Credit: ESO/C. Malin

A search for a line polarization calibration catalogue for ALMA

Felipe Alves

German ALMA Regional Center

Argelander-Institut für Astronomie

Bonn - Germany

Argelander-Institut für Astronomie

EUROPEAN ARC
ALMA Regional Centre || Germany

Team

- Wouter Vlemmings (Nordic node)
- Liz Humphreys (EU node)
- Sofia Ramstedt (Uppsala University)
- Ramprasad Rao (SMA/ASIAA)
- Andrés Pérez-Sánchez (AIfA)

ALMA Polarization System

- So far…
  - Linear polarization feeds (X and Y)
  - Dual or single polarization modes available: XX YY
  - Max 2 GHz / polarization
  - Better sensitivity (dual) or better resolution (single)

- Full capabilities:
  - Parallel- and cross-handed visibilities: XX YY XY YX
  - Cycle 2: continuum (TDM) observations (~ 31.25 MHz wide channels)

ALMA Polarization System

Approximation for weakly polarized sources

Cotton, 1999

$$
\begin{aligned}
XX &= g_{nX} g^*_{mX} [I + Q\cos 2\chi + U \sin 2\chi] \\
XY &= g_{nX} g^*_{mY} [(d_{nX} - d^*_{mY})I - Q\cos 2\chi + U \sin 2\chi + iV] \\
YX &= g_{nY} g^*_{mX} [(d_{nY} - d^*_{mX})I - Q\cos 2\chi + U \sin 2\chi - iV] \\
YY &= g_{nY} g^*_{mY} [I - Q\cos 2\chi - U \sin 2\chi].
\end{aligned}
$$

X – Y phase difference (Φ_{XY}) known better than 1 degree
=> 0.1 % polarization accuracy

Calibration:

- *Unpolarized* sources: solve for *d*-terms (leakage) but Φ_{XY} unknown;
- *Polarized* sources with **known** polarization: solve for both *d*-terms and Φ_{XY}.
- *Polarized* sources with **unknown** polarization: observations over a large range of parallactic angle coverage are necessary (≥ 90°), solve for *d*-terms and Φ_{XY}.

Calibration

- Challenge: find suitable calibrators
  - Strong enough
  - Stable properties
  - Good parallactic angle coverage
- Solution: sources with known polarization properties

Goal: to obtain a sufficiently large set of polarization calibrators

Using molecular lines for polarization calibration

- It is important to measure how the polarization varies with time and frequency

$$P(\omega,t), \quad \chi(\omega,t)$$

- Leakage (*D*-terms) dependence with frequency

- Linear polarization model from a rescaled Stokes I spectrum (Kemball et al. 1995) => *D* (ω,t)

$$Q(\omega_i) + jU(\omega_i) = \beta_i I(\omega_i)$$

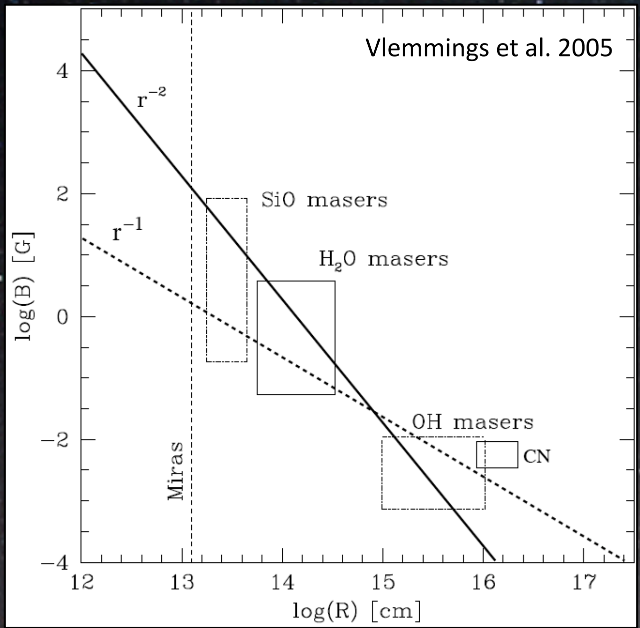
- Task previously done with SPCAL (at AIPS) and already built in the POLCAL task of CASA.

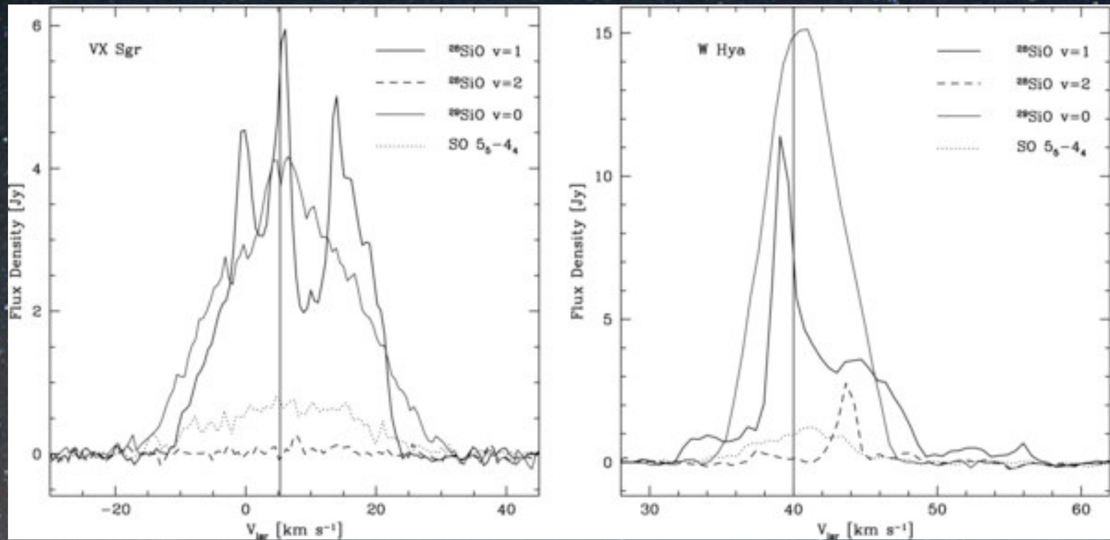
- Many studies have used polarized lines as a replacement for a continuum polarization calibrator to do leakage calibration (Kemball et al. 1995; Kemball & Diamond 1997; Vlemmings et al. 2002, 2005)

