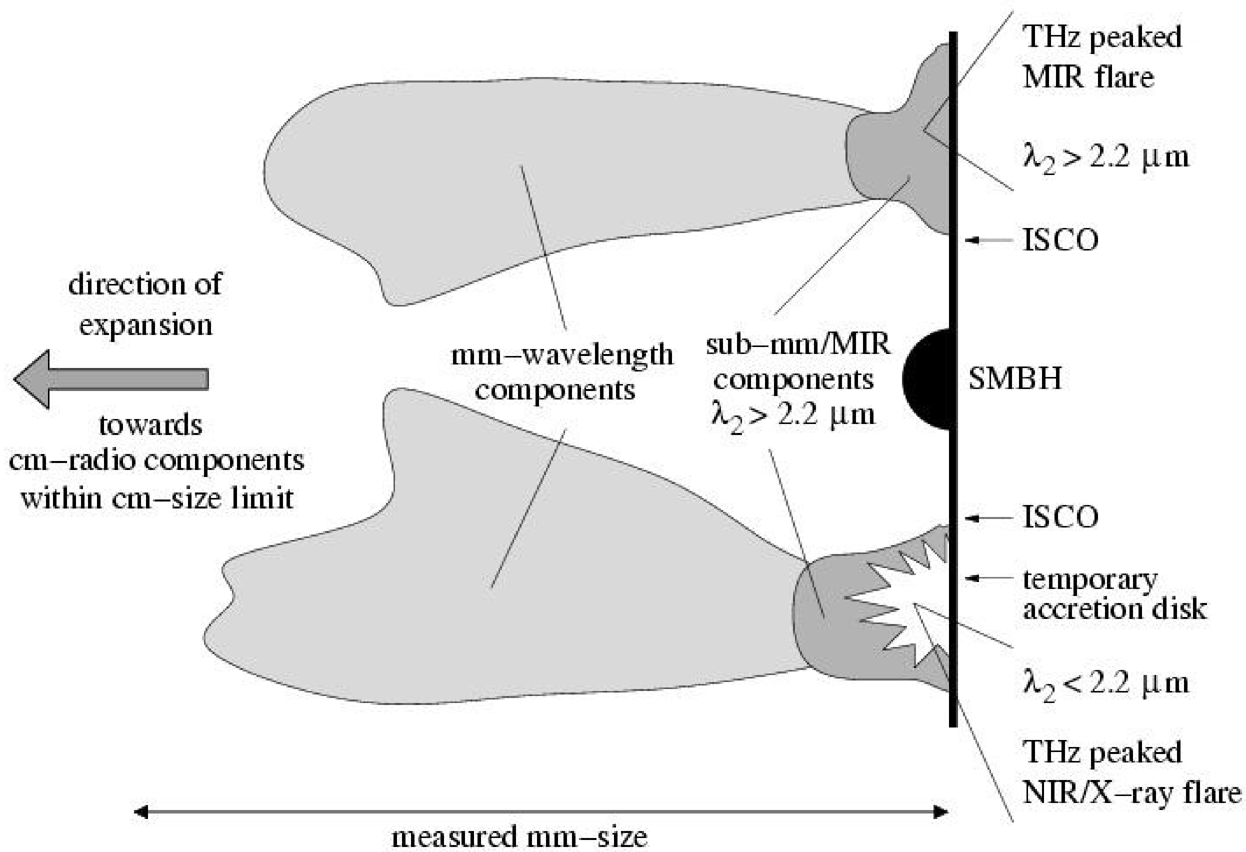
Adiabatic Expansion of Source Components in the Temporary Accretion Disk of SgrA*

The expansion occurs due to differential rotation on a single orbital time scale.

Eckart et al. 2008, ESO Messenger
Eckart et al. 2009, A&A 500, 935



Emission from a disk with a short jet



Eckart et al. 2008a, see also Markoff et al. 2005, 2007

Summary

- Orbiting spot model describes successfully the observed intra-flare variability

- SSC model with THz peaked synchrotron spectra plus adiabatic expansion described successfully the variable flux density of SgrA*

- Low expansion velocities imply expansion within the accretion disk, flaring of a disk corona, and/or expansion of a component with additional bulk velocity.

Thank You!

Flare analysis

Low expansion speeds ~0.005c-0.017c

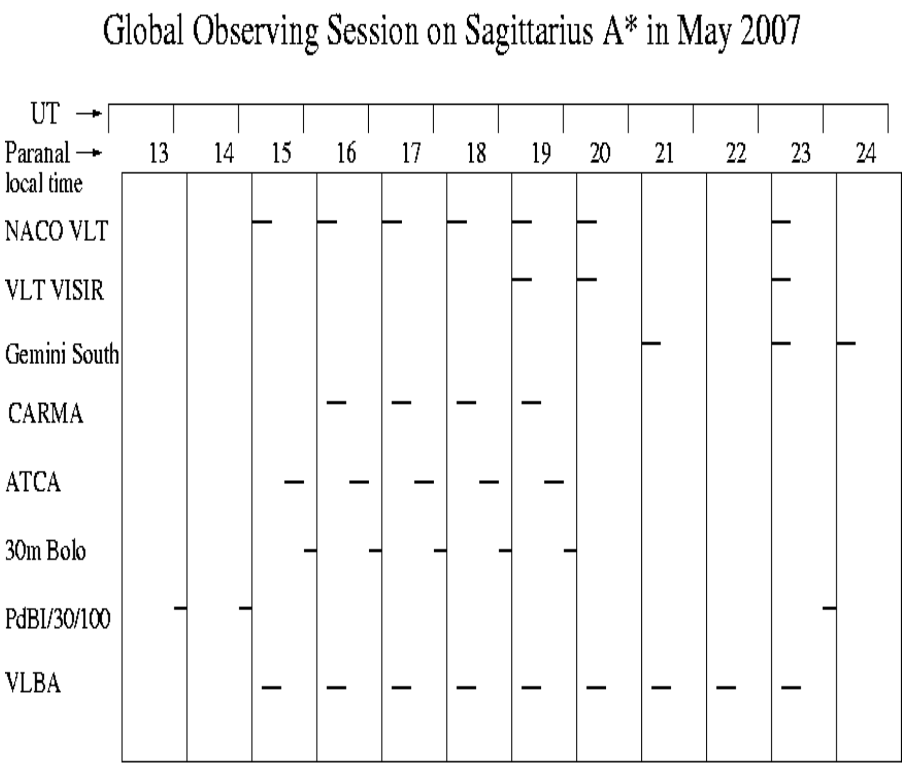
Spectral indices ~0.6-1.3

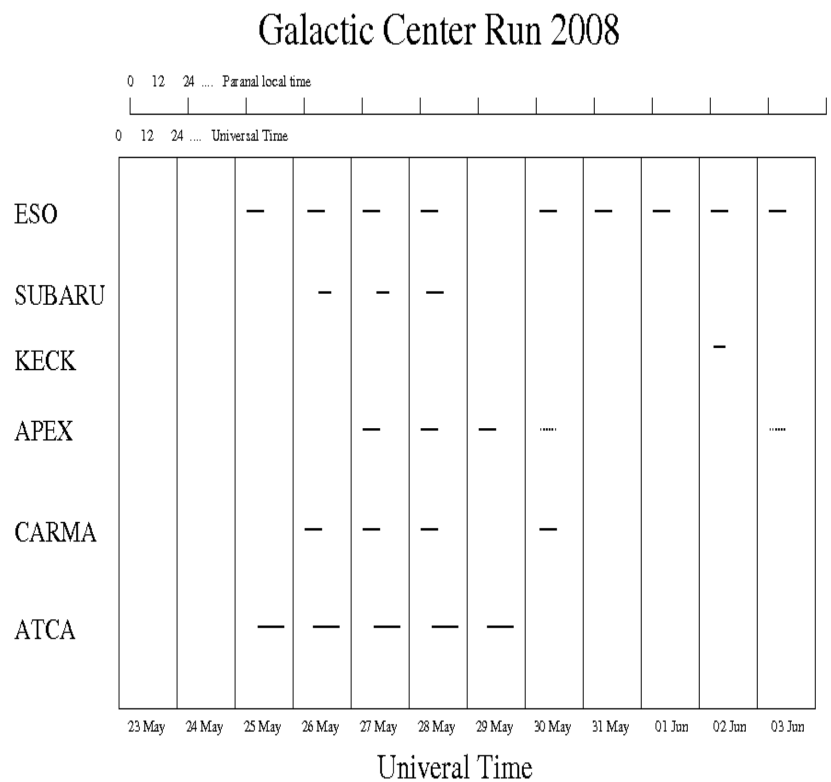
Time delay between NIR and mm flares ~1.5±0.5 hours

Source sizes ~1 R_s

Low expansion speeds due to:
a) Large bulk motion of components compared to V_{exp}
or
b) The expanding gas cannot escape Sgr A*

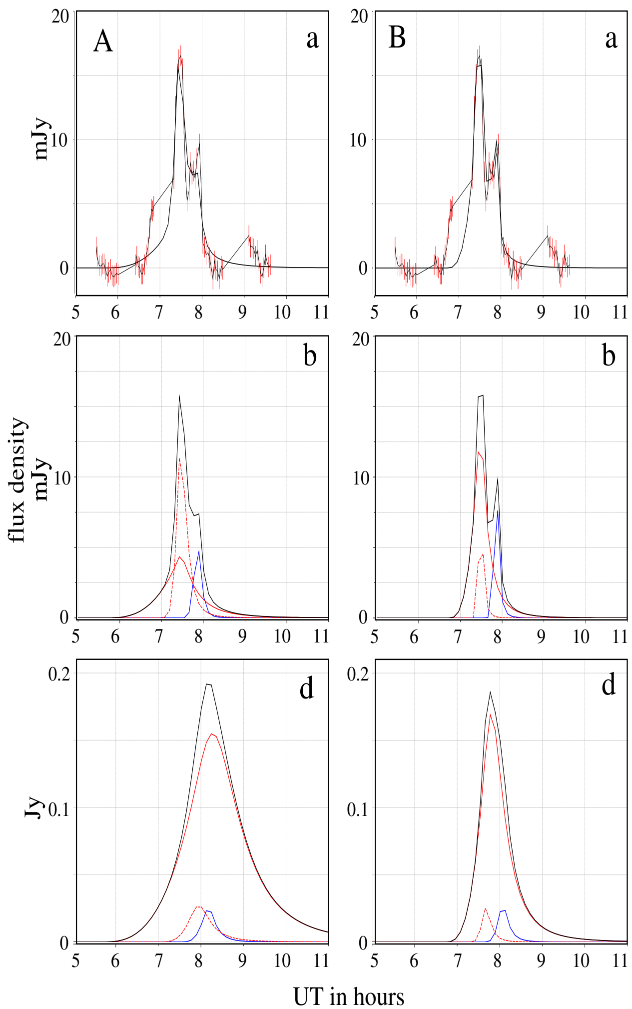
Global coordinated multi-wavelength observing sessions





