INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

OAC Osservatorio Astronomico di Cagliari

6.7 GHz CH_3OH maser polarization in massive star-forming regions: the Flux-Limited Sample

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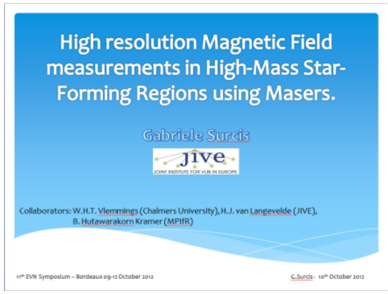
Surcis et al. 2022, A&A, 658, A78

The Neverending Story

"Without a past you can't have a future." – Michael Ende

- ***11th EVN symposium – Bordeaux (France) 2012***

  Surcis et al. 2012, A&A, 541, A47
  Surcis et al. 2013, A&A, 556, A73

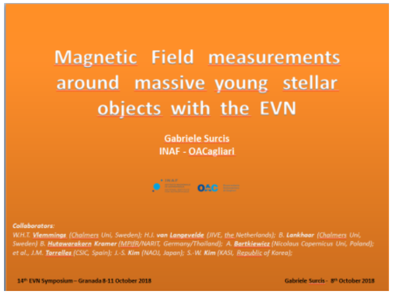


- ***12th EVN symposium – Cagliari (Italy) 2014***

  Surcis et al. 2015, A&A, 578, A102

- ***14th EVN symposium – Granada (Spain) 2018***

  Surcis et al. 2019, A&A, 623, A130



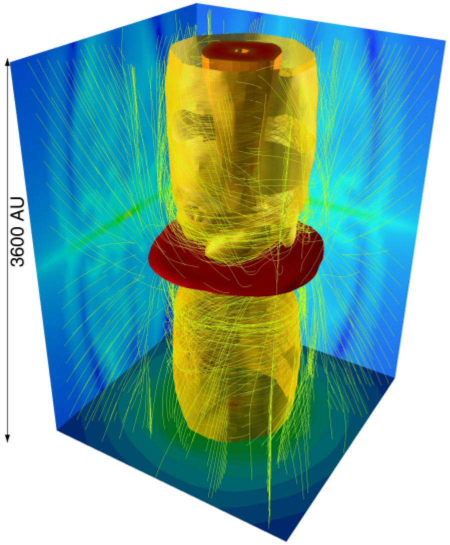
Outline

"What I've started I must finish. I've gone too far to turn back. Regardless of what may happen, I have to go forward." - Michael Ende

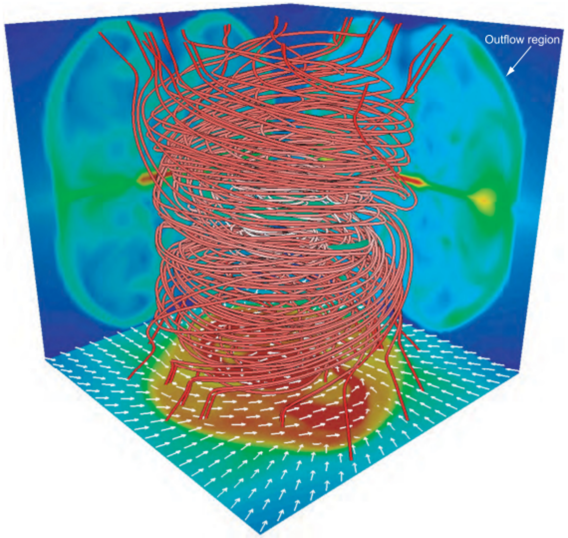
- Background: magnetic field and outflows in massive YSOs
- The Flux-Limited Sample
- Results:
  - Statistical analysis
  - Polarimetric characteristics of the 6.7 GHz CH_3OH masers
- Conclusions

Background

MHD simulations showed that the magnetic field plays a crucial role in the launching of molecular outflows during the formation of massive Young Stellar Objects (YSOs)



Matsushida et al. 2018, MNRAS, 475, 391



Machida & Hosokawa 2020, MNRAS, 499, 4490

Background

Seifried et al. 2012, MNRAS, 422, 347

strong initial magnetic field intensities (μ=5)