SiO masers

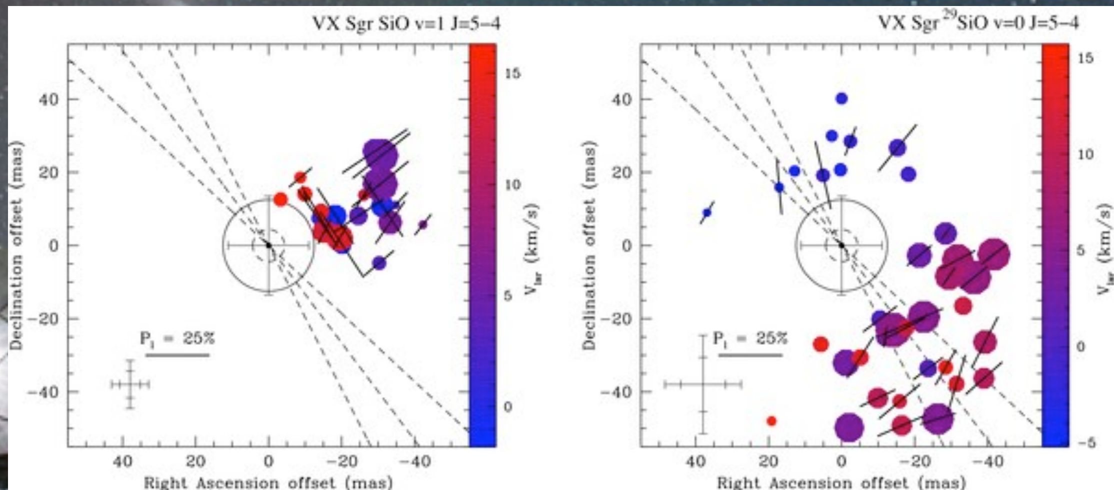
- Just a few strongly polarized continuum sources at high frequencies
- SiO masers:
  - Bright emission
  - Strongly polarized
- Science:
  - masers excited in regions very close to the stellar surface (a few AU),
  - dynamical influence of the magnetic field in the formation of CSE,

SiO masers





Vlemmings et al. 2011



W Hya: ^{29}SiO peak emission ~ 15 Jy

VX Sgr: mean polarization fraction between 13 % and 56 %

v	$J_u - J_d$	Freq (GHz)	A (s^{-1})	ALMA band
		^{28}SiO		
0	1 - 0	43.42386	3.036×10^{-6}	1
	2 - 1	86.84699	2.915×10^{-5}	2
	1 - 0	43.12208	3.011×10^{-6}	1
	2 - 1	86.24344	2.891×10^{-5}	2
	3 - 2	129.36326	1.045×10^{-4}	4
1	4 - 3	172.48102	2.569×10^{-4}	5
	5 - 4	215.59592	5.131×10^{-4}	6
	6 - 5	258.70725	9.003×10^{-4}	6
	7 - 6	301.81430	1.445×10^{-3}	7
	1 - 0	42.82059	2.986×10^{-6}	1
	2 - 1	85.64046	2.866×10^{-5}	3
	3 - 2	128.45881	1.036×10^{-4}	4
2	4 - 3	171.27507	2.547×10^{-4}	5
	5 - 4	214.08848	5.088×10^{-4}	6
	6 - 5	256.89831	8.927×10^{-4}	6
	7 - 6	299.70386	1.433×10^{-3}	7
	1 - 0	42.51938	2.951×10^{-6}	1
3	3 - 2	127.55521	1.027×10^{-4}	4
	4 - 3	170.07057	2.525×10^{-4}	5
	5 - 4	212.58248	5.044×10^{-4}	6
4	5 - 4	211.07784	4.986×10^{-4}	6

v	$J_u - J_d$	Freq (GHz)	A (s^{-1})	ALMA band
		^{29}SiO		
	1 - 0	42.87992	2.114×10^{-8}	1
	2 - 1	85.75906	2.460×10^{-7}	2
0	3 - 2	128.63685	9.696×10^{-7}	4
	4 - 3	171.51255	2.532×10^{-6}	5
	5 - 4	214.38548	5.334×10^{-6}	6
	6 - 5	257.25493	9.869×10^{-6}	6
	3 - 2	127.74849	3.350×10^{-4}	4
1	4 - 3	170.32807	8.745×10^{-4}	5
	6 - 5	255.47849	3.407×10^{-3}	6
2	6 - 5	253.70317	1.11139	6
		^{30}SiO		
	1 - 0	42.373426	2.016×10^{-8}	1
0	2 - 1	84.746170	2.346×10^{-7}	2
	5 - 4	211.853473	5.081×10^{-6}	6
1	4 - 3	168.323352	8.054×10^{-4}	5
2	4 - 3	167.160563	2.542×10^{-1}	5

For typical *B* strengths in SFR and CSE of late-type stars:

SiO, H_2O and HCN: very high polarized maser emission

Pol. levels up to 13%, 14% and 19% (without considering anisotropic pumping and any other non-Zeeman effect).