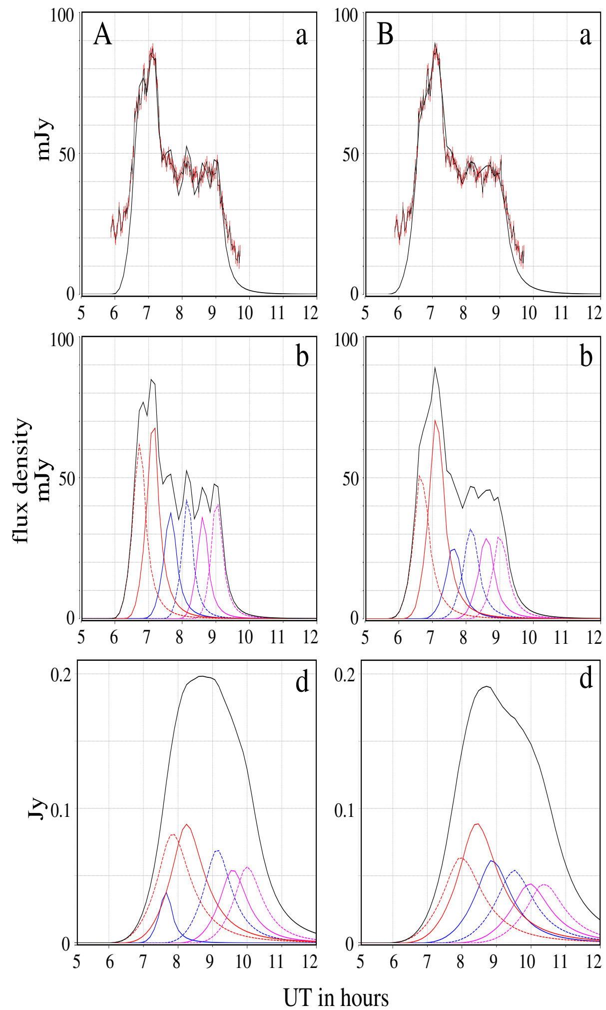
Large number of collaborators from the US, Germany, France, Spain and Japan:

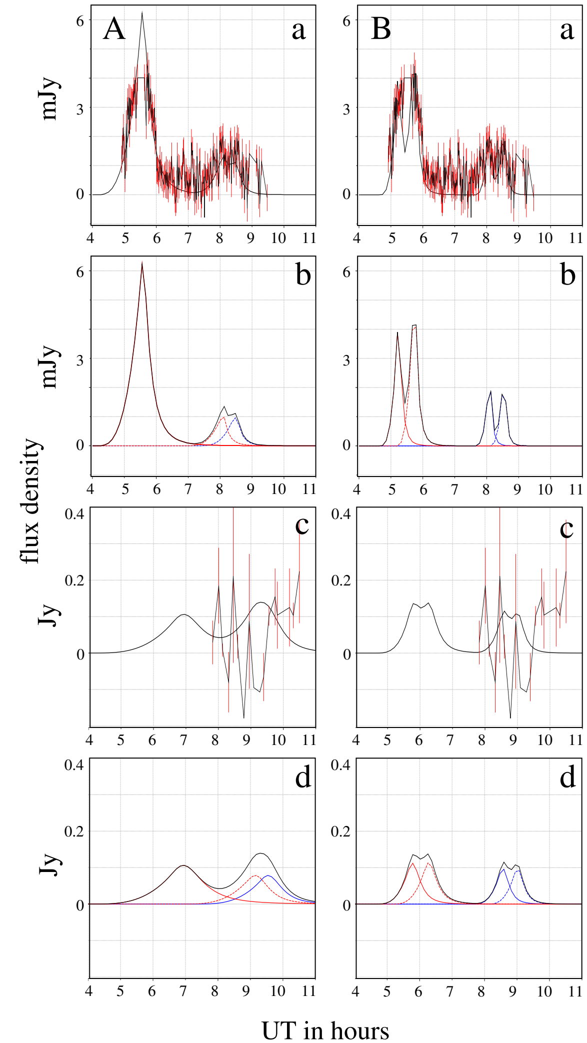
Eckart, Baganoff, Morris, Schödel, Vogel, Teuben, Bautz, Brandt, Garmire, Ricker, Straubmeier, Bower, Goldston, Krips, Muzic, Moultaka, Najarro, Sjouwerman, Gezari, Krichbaum, Zensus, Schuster, Wiesemeier, Weiss, Tamura, Nishiyama Karas, Dovciak, Duschl - and others



May 15, 2007

May 26, 2008





May 19, 2007

Astronomy & Astrophysics manuscript no. NIRmmflare
November 5, 2009

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Coordinated NIR/mm observations of flare emission from Sagittarius A*

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ABSTRACT

Context. We report on a successful, simultaneous observation and modelling of the millimeter to near-infrared (NIR) flare emission of the Sgr A* counterpart associated with the super-massive ($4\times10^6 M_\odot$) black hole at the Galactic Centre (GC). In comparison to previously published papers, we present one of the best mm/sub-mm light curves with a continuous coverage of Sgr A*.
Aims. We study and model the physical processes giving rise to the variable emission of Sgr A*.
Methods. Our non-relativistic modelling is based on simultaneous observations that have been carried out in May 2007 and 2008, using the NACO adaptive optics (AO) instrument at the European Southern Observatory's Very Large Telescope and the mm telescope arrays CARMA in California, ATCA in Australia and the 30 m IRAM telescope in Spain. We emphasize the importance of multi-wavelength simultaneous fitting as a tool for imposing adequate constraints on the flare modelling.
Results. The observations reveal flaring activity in the mm domain and in the NIR. Inspection and modelling of the light curves show that the mm follows the NIR emission with a delay of 1.5±0.5 hours. We explain the flare emission delay by an adiabatic expansion of source components. The derived physical quantities that describe the flare emission give a source component expansion speed of $v_{exp} \sim 0.005 - 0.017c$, source sizes around one Schwarzschild radius with flux densities of a few Janskys, and spectral indices of α=0.6 to 1.3. These source components peak in the THz regime.
Conclusions. These parameters suggest that the adiabatically expanding source components either have a bulk motion greater than v_{exp} or the expanding material contributes to a corona or disk, confined to the immediate surroundings of Sgr A*.

Key words. black hole physics, infrared: general, accretion, accretion disks, radio, Galaxy: centre, nucleus

1. Introduction

Sgr A*, the compact non-thermal radio and infrared source at the centre of the Milky Way galaxy (~8 kpc away) is known to be associated with a super-massive black hole (SMBH) of mass $\sim4\times10^6 M_\odot$ (Eckart & Genzel 1996; Genzel et al. 1997, 2000; Ghez et al. 1998, 2000, 2004b,a, 2005; Eckart et al. 2002; Schödel et al. 2002, 2003; Eisenhauer et al. 2003, 2005; Gillessen et al. 2009; Ghez et al. 2009). The close proximity of Sgr A* makes it an ideal case to study the evolution and physics of SMBHs located in the nuclei of galaxies. The SMBH radiates far below its Eddington luminosity at all wavelengths, partly due to its low observed accretion rate. For Sgr A* we assume R_s=$2R_g$=$2GM/c^2$~9 μas, with R_s being one Schwarzschild radius and R_g the gravitational radius of the SMBH.

Evidence for flaring activity occuring from a few hours to days has been found from variability studies ranging from the radio to sub-mm wavelengths (Bower et al. 2002; Herrnstein et al. 2004; Zhao et al. 2003, 2004; Mauerhan et al. 2005). There is also evidence that variations in radio/sub-mm emission are linked to NIR/X-ray flares, with the radio/sub-mm flares occuring after a delay of ~100 minutes after the NIR/X-ray flares

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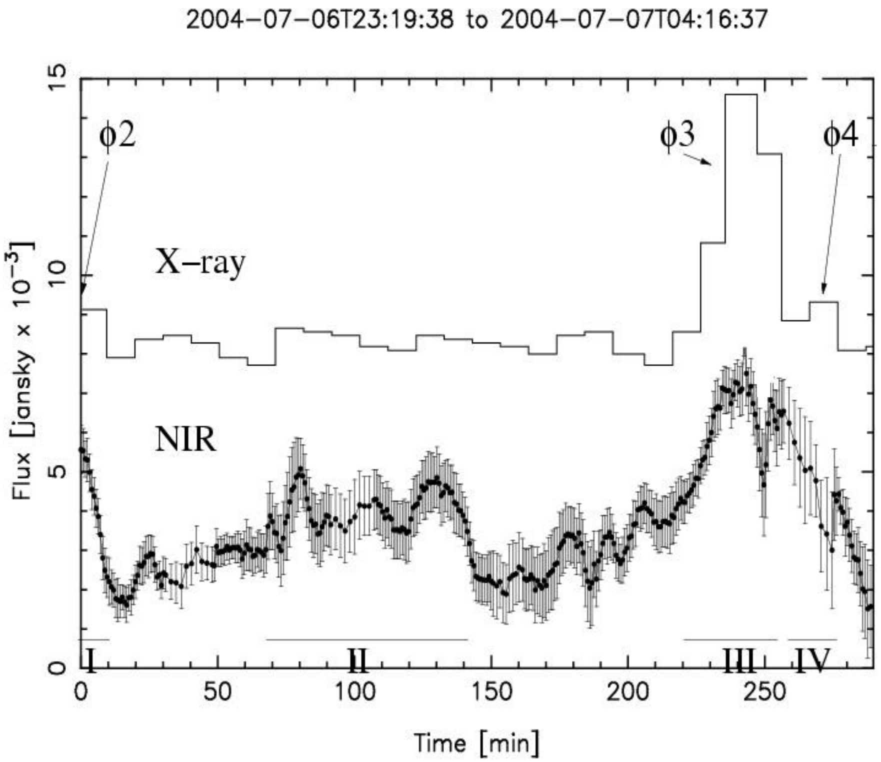
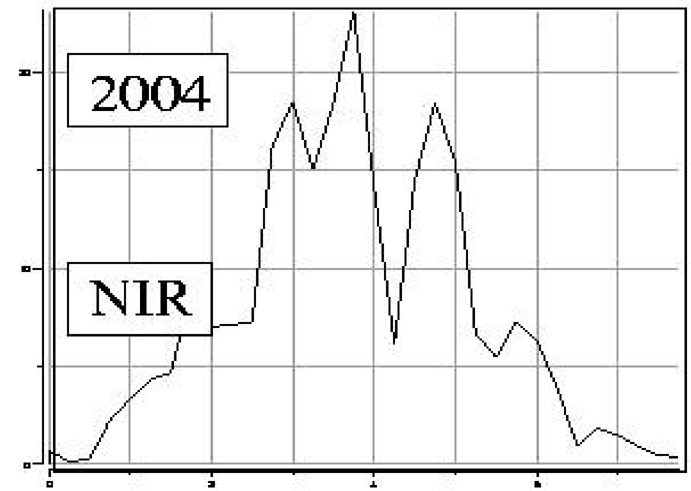
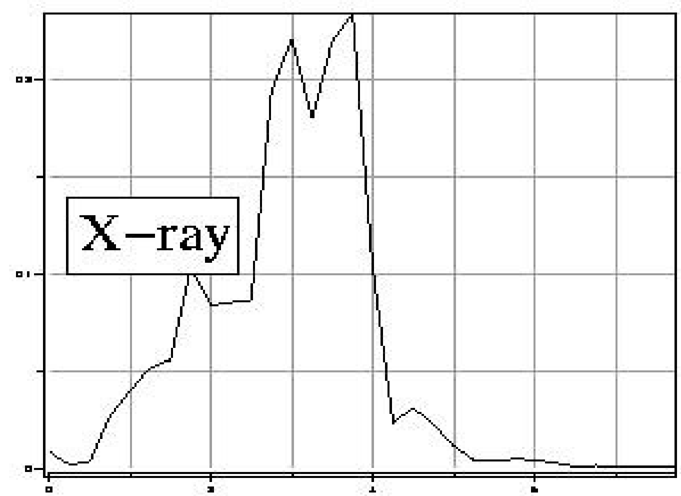
Kunneriath et al.,
Submitted to A&A, November 2009

SSC disk modelling of individual flares: 2004



Indication for adiabatic source component expansion:
Expansion by 30%
explains difference between
NIR and X-ray flare structure.