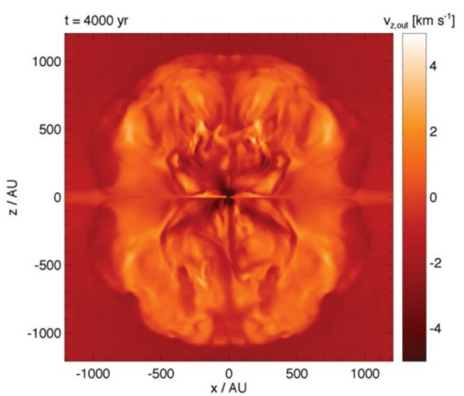
↓

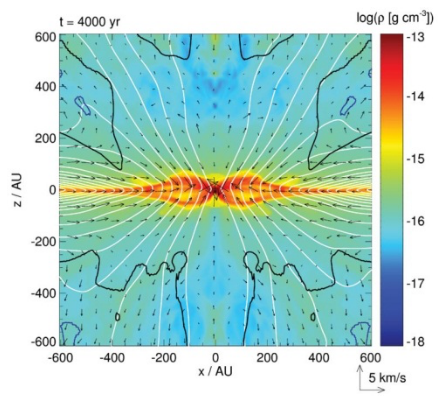
slow & poorly collimated outflows

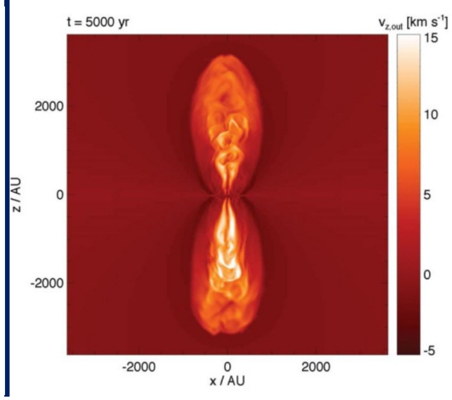
low initial magnetic field intensities (μ=20-120)