	Transition	Freq (GHz)	A (s^{-1})	ALMA band
		H_2O		
	3_{13} - 2_{20}	183.31012	3.629×10^{-6}	5
	10_{29} - 9_{36}	321.22564	6.348×10^{-6}	7
	5_{15} - 4_{22}	325.15292	1.166×10^{-5}	7
	17_{413} - 16_{710}	354.8089	1.096×10^{-5}	7
	7_{53} - 6_{60}	437.34667	2.212×10^{-5}	8
	6_{43} - 5_{50}	439.15081	2.857×10^{-5}	8
	6_{42} - 5_{51}	470.88895	3.534×10^{-5}	8
	4_{40} - 5_{33}	96.26116	4.719×10^{-7}	3
$v_2 = 1$	5_{50} - 6_{43}	232.68670	4.770×10^{-6}	6
	6_{61} - 7_{52}	293.6645	-[a]	6
	1_{10} - 1_{01}	658.00655	5.568×10^{-3}	9

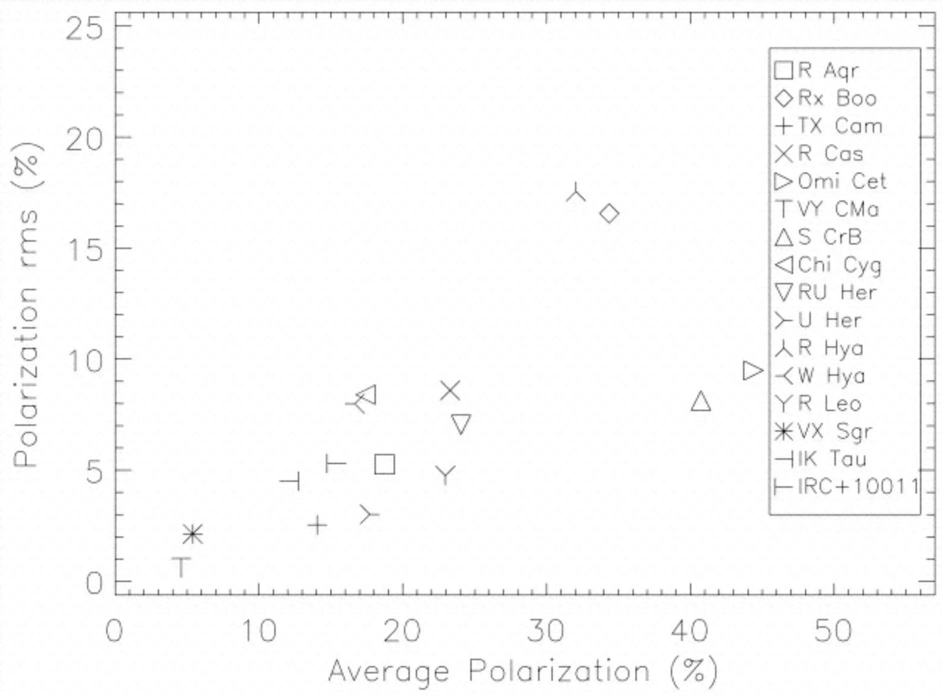
	Transition	Freq (GHz)	A (s^{-1})	ALMA band
		HCN		
	1 - 0	88.631602	$1.771\times10^{-}$[illegible]	2/3
$v_2 = 2^0$	1 - 0	89.0877	1.483×10^{-4}	2/3
	2 - 1	177.2387	4.578×10^{-5}	5
$v_2 = 1^{1c}$	3 - 2	267.1993	2.262×10^{-4}	6
	4 - 3	354.4605	6.122×10^{-4}	7
$v_2 = 4$	9 - 8	804.7509	-[a]	10
$v_1 = 1^1 \rightarrow v_2 = 4^0$	10 - 9	890.761	-[a]	10