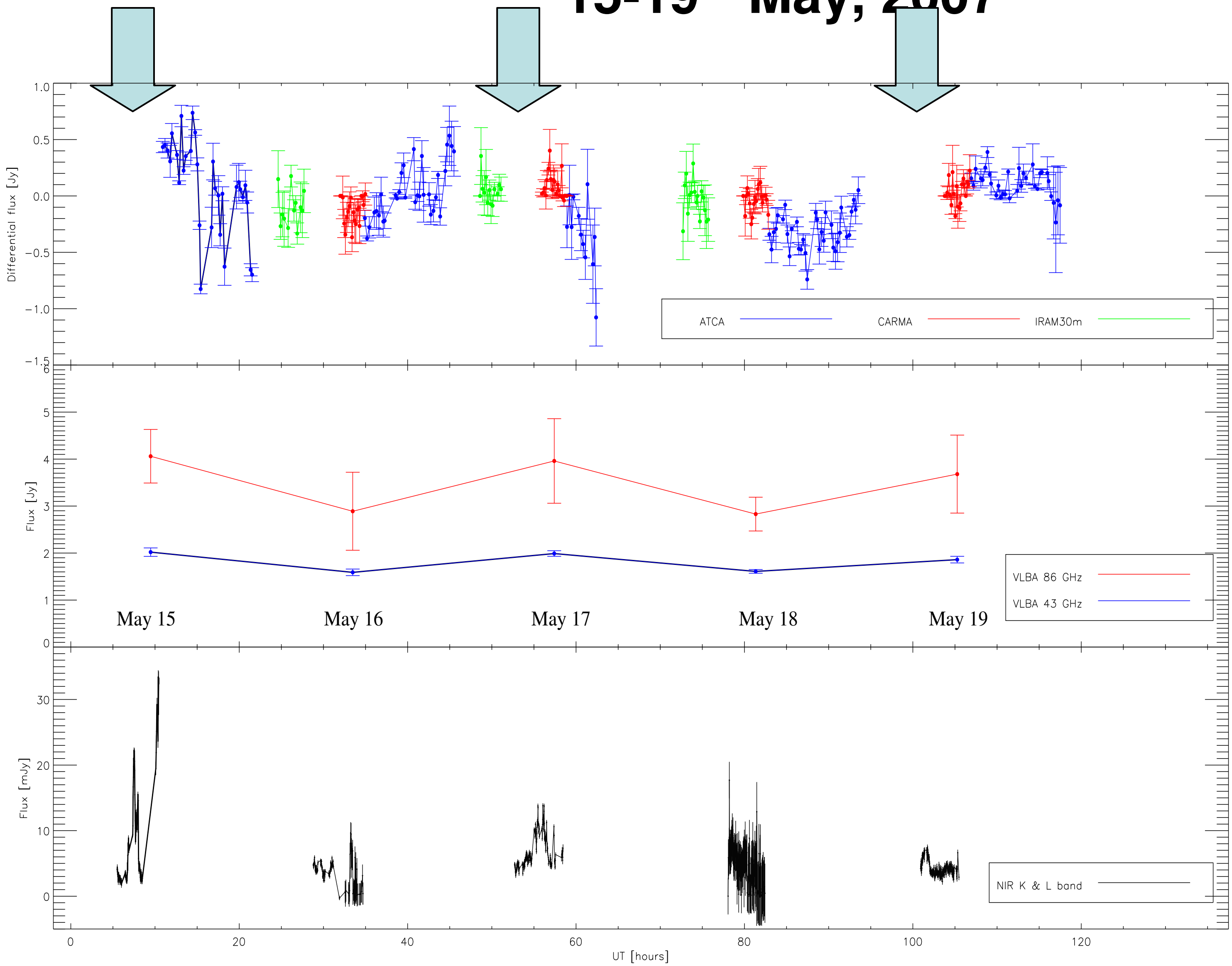




Eckart et al. 2009; A&A 500, 395

2 flare phases φ3 φ4

Combined differential light curve in the mm-regime
CARMA, ATCA and IRAM 30m
15-19th May, 2007

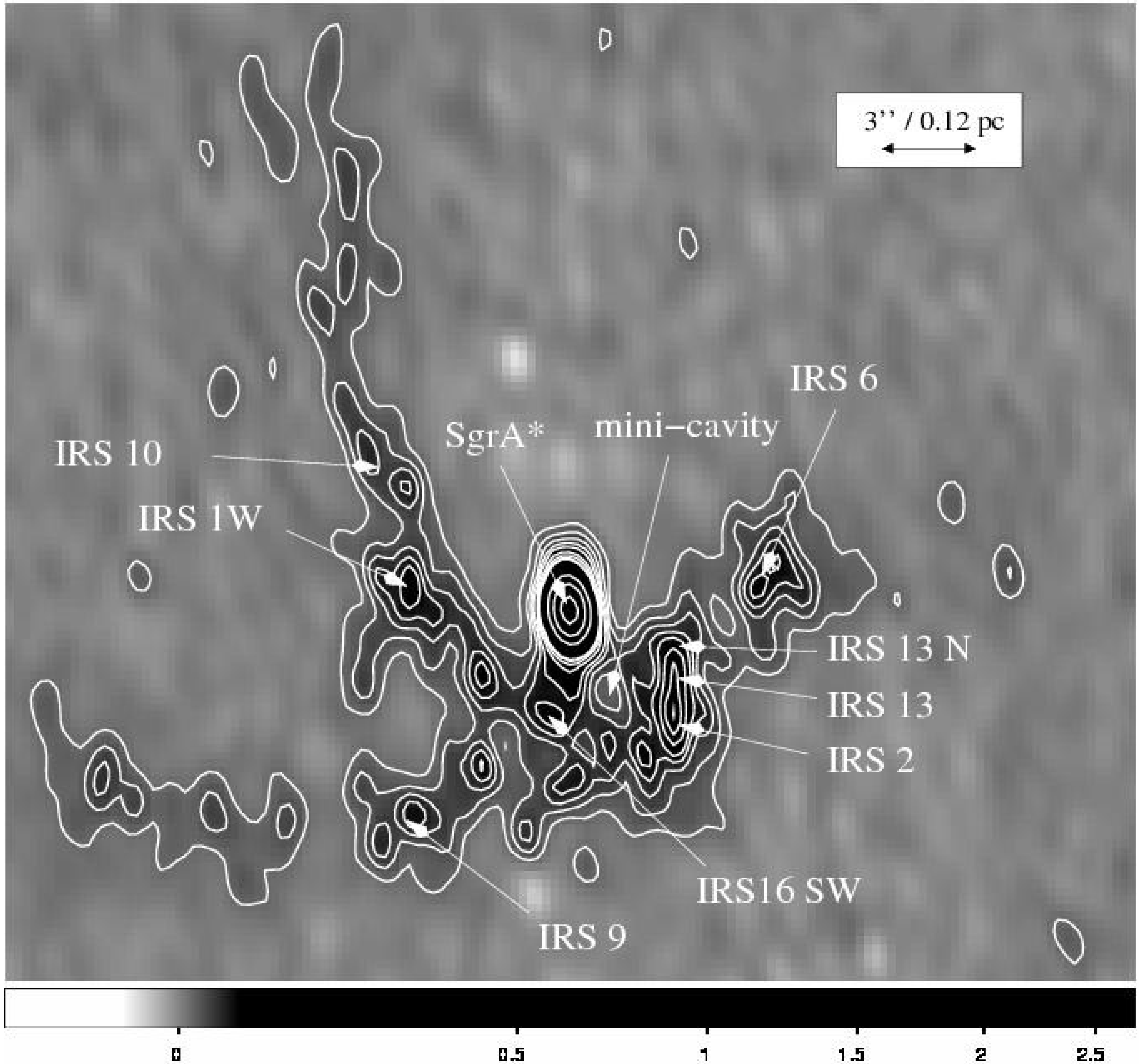


CARMA
ATCA
30 m

VLBA
86 GHz
43 GHz
(Lu et al. 2008)