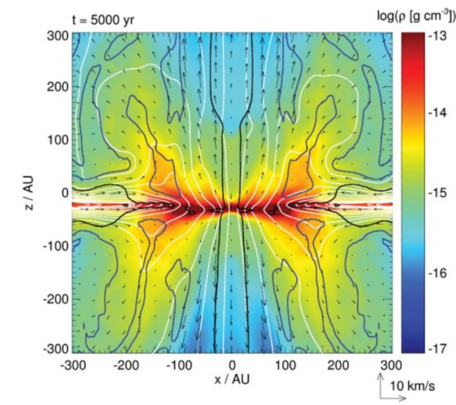
↓

fast & collimated outflows







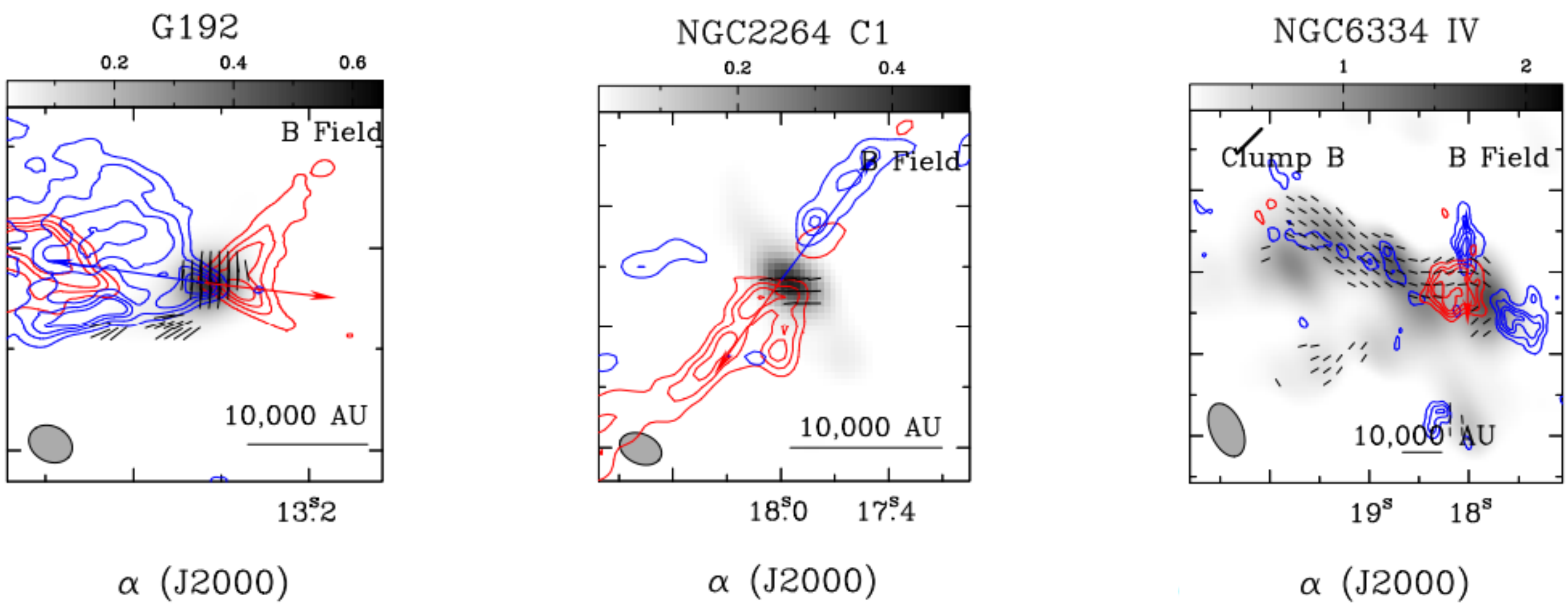


Magnetic field vs outflow orientation

Polarimetric observations of dust (*arcsec resolution*)

Zhang et al. 2014, ApJ, 792, 116

Some example (SMA; ~2'')



Background

Magnetic field vs outflow orientation

Polarimetric observations of dust (*arcsec resolution*)

Zhang et al. 2014, ApJ, 792, 116

Statistical analysis:

- based on 21 sources (SMA; ~2'')
- Slight preference at 0° and 90°
- Small sample ⟶ random distribution

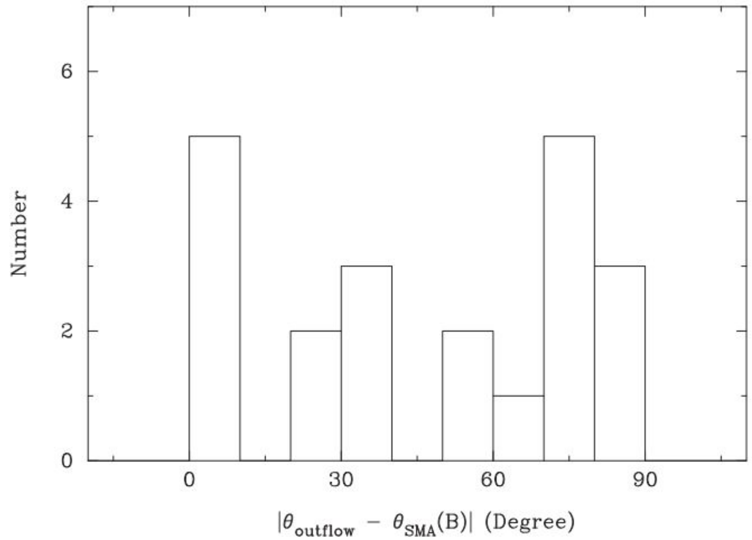


Figure 4. Difference between the position angle of the outflow axis and magnetic fields in the core where outflows originate. When the angle difference is 0°, the major axis of the outflow is aligned with the core magnetic field.

Background

Magnetic field vs outflow orientation

Polarimetric observations of **masers** (milliarcsec *resolution*)

Surcis et al. 2015, A&A, 578, A102

Surcis et al. 2019, A&A, 623, A130

From my talk at the 14th EVN Symposium (Granada, 2018)

Preliminary results:

Magnetic field is preferably oriented along the large scale molecular outflows

"A story can be new and yet tell about olden times. The past comes into existence with the story." - Michael Ende

The Flux-Limited sample

Pestalozzi et al (2005): catalogue of 6.7 GHz CH_3OH masers

Massive star-forming regions with

Declination > -9°

$\text{Flux}_{\text{single-dish}}$ > 50 Jy

in 2011: $\text{Flux}_{\text{single-dish}}$ > 20 Jy

31

Observations

1 source (Cepheus A) was observed with the MERLIN in 2006

+

11 sources were observed with the EVN from 2008 to 2011

19 sources left

31

Observations

Large EVN project (2012)