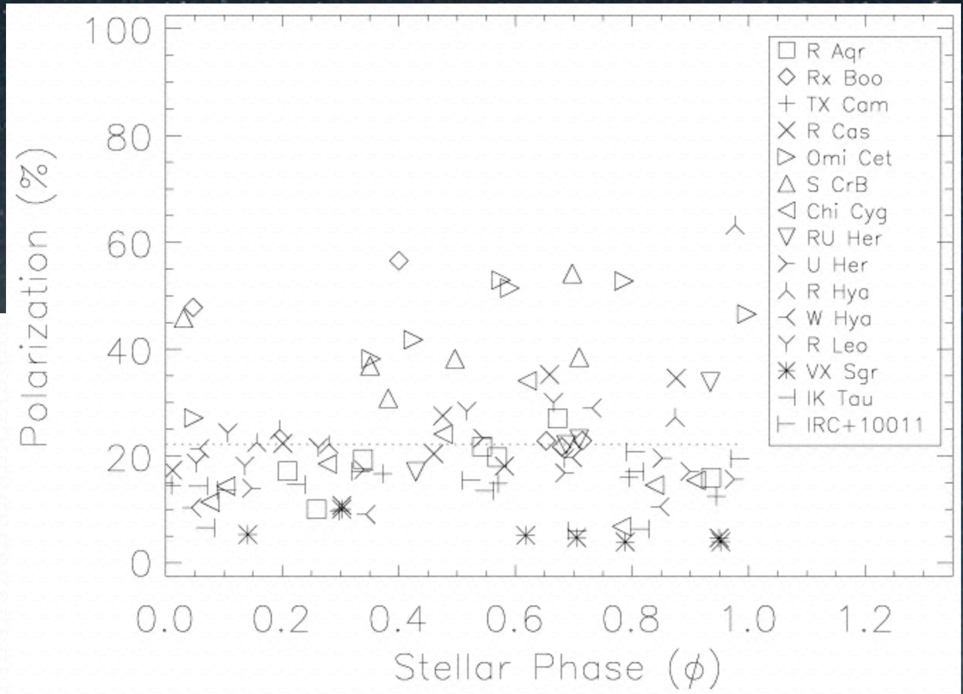
Pérez-Sánchez & Vlemmings, 2013

SiO masers

Glenn et al. 2003:

SiO masers monitoring @ 86 GHz





Monitoring reveals polarization stability over ~ 2.5 years

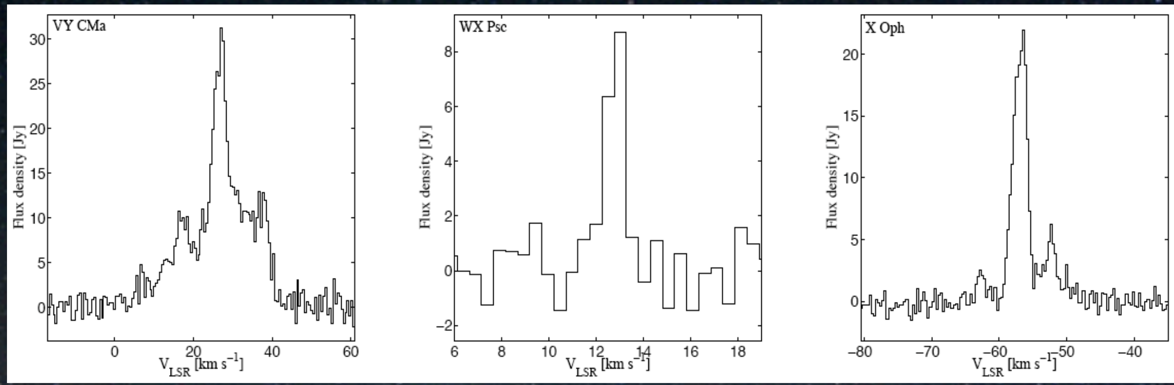
APEX observations

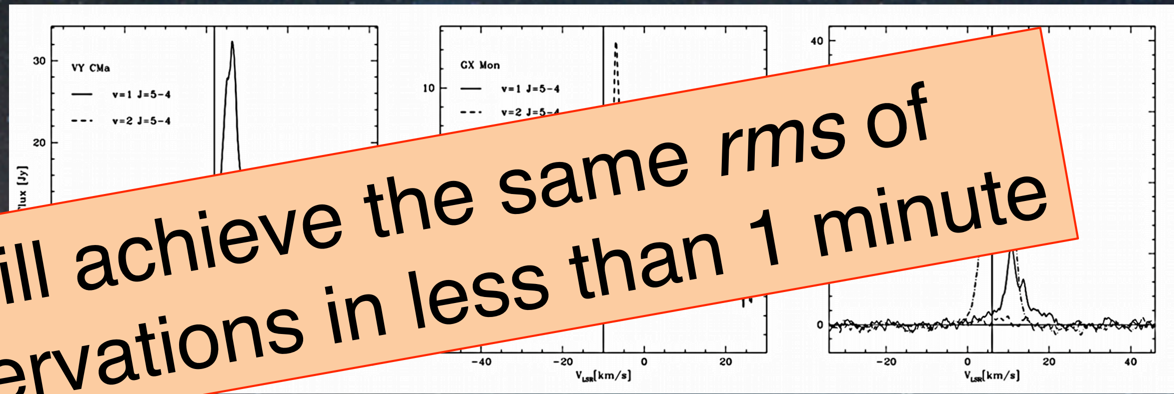
^{28}SiO 5-4 v=1	215.5959 GHz
^{28}SiO 5-4 v=2	214.0885 GHz
^{29}SiO 5-4 v=0	214.3858 GHz

- Multi-epoch observations
  - Mar, Jun, Oct, Dec 2008
  - Apr, Jun 2010
  - Sep 2011
- 36 sources: evolved stars (AGB stars and supergiants)
- 32 detections at least of one transition
- 20% of sources => v=2 stronger than v=1
- Peak fluxes as high as 160 Jy (W Hya)
- Narrow linewidths (< 5 km/s)
- Wide velocity range