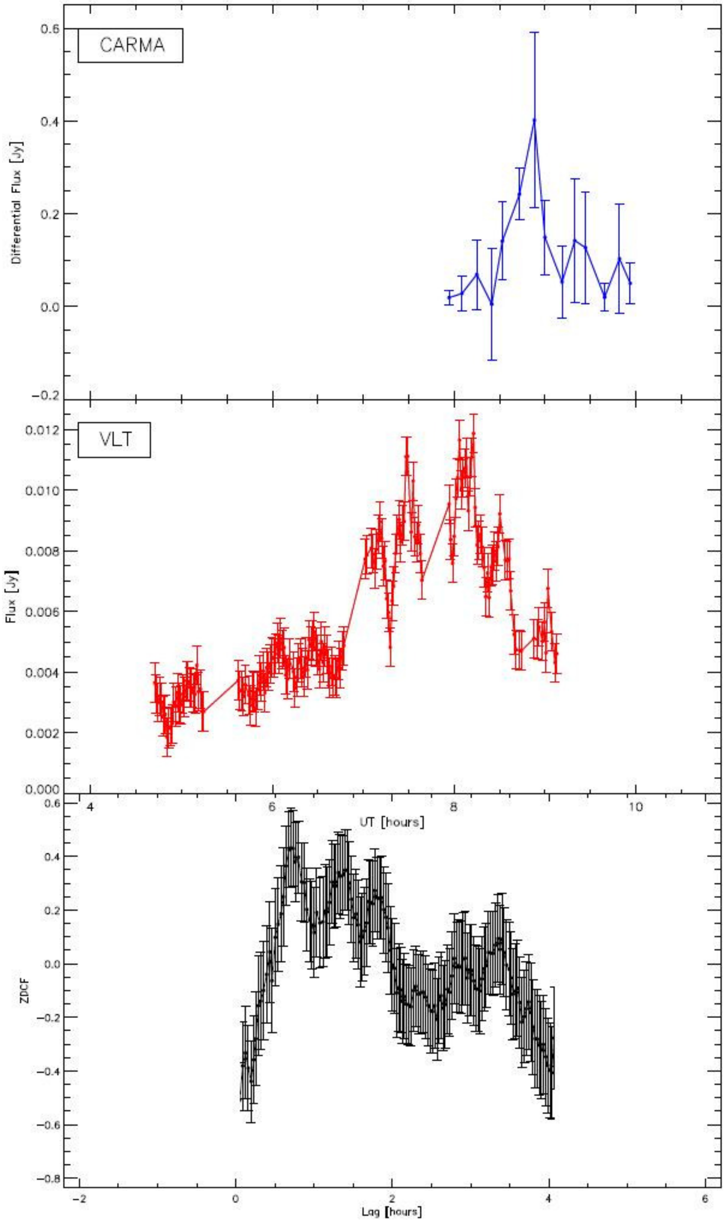
VLT K & L'-band

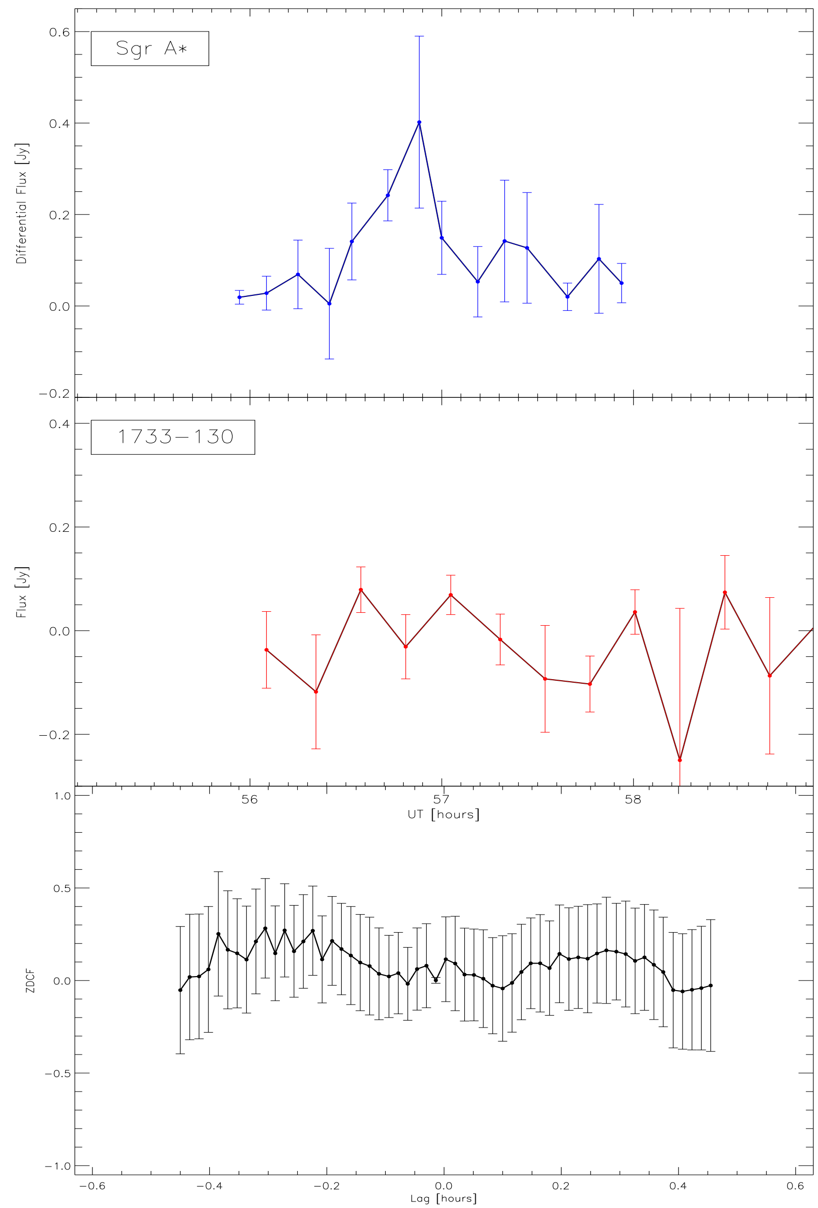
Kunneriath et al., 2010



~1.5''Combined BCD array CARMA map 2007/2008 (100 GHz)

May 17, 2007 – Light curves

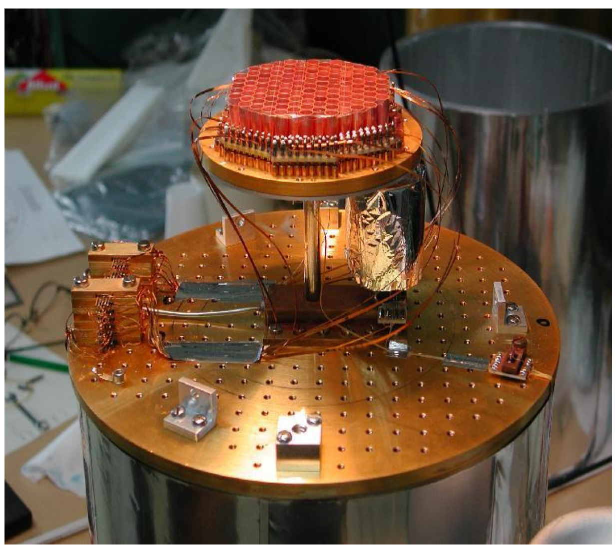




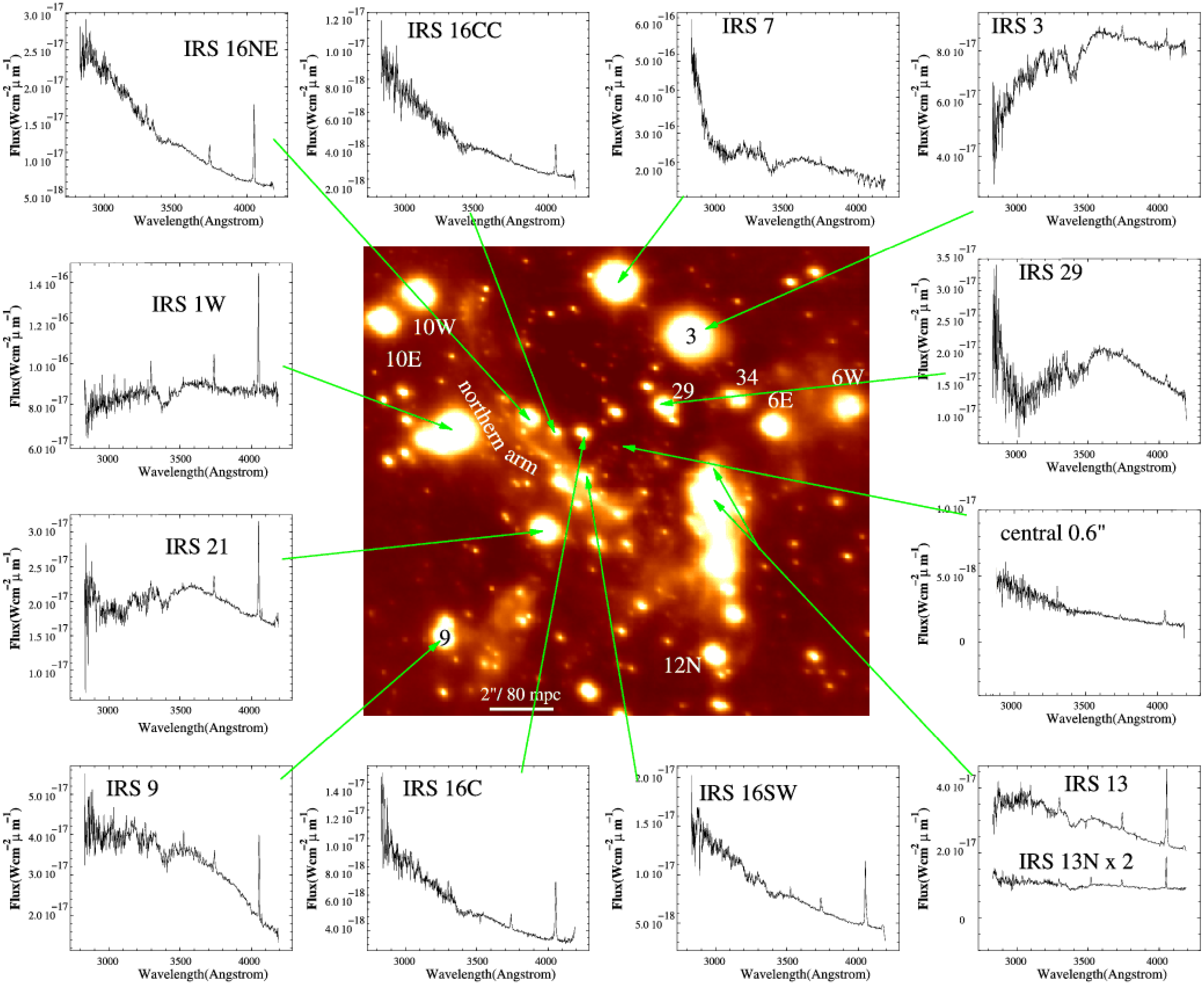
May 2007

CARMA, Cedar Flat, Eastern California, USA
6 x 10.4 m, 9 x 6.1 m, 100 GHz
Calibrator sources 3C273, 1733-130