These sources were observed with the EVN between 2012 and 2015

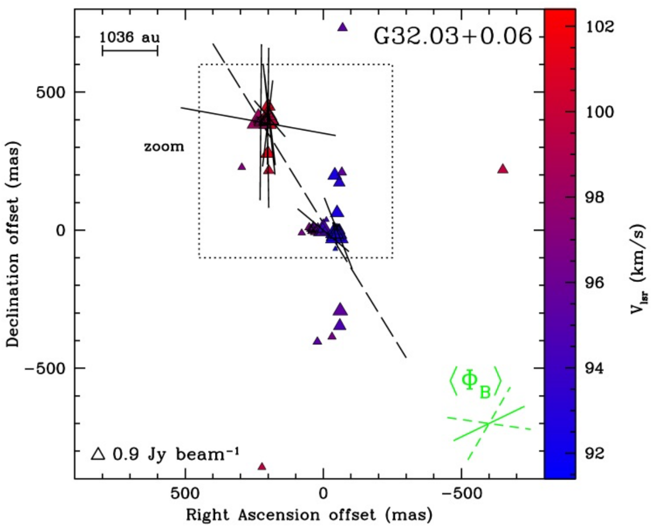
19 sources left

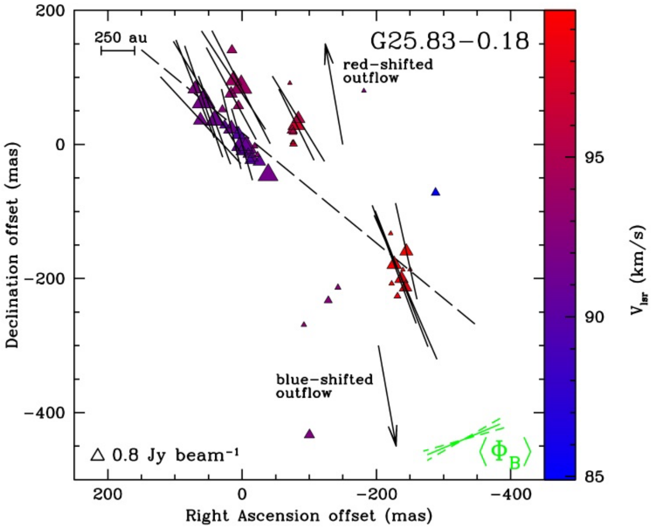
Total observing time	= 133 hours
Frequency band	= M (6.7 GHz)
Bandwidth	= 2 MHz (100 km/s)
Spectral resolution	= ~0.05 km/s
Polarization products	= RR, LL, RL, LR

Results

We detected
linearly polarized CH_3OH maser emission toward
30 massive young stellar objects

Some examples:

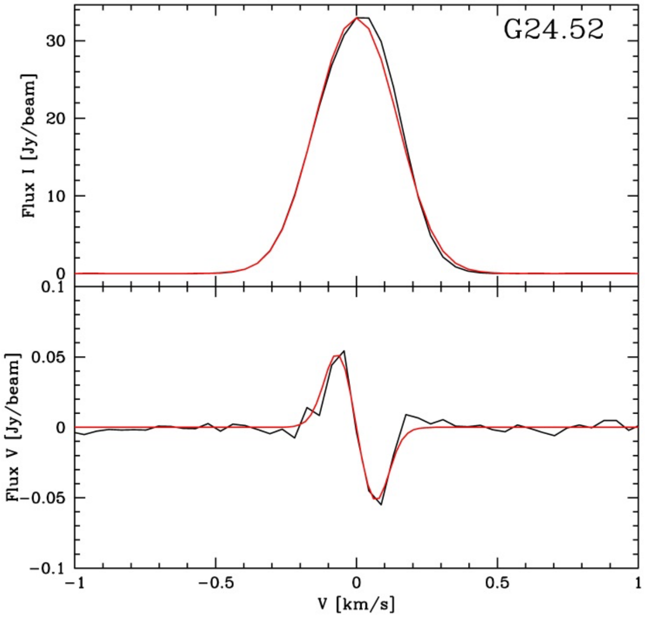


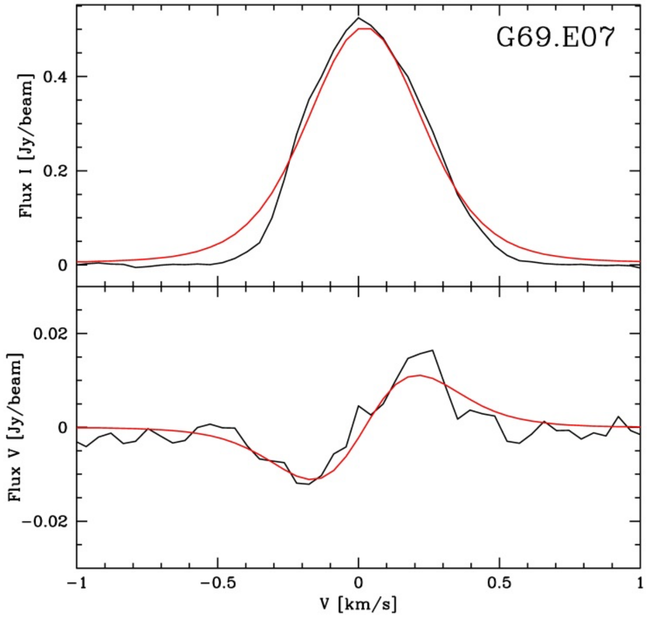


Results

We detected
circularly polarized CH_3OH maser emission toward
14 massive young stellar objects