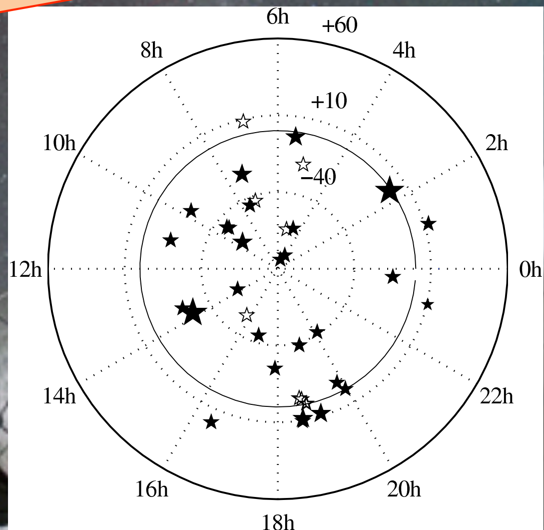
Ramstedt et al. 2012

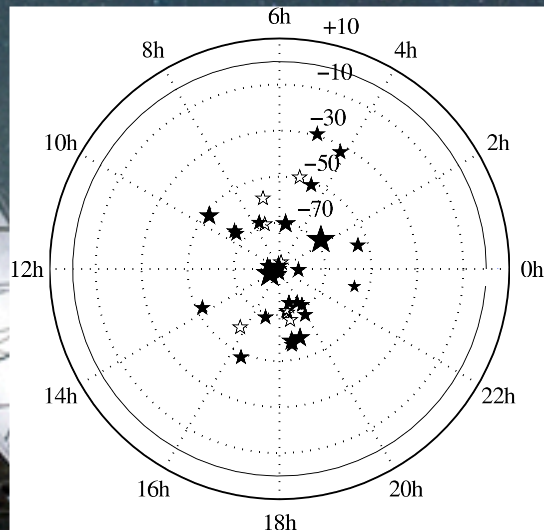
source	v=1	v=2
W Hya	159.4	N
R Crt	2.9	N
R Hya	10.4	N
IRAS 13442-6109	5.8	N
IRAS 18595-3947	8.8	N
V2234 Sgr	3.4	7.4
RS Sco	5.0	N
IRAS 18387-0423	N	N
IRAS 18348-0526	N	11.1
o Ceti	127.0	N
WX Psc	8.7	23.0
R Dor	12.9	N
U Dor	N	N
R Aqr	5.0	3.5
R Peg	1.0	N
VY CMa	31.2	16.2
L2 Pup	N	[illegible]
GX Mon	[illegible]	[illegible]
GY Aql	[illegible]	[illegible]
RR Aql	[illegible]	[illegible]
U Men	[illegible]	[illegible]
SVS01835	[illegible]	[illegible]
T Lep	[illegible]	[illegible]
DU Pup	6.7	N
RW Vel	6.3	N
RS Vel	7.4	3.9
R Car	64.0	N
IW Hya	5.5	4.5
R Aql	21.7	N
S Ori	50.0	1.2
IRSV 1540	N	4.9
U Her	3.6	N
OH 2.6-0.4	7.4	N
V1111 Oph	2.3	0.8
X Oph	21.1	11.0
OH 31.0+0.0	N	N





ALMA will achieve the same *rms* of APEX observations in less than 1 minute





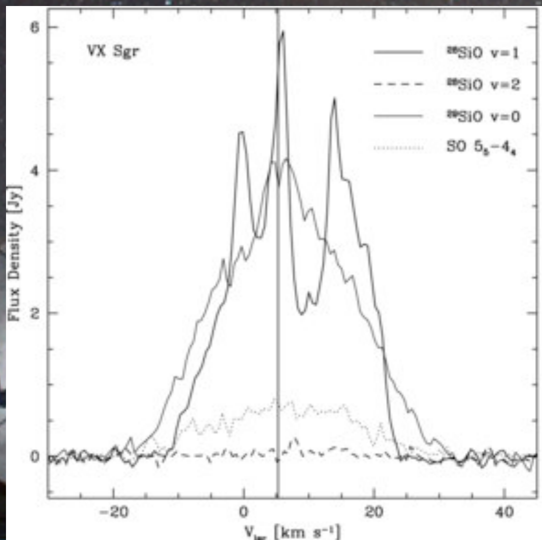
SMA observations

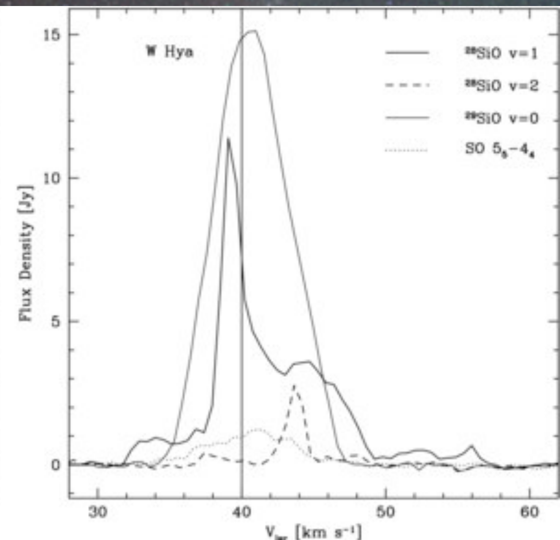
- 14 evolved stars (AGB and supergiants)
- Extended configuration polarization observations
- 2 full tracks, spectral resolution ~ 0.56 km/s
- Spatial resolution ~ 1.2 arcseconds, possibly super-resolving the strongest cases
- 2 sidebands with a 4 GHz bandwidth each
- All SiO maser lines + SO and SiO thermal
- Continuum