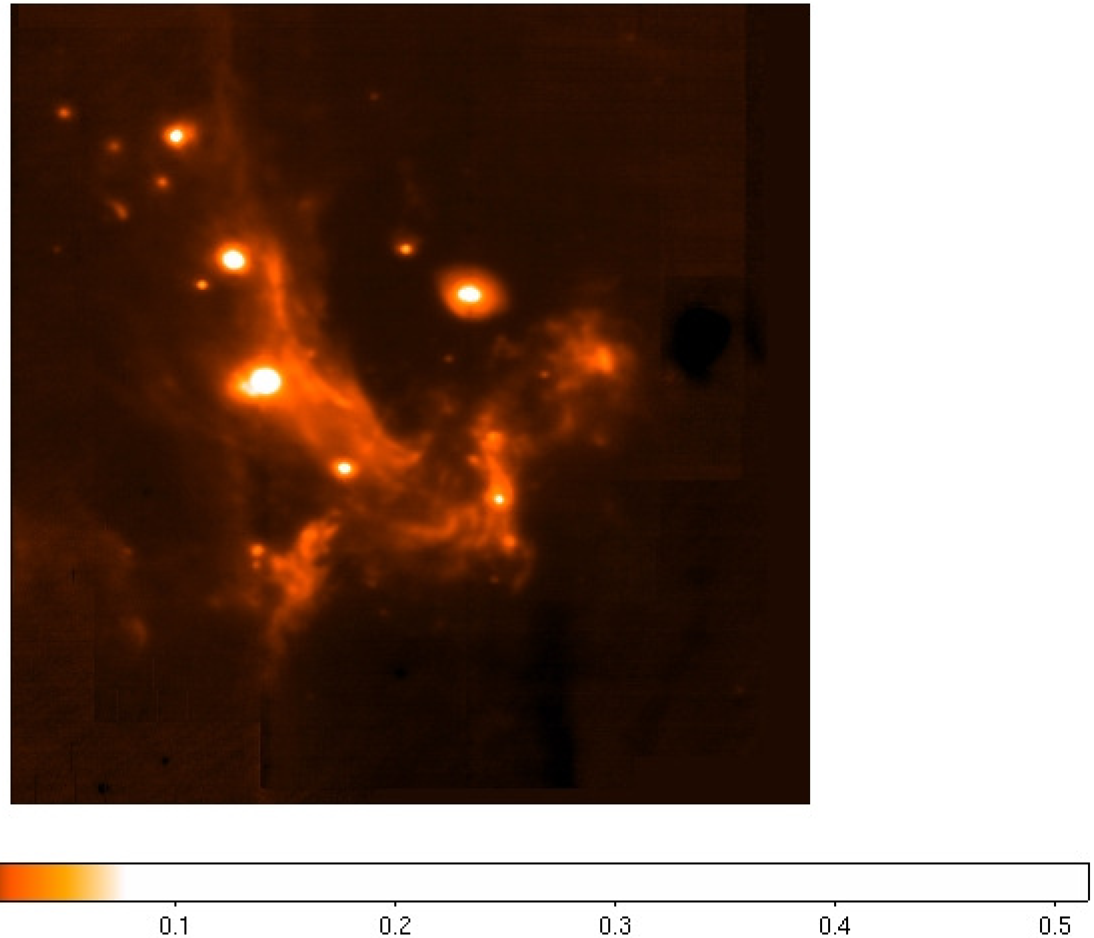
ATCA, Paul Wild Observatory, Australia
Six 22-m telescopes, 86 GHz
Calibrator sources 1253-055, 1921-293 and Uranus



MAMBO 2, 30-m IRAM telescope at Pico Veleta, Spain
1.2 mm wavelength
Bolometer calibrator source G10.62.

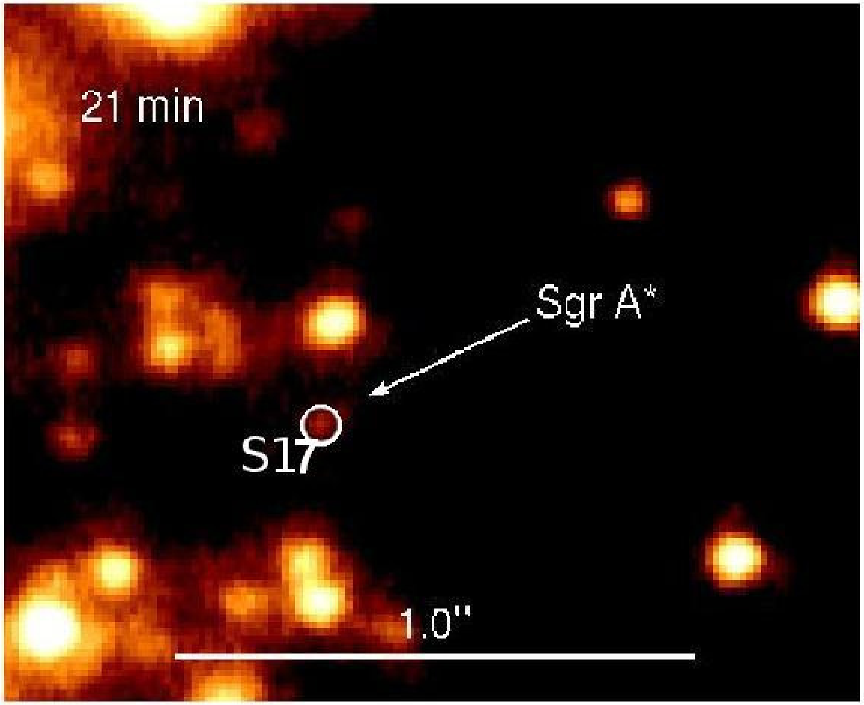


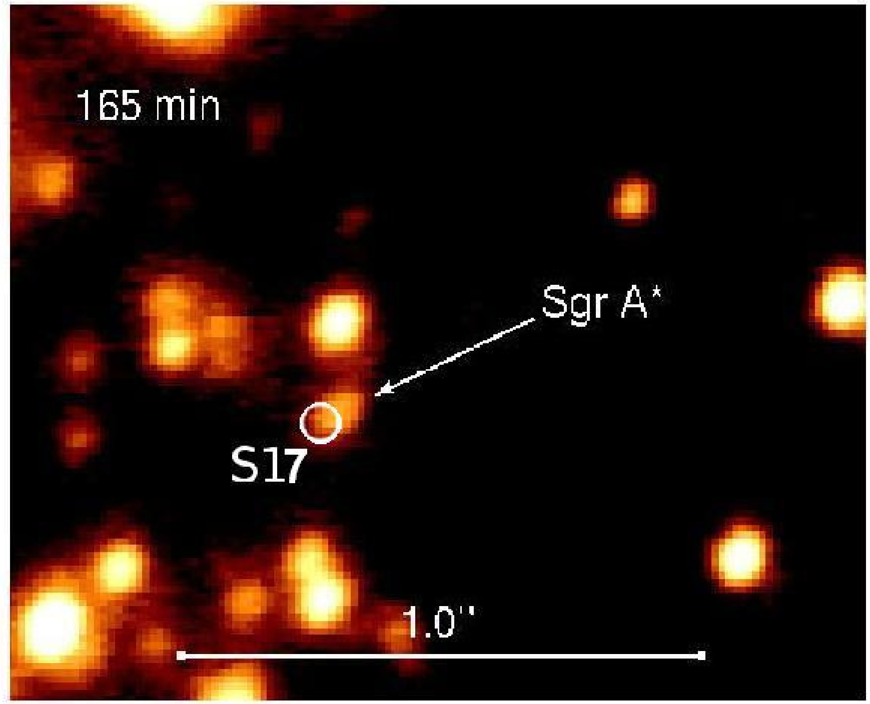
L-band ISAAC image, Moultaka et al. 2004

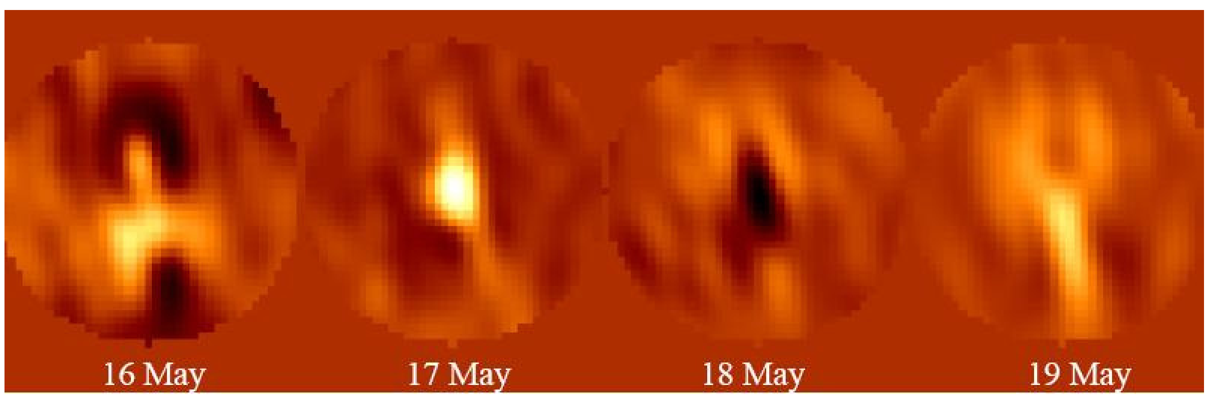


VISIR 8.6 μ map (Rainer Schoedel)