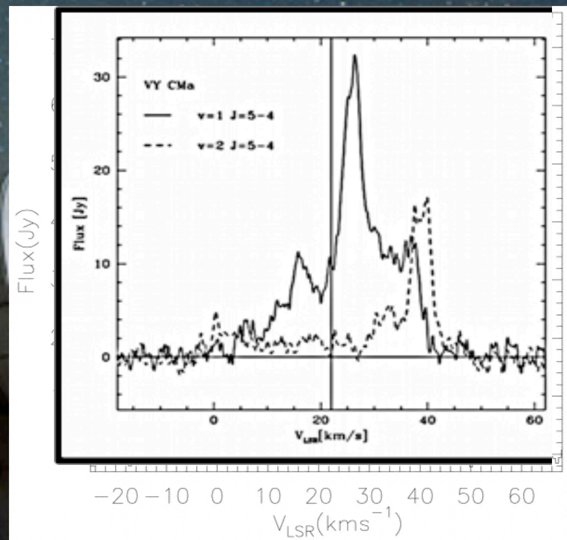
Source	RA	Dec	F_{APEX} (Jy) (SiO 5-4, v=1)	Polarized Flux[3] (Jy)	*rms* (5σ detection) (Jy/beam)	on-source time
O Ceti[1]	02:19:20.79	-02:58:39.5	127	13	2.5	> 0.5 hours
S Ori[1]	05:29:00.89	-04:41:32.8	50	5	1.0	> 0.5 hours
WX Psc[1]	01:06:25.98	+12:35:53.0	8.7	0.87	0.17	0.7 hours
GX Mon[1]	06:52:47.02	+08:25:19.20	12.4[5]	1.2	0.25	> 0.5 hours
VY Cma[1]	07:22:58.30	-25:46:03.20	31.2	3.1	0.62	> 0.5 hours
R Leo[1,4]	09:47:33.49	+11:25:43.67	190	19	3.8	> 0.5 hours
S Per[1,4]	02:22:51.71	+58:35:11.45	8	0.8	0.16	1.5 hours
W Hya[2]	13:49:02.00	-28:22:03.49	159	16	3.2	> 0.5 hours
R Aql[2]	19:06:22.25	+08:13:48.0	21.7	2.2	0.43	> 0.5 hours
X Oph[2]	18:38:21.12	+08:50:02.7	21.1	2.1	0.42	> 0.5 hours
OH 2.6-0.4[2]	17:53:18.60	-26:56:36.0	7.4	0.74	0.15	1.3 hours
R Hya[2]	13:29:42.78	-23:16:52.78	10.4	1.0	0.21	0.6 hours
VX Sgr[2]	18:08:04.05	-22:13:26.63	6	0.6	0.12	1.9 hours
RR Aql[2,4]	19:57:36.06	-01:53:11.34	18	1.8	0.36	> 0.5 hours

SMA observations

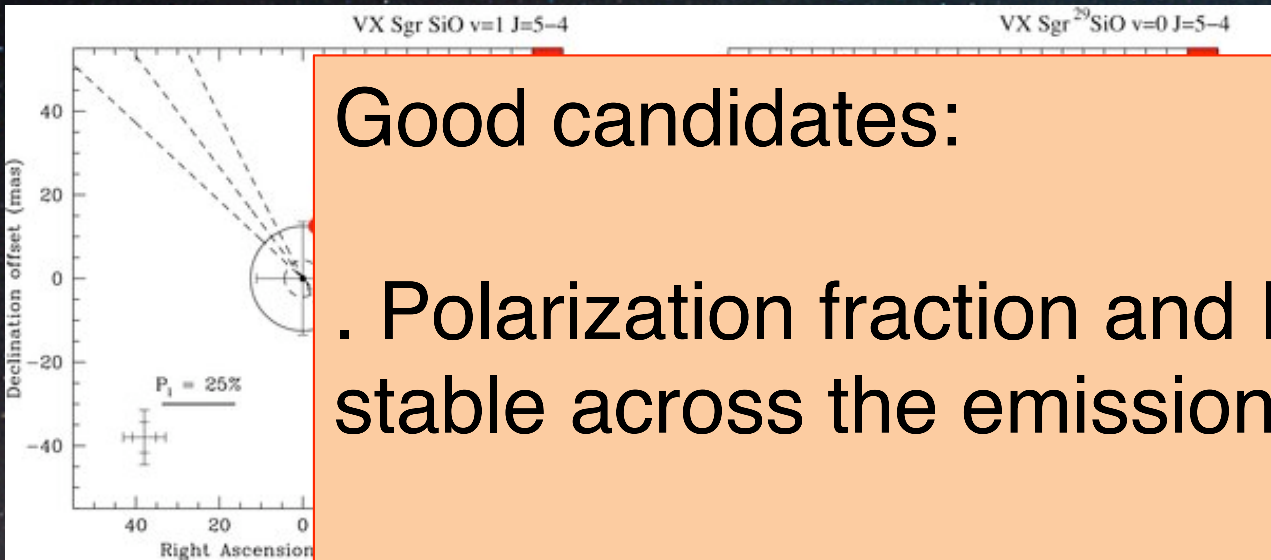
- Check for polarization stability
  - VX Sgr (2008 ext.: Vlemmings et al. 2011)
  - W Hya (2008 ext.: Vlemmings et al. 2011)
  - VY CMa (2002 comp: Shinnaga et al. 2004)