May 17, 2007



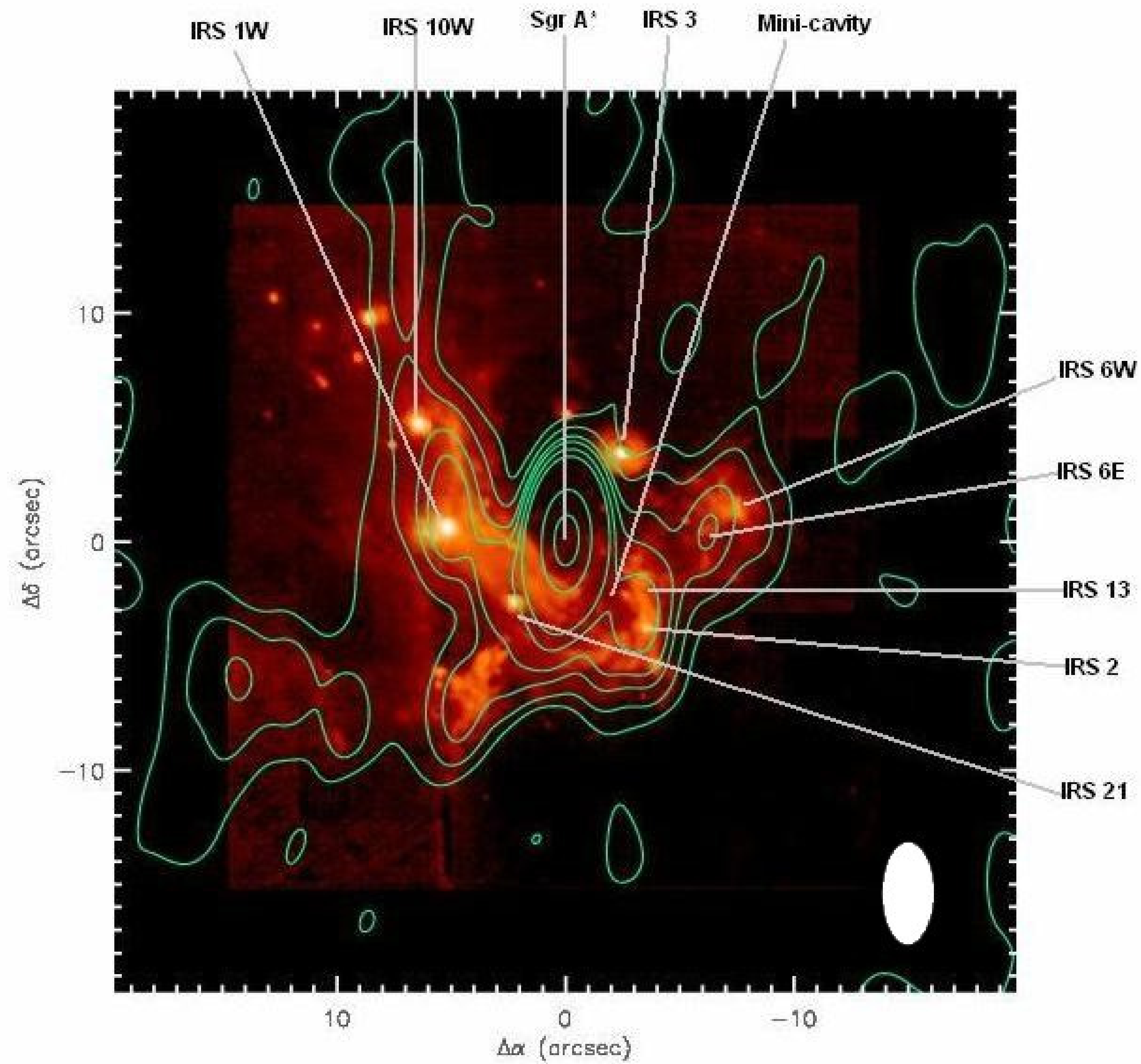




CARMA difference maps at 3mm

date	model label	source	Δt hours	v_{exp} in c	$S_{max,obs}$ [Jy]	α_{synch}	R_0 [R_s]	$\nu_{max,obs}$ [GHz]	B [G]	$S_{NIR,synch}$ [mJy]	$S_{NIR,SSC}$ [mJy]	$S_{X-ray,SSC}$ [nJy]
$1\ \sigma \rightarrow$			±1.0	±0.001	±0.1	±0.1	±0.1	±250	±10	±1.0	±1.0	±20
15 May 2007	A	α	0.0	0.007	0.6	0.85	1.3	340	33	3.1	<0.03	<10
		β	0.0		0.3	0.60	0.3	840	29	12	<0.03	<10
		γ	0.30		0.3	0.75	0.2	840	32	5.6	<0.03	<10
15 May 2007	B	α	0.0	0.017	0.6	0.65	1.3	340	37	8.3	<0.02	<40
		β	0.0		0.3	0.65	0.3	840	30	8.4	<0.02	<40
		γ	0.37		0.3	0.65	0.35	810	32	8.4	<0.02	<40
17 May 2007	A	α	0.0	0.010	1.0	1.00	0.8	840	66	4.7	<0.01	<10
		β	0.45		0.5	0.97	0.3	1250	66	4.0	<0.01	15
		γ	-0.59		1.3	1.11	1.0	840	69	3.2	<0.01	<10
		δ	-0.96		0.5	1.02	0.3	1250	68	3.2	<0.01	12
17 May 2007	B	α	0.0	0.011	0.25	0.70	0.2	1360	86	8.1	<0.01	19
		β	0.36		0.25	0.70	0.2	1360	86	8.1	<0.01	19
		γ	-0.69		0.17	0.70	0.2	1360	65	5.1	<0.01	21
		δ	-1.05		0.17	0.70	0.2	1360	65	5.1	<0.01	21
		ϵ	-0.33		1.75	1.05	1.6	570	68	7.1	<0.01	<2
19 May 2007	A	α	0.0	0.007	1.30	1.07	1.0	1360	67	3.5	<0.01	<10
		β	2.50		1.10	1.10	0.8	1360	67	0.5	<0.01	<10
		γ	2.90		1.10	1.10	0.8	1360	67	0.5	<0.01	<10
19 May 2007	B	α	0.0	0.017	1.33	1.13	1.0	720	68	2.5	<0.01	<10
		β	0.50		1.33	1.09	1.0	720	67	3.1	<0.01	<10
		γ	2.85		1.50	1.30	0.8	820	72	1.2	<0.02	<10
		δ	3.30		1.50	1.30	0.8	850	72	1.2	<0.02	<10
26 May 2008	A	α	0.0	0.007	1.4	0.70	0.6	1090	44	39	<0.02	24
		β	-0.40		1.3	0.70	0.6	1090	56	35	<0.02	13
		γ	0.52		1.1	0.77	0.6	1030	36	23	<0.02	18
		δ	1.03		1.3	0.80	0.5	1160	33	23	<0.04	33
		ϵ	1.48		1.0	0.77	0.5	1160	58	20	<0.01	<10
		ζ	1.90		1.0	0.73	0.5	1160	56	24	<0.01	<10
26 May 2008	B	α	0.0	0.005	1.1	0.68	0.5	1090	30	31	<0.02	41
		β	-0.45		1.0	0.68	0.5	1090	40	26	<0.02	18
		γ	0.52		1.0	0.83	0.5	1030	31	15	<0.02	17
		δ	1.03		1.0	0.80	0.5	1160	34	17	<0.03	23
		ϵ	1.48		0.8	0.77	0.5	1160	48	16	<0.01	<10
		ζ	1.90		0.8	0.77	0.5	1160	48	16	<0.01	<10

Table 1. Source component parameters for the combined SSC and adiabatic expansion model of the 15, 17 and 19 May 2007 and the 26 May 2008 flares. Labels A and B refer to models with lower and higher expansion velocities respectively. The flare times Δt are given with respect to the peak of the brighter NIR flares. The adiabatic expansion velocity v_{exp}, the optically thin spectral index α_{synch} and the cutoff frequency ν_0 are given. In addition to v_{exp} the R_0 values are responsible for the position and width of the infrared flares peaks in time. Different values for α_{synch} are required to match the infrared flux densities.



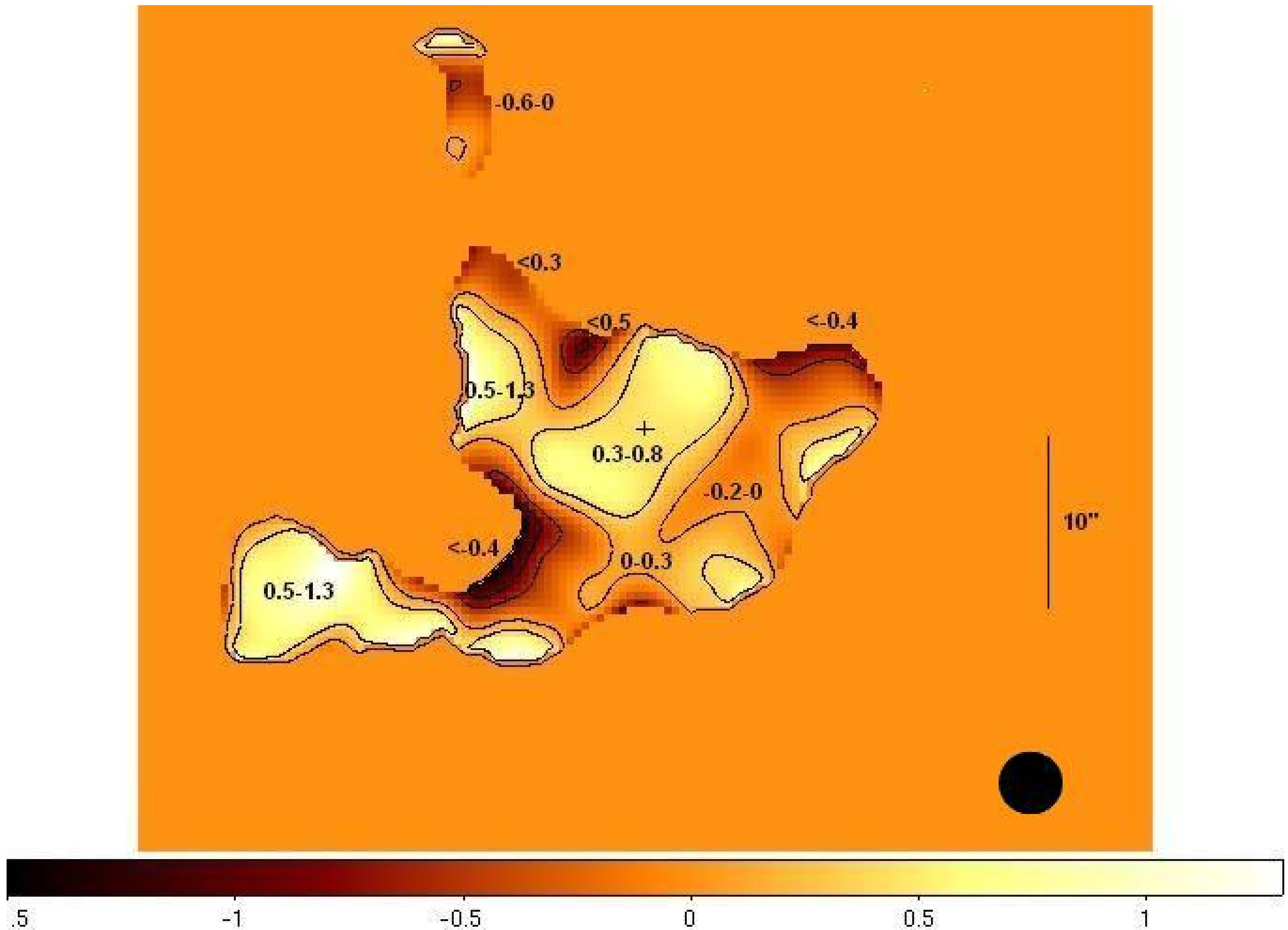
MIR VLT/VISIR map at 8.6 µm overlaid with 1.3 mm D array contours