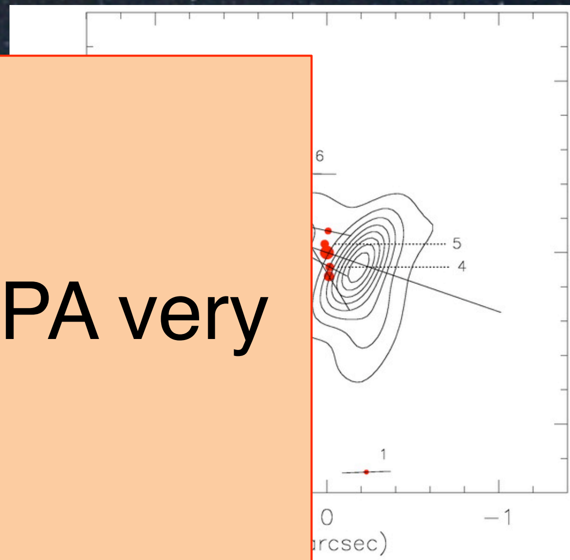






SMA observations





Good candidates:

. Polarization fraction and EVPA very stable across the emission

. Not much variability

V_{lsr} (km s^{-1})	$\Delta\alpha$[a] (mas)	$\Delta\delta$[a] (mas)				
		$v = 1, {}^{28}$SiO masers				
−8.0	−44.7 ± 13.6	−26.1 ± 17.5	$0.50^{+0.06}_{-0.13}$	$0.28^{+0.20}_{-0.08}$	18^{+27}_{-9}	56
−5.2	−22.2 ± 9.3	10.7 ± 12.1	$0.94^{+0.09}_{-0.18}$	$0.54^{+0.29}_{-0.11}$	25^{+9}_{-8}	57
−2.3	−24.3 ± 5.5	6.5 ± 7.3	$2.14^{+0.03}_{-0.12}$	$0.71^{+0.21}_{-0.12}$	21^{+7}_{-3}	33
−1.8	−14.4 ± 4.5	7.1 ± 5.8	$3.20^{+0.14}_{-0.14}$	$0.80^{+0.10}_{-0.16}$	31^{+9}_{-4}	25
−1.2	−18.3 ± 3.8	8 ± 4.8	$4.11^{+0.07}_{-0.07}$	$1.06^{+0.10}_{-0.10}$	33^{+4}_{-3}	26
−0.6	−31.2 ± 3.6	10.7 ± 4.7	$4.29^{+0.05}_{-0.11}$	$1.23^{+0.18}_{-0.14}$	34^{+5}_{-3}	29
−0.1	−20.1 ± 3.9	0.3 ± 5.2	$3.76^{+0.13}_{-0.06}$	$1.16^{+0.18}_{-0.13}$	33^{+5}_{-3}	31
0.5	−13.5 ± 4.5	7.4 ± 6.0	$3.17^{+0.08}_{-0.08}$	$0.86^{+0.10}_{-0.10}$	35^{+7}_{-6}	27
1.1	−16.2 ± 5.1	20.3 ± 6.5	$2.85^{+0.08}_{-0.08}$	$0.62^{+0.15}_{-0.10}$	40^{+13}_{-6}	22
1.6	−18.3 ± 5.5	22.4 ± 7.0	$2.73^{+0.04}_{-0.08}$	$0.34^{+0.12}_{-0.07}$	37^{+20}_{-10}	13

Number	Velocity[a] (km s^{-1})	Range (km s^{-1})	Peak Intensity (Jy)	*X* Offset[c] (arcsec)	*Y* Offset[c] (arcsec)	P.A. (deg)	Degree of Linear Polarization (%)
1	42.1	41.6–42.7	7.4	−0.23 ± 0.30	−1.28 ± 0.50	92 ± 30	63 ± 31
2	35.9	33.1–37.6	63.9	0.00	0.00	71 ± 5	56 ± 4
3	26.9	25.2–30.3	33.6	−0.01 ± 0.06	−0.14 ± 0.09	31 ± 24	23 ± 6
4	24.1	22.4–24.1	23.7	−0.02 ± 0.09	−0.08 ± 0.13	62 ± 21	16 ± 4
5	16.1	13.9–17.3	23.0	0.01 ± 0.10	0.05 ± 0.15	...	<10
6	12.2	11.1–13.3	20.2	0.14 ± 0.07	0.46 ± 0.10	89 ± 12	32 ± 6
7	0.9	−0.3–2.0	15.9	−0.01 ± 0.15	0.13 ± 0.21	78 ± 60	29 ± 25

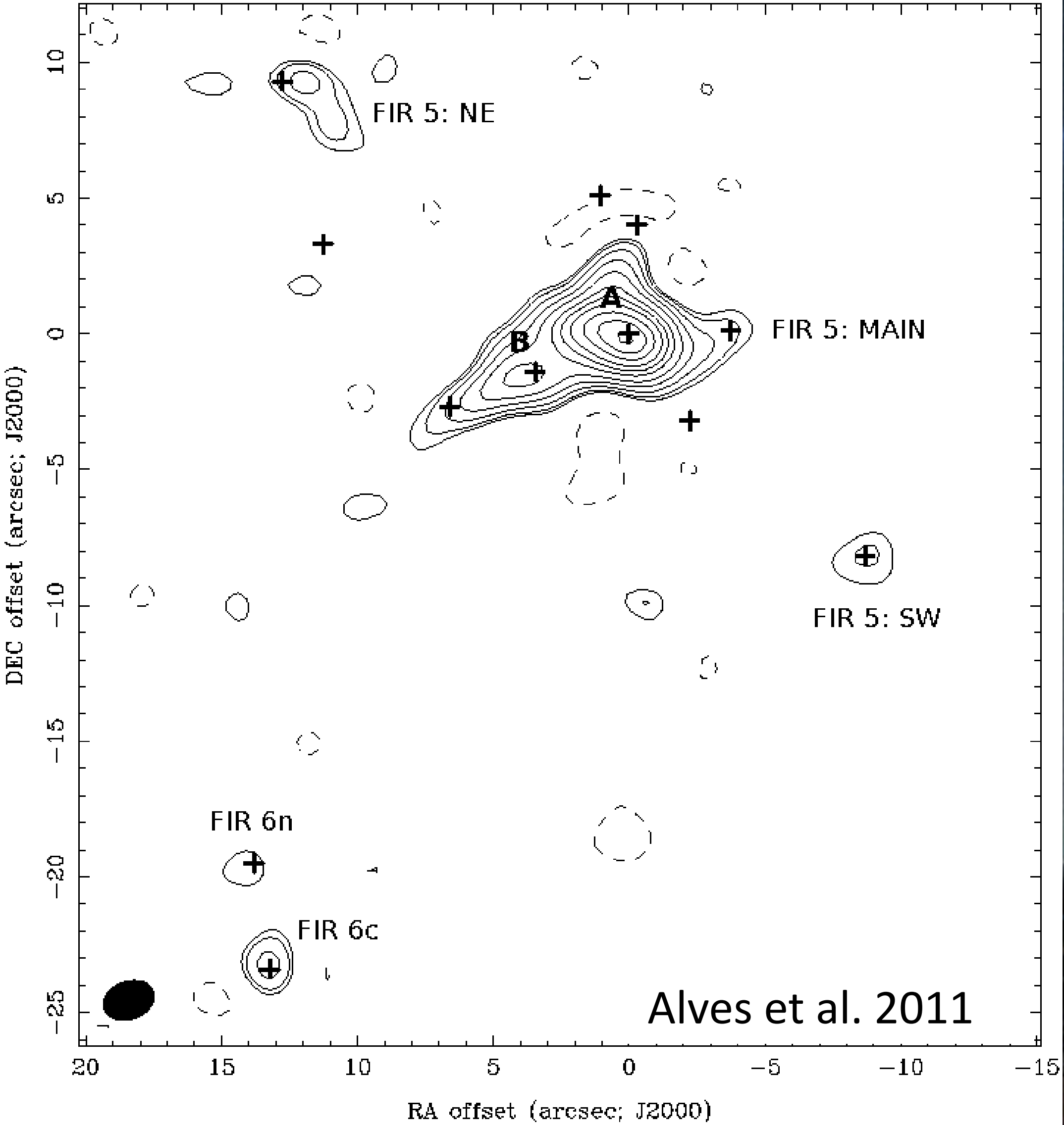
Future work

- Observe SiO masers in other bands (86 GHz)
- ALMA Polarization CSV and calibrators catalogue
- Implementing realistic source structure models in the available simulators
- Polarization analysis tools: angle dispersion, dynamic parameters such as B-field energies and mass-to-flux ratio (to the suite of ALMA data analysis tools)
- Advanced polarization observation interpretation

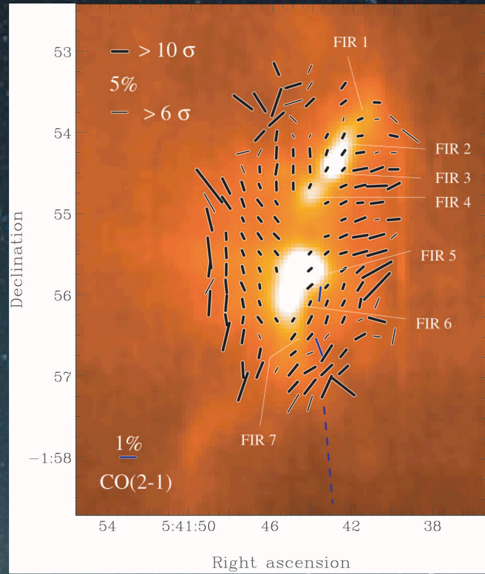
Science

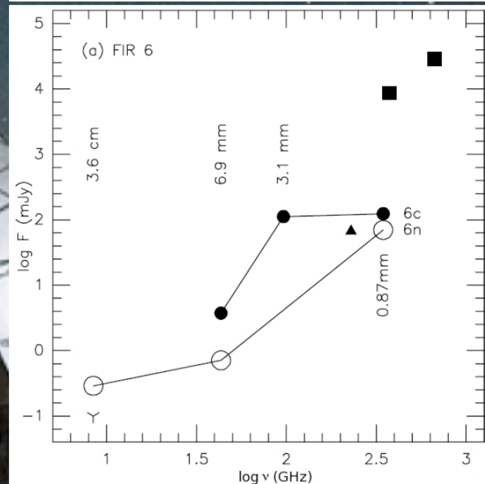
- Dust continuum polarization (Cycle 2) + Zeeman + Goldreich-Kylafis effect (future) toward
  - Protostellar cores with hourglass *B*-field morphology
    - Compare with SMA polarization maps (commissioning)
    - Resolve *B*-fields at circumstellar disk
    - Compare core B-field with filaments
  - Pipe nebula: B59, Core 109
  - NGC 2024 FIR 5 (compare dust polarized emission with SMA data and resolve outflow powering sources)

NGC 2024 FIR 5



Alves et al. 2011





Matthews et al. 2002

Choi et al. 2012

NGC 2024 FIR 5

-Depolarization

-Field morphology at disk scales

-Evolutionary stage of each component

-Complex outflow emission traced by CO