Spectral index map

$$\alpha = \frac{log(S_1/S_2)}{log(\nu_1/\nu_2)}$$

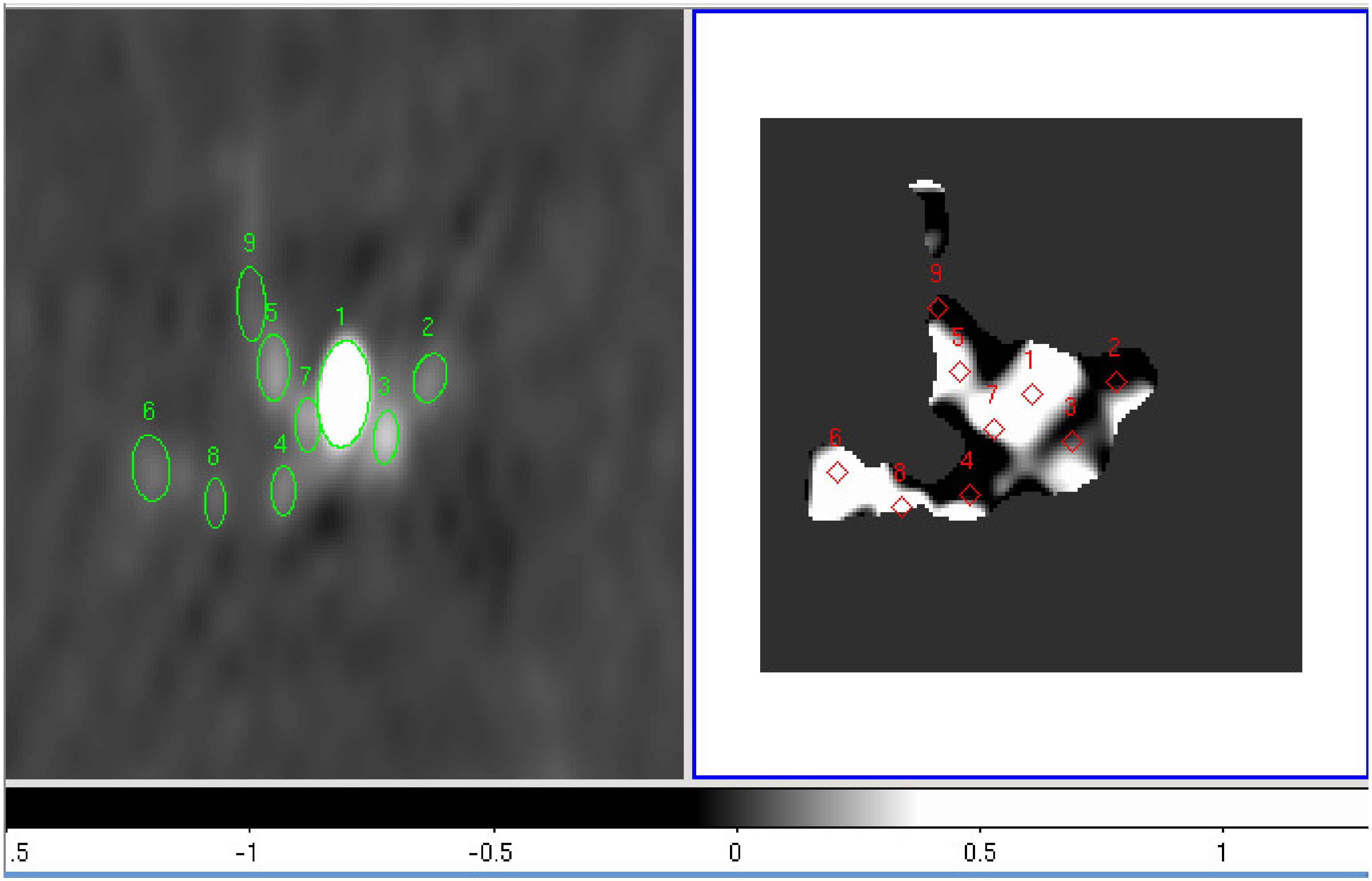
Step 1: Take two maps – 1.3mm and 3mm
Step 2: Convolve them both to the same resolution 3x3” in this case
Step 3: Align both maps
Step 4: Multiply both maps to create a mask
Step 5: Divide maps, with the mask setting a lower flux limit

Spectral index map of the central 1.5 pc



$S_\nu \sim \nu^\alpha$

Spectral index of Sgr A* ~0.45±0.15



Region	RA	Dec	net_counts	flux(Jy)	Spectral index
1	17:45:40.04	-29:00:28.10	112.005	1.29	0.45
2	17:45:39.56	-29:00:27.20	2.332	0.027	-0.12
3	17:45:39.811	-29:00:31.55	4.309	0.049	0.04
4	17:45:40.394	-29:00:35.45	1.680	0.019	-0.22
5	17:45:40.452	-29:00:26.45	4.131	0.048	0.47
6	17:45:41.149	-29:00:33.80	2.454	0.028	0.67
7	17:45:40.257	-29:00:30.65	3.268	0.038	0.55
8	17:45:40.783	-29:00:36.35	0.719	0.008	0.96
9	17:45:40.577	-29:00:21.80	1.288	0.015	-0.36

Conferences, schools, other activities

Summer/winter schools

- European Radio Interferometry School, Bonn, September 2007

Conferences/workshops

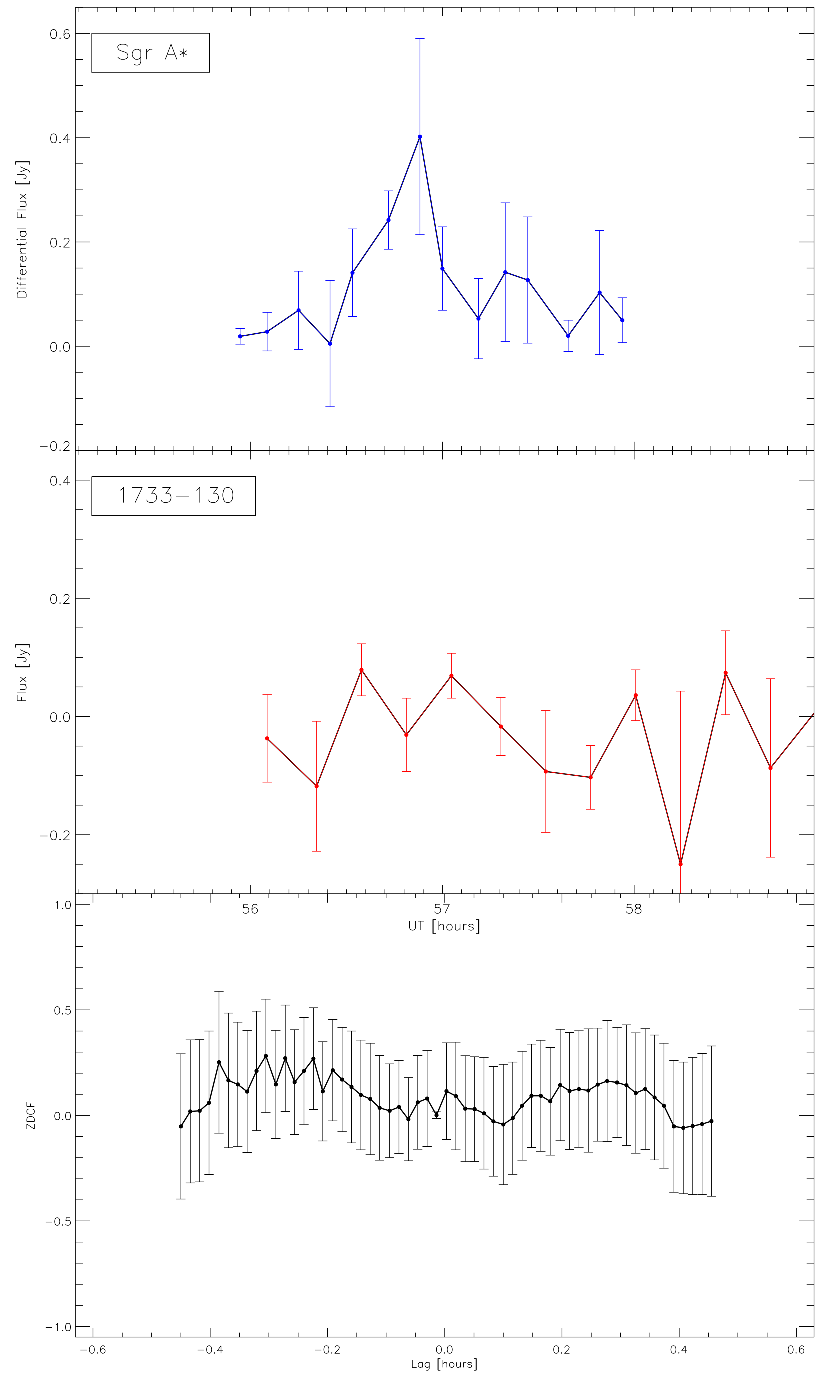
- Galactic Center Workshop 2009, Shanghai, October 2009 (contributed talk)
- CARMA Science Symposium, Chicago, October 2009 (poster)
- SPP Meeting, Bad Honnef, May 21-23, 2009 (poster)
- AHAR conference, Bad Honnef, April 2008 (poster)

IMPRS activities

- IMPRS Seminars: December 2007 and May 2009
- Soft Skills Seminar: Time and Self-management by Sabine Hatzl, December 2009
- IMPRS Retreat, August 2007
- Lectures at the University of Cologne: AGNs, Star Formation, Astrophysics II, Cosmology
- Time Series Analysis lectures, January-February 2010

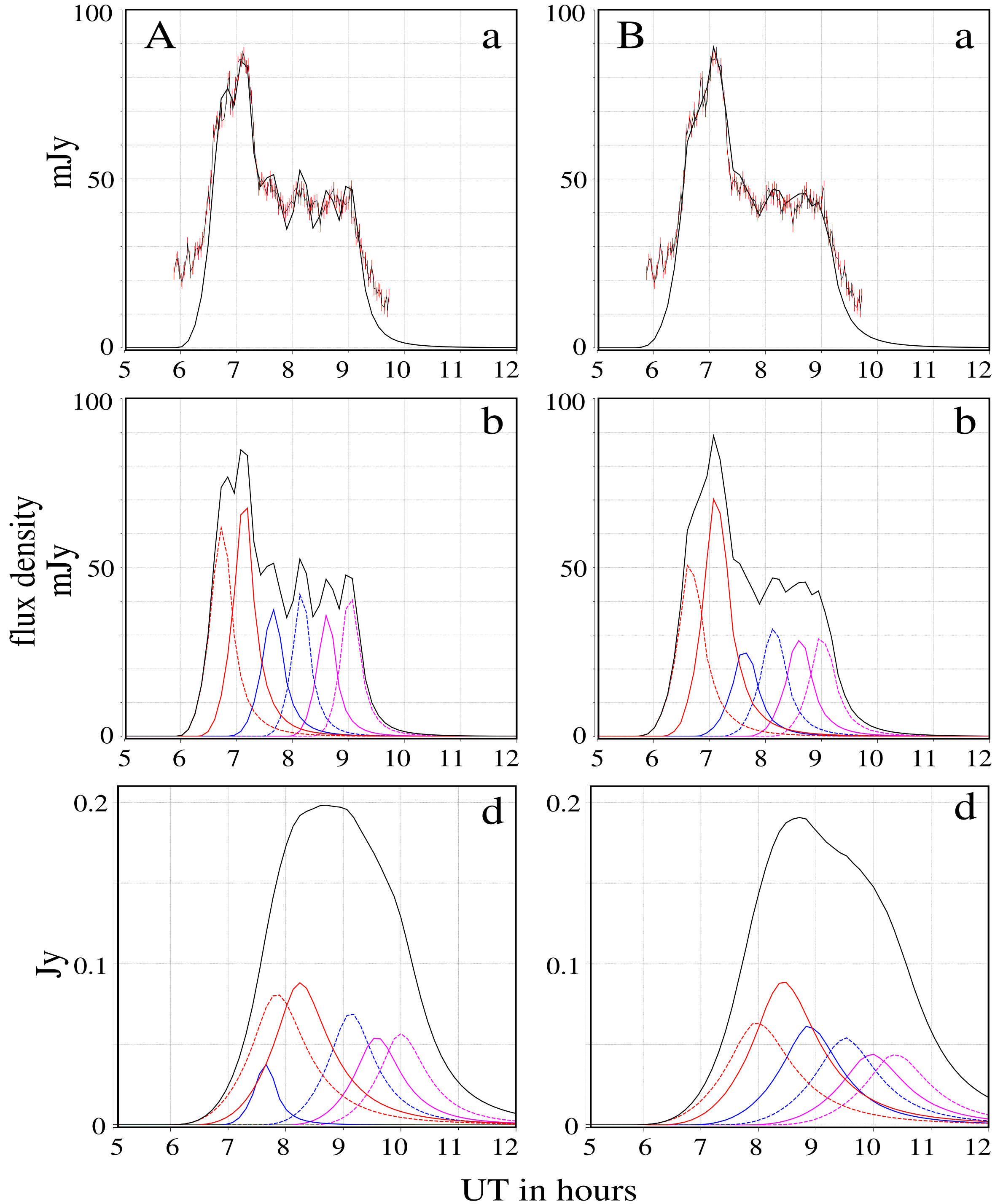
Publications (published, in press, submitted)

- **Kunneriath** et al., Coordinated NIR/mm observations of flare emission from Sagittarius A* , A&A, submitted
- **Kunneriath**, D., Eckart, A., Vogel, S., et al., Coordinated mm/sub-mm observations of Sagittarious A* in May 2007 –- J. Phys.: Conf. Ser. 131 012006
- **Kunneriath** et al., The Galactic Centre in the mm-regime: Observations with CARMA, Proceedings of the Galactic Center Workshop 2009, Shanghai. To be published in the Astronomical Society of the Pacific Conference Series
- Eckart, A., Baganoff, F.K., Morris, M.R., **Kunneriath**, D. et al., Modeling mm- to X-ray flare emission from Sagittarius A*, A&A, Volume 500, Issue 3, 2009, pp.935-946
- Eckart, A., Schödel, R., ..., **Kunneriath**, D., et al., Simultaneous NIR/sub-mm observation of flare emission from Sagittarius A*, A&A 492, 337-344, 2008
- Eckart, A., ..., **Kunneriath**, D., Coordinated multi-wavelength observations of Sgr A*, J. Phys.: Conf. Ser. 131 012002
- Lu, R.-S., Krichbaum, T. P., Eckart, A., König, S., **Kunneriath**, D., Witzel, G., Witzel, A., Zenzus, J. A., High-frequency VLBI observations of Sgr A* during a multi-frequency campaign in May 2007, J. Phys.: Conf. Ser. 131 012059

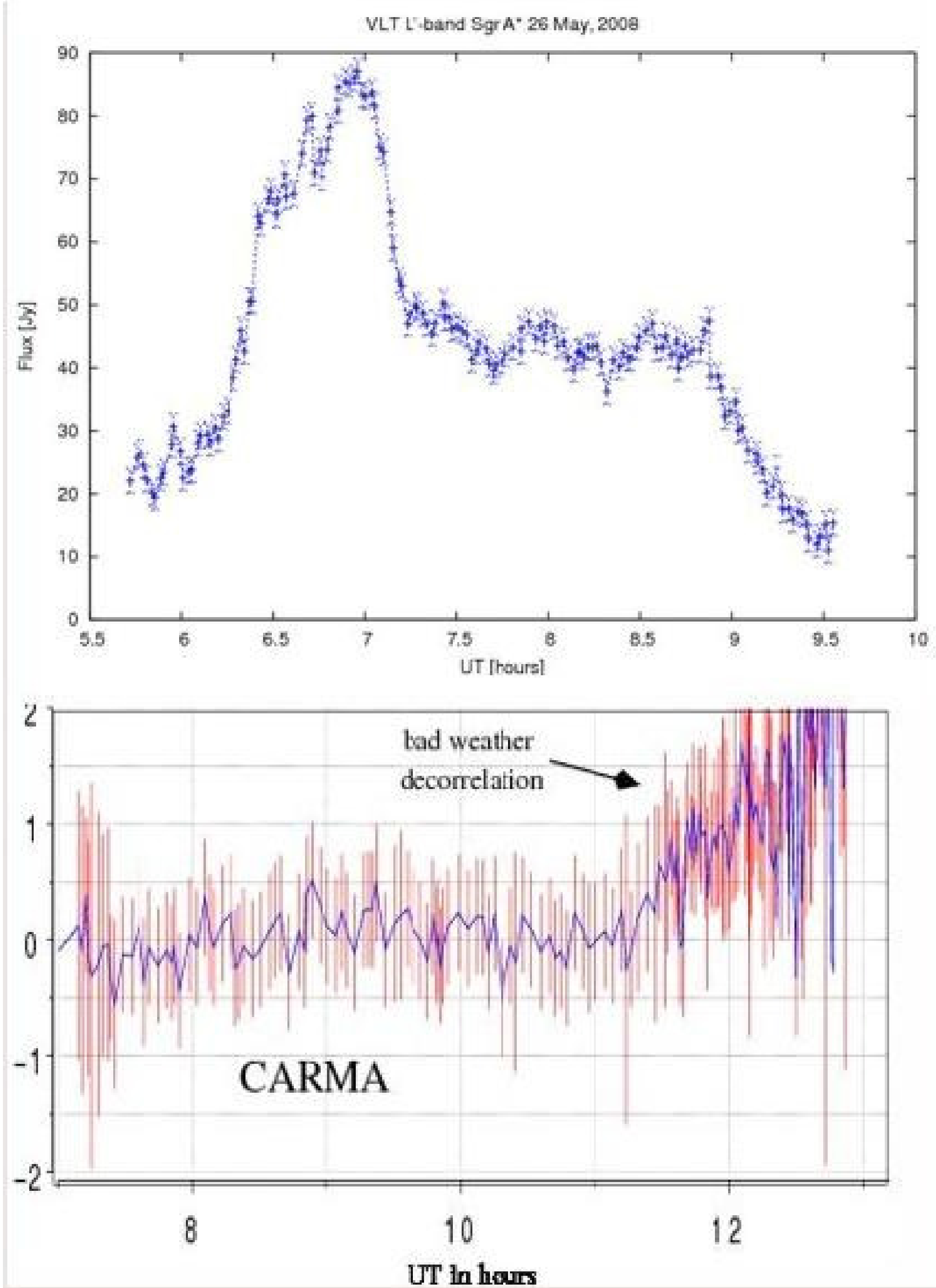


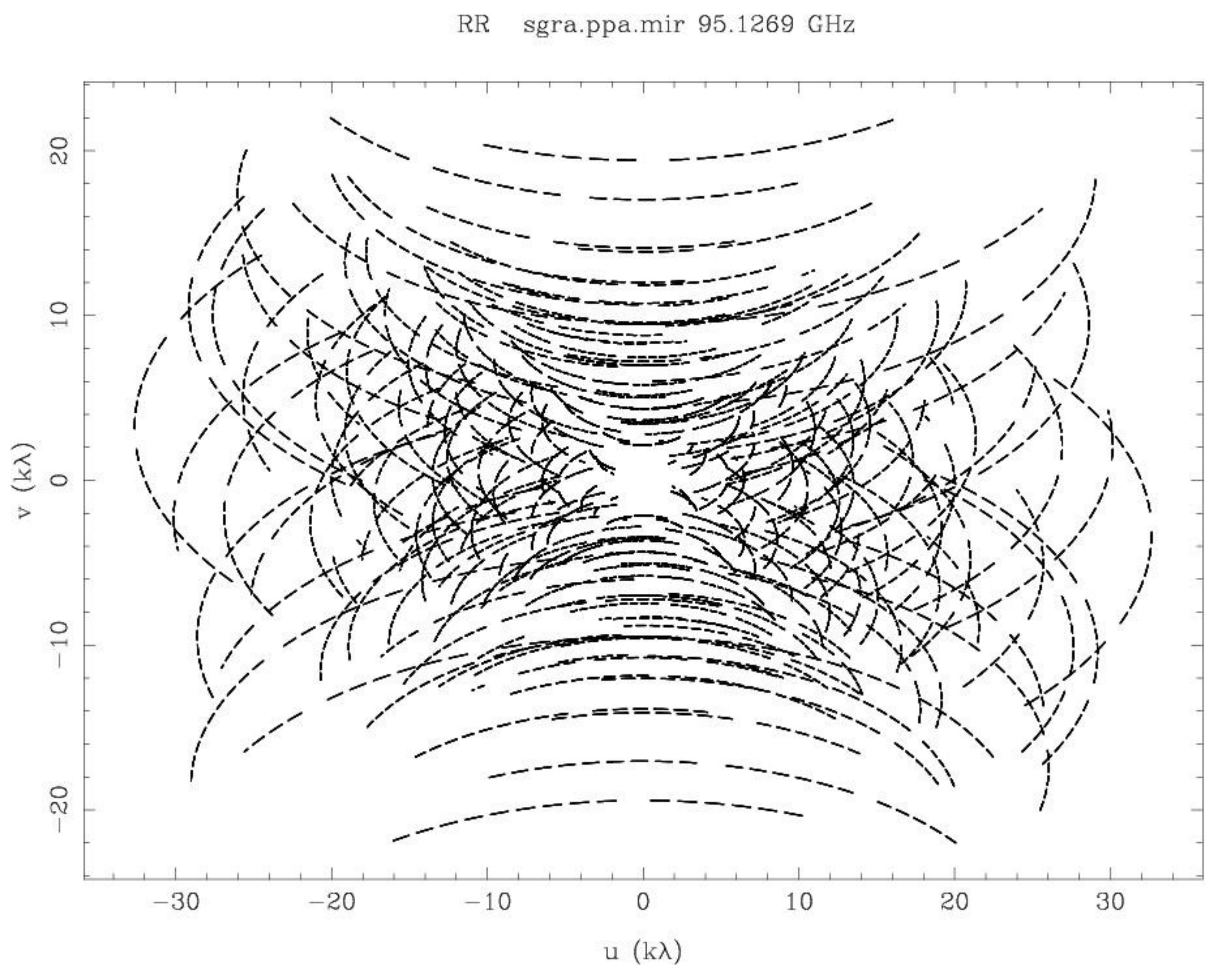
Sgr A*
Differential Flux [Jy]
0.6
0.4
0.2
0.0
−0.2
1733−130
Flux [Jy]
0.4
0.2
0.0
−0.2
56
57
58
UT [hours]
ZDCF
1.0
0.5
0.0
−0.5
−1.0
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
Lag [hours]

Modelling of May 26, 2008 flares



May 26, 2008


VLT L'-band SgrA* 26 May, 2008
Flux [Jy]
UT [hours]
bad weather
decorrelation
CARMA
UT in hours


RR sgra.ppa.mir 95.1269 GHz
v (kλ)
u (kλ)
20
10
0
−10
−20
−30
−20
−10
0
10
20
30