Some examples:





Statistical analysis

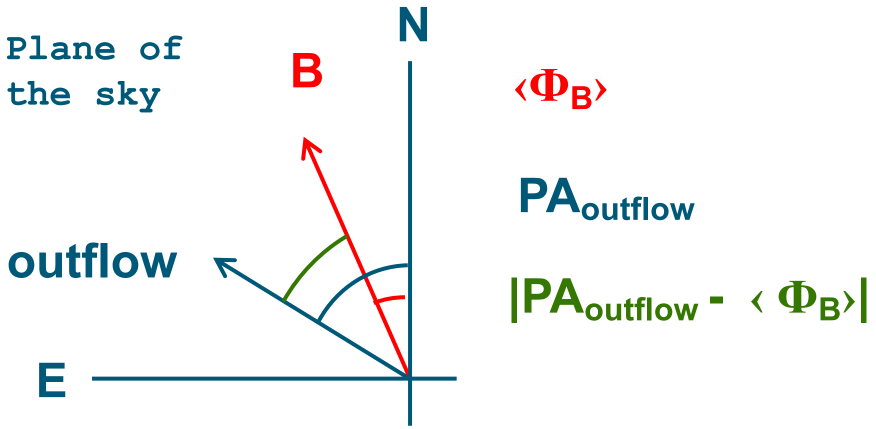
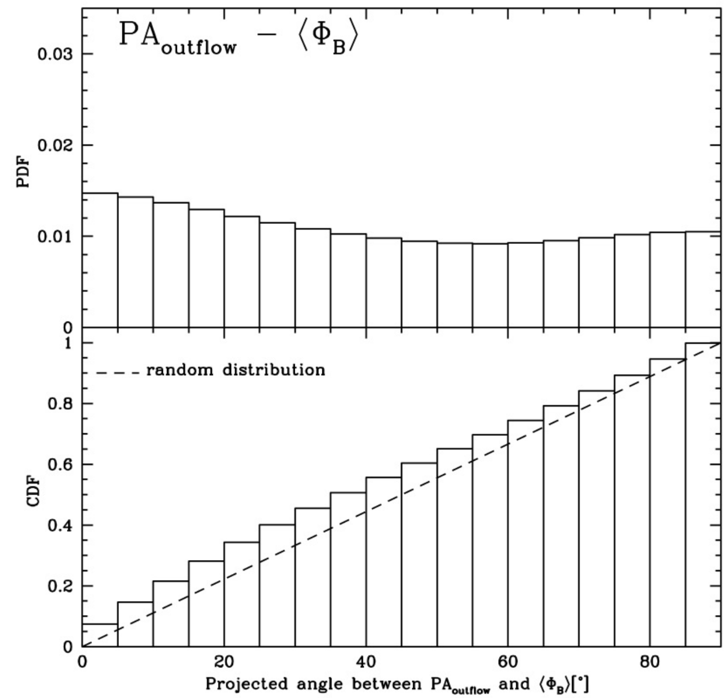


Table 3. Results of the Kolmogorov-Smirnov test.

(1) Angle	(2) $N^{(a)}$	(3) $D^{(b)}$	(4) $\lambda^{(c)}$	(5) $Q_{\mathrm{K-S}}(\lambda)^{(d)}$
$\lvert \mathrm{PA_{outflow}} - \langle \Phi_{\mathrm{B}} \rangle \rvert$	27	0.28	1.50	0.02
$\lvert \mathrm{PA_{CH_3OH}} - \mathrm{PA_{outflow}} \rvert$	29	0.20	1.01	0.18
$\lvert \mathrm{PA_{CH_3OH}} - \langle \chi \rangle \rvert$	40	0.10	0.66	0.77

Notes. [a] N is the number of elements considered in the K–S test. [b] D is the maximum value of the absolute difference between the data set, composed of N elements, and the random distribution. [c] λ is a parameter given by $\lambda = (\sqrt{N} + 0.12 + 0.11/\sqrt{N}) \times D$. [d] $Q_{\mathrm{K--S}}(\lambda) = 2\sum_{j=1}^{N}(-1)^{j-1}\, e^{-2j^2\lambda^2}$ is the significance level of the K–S test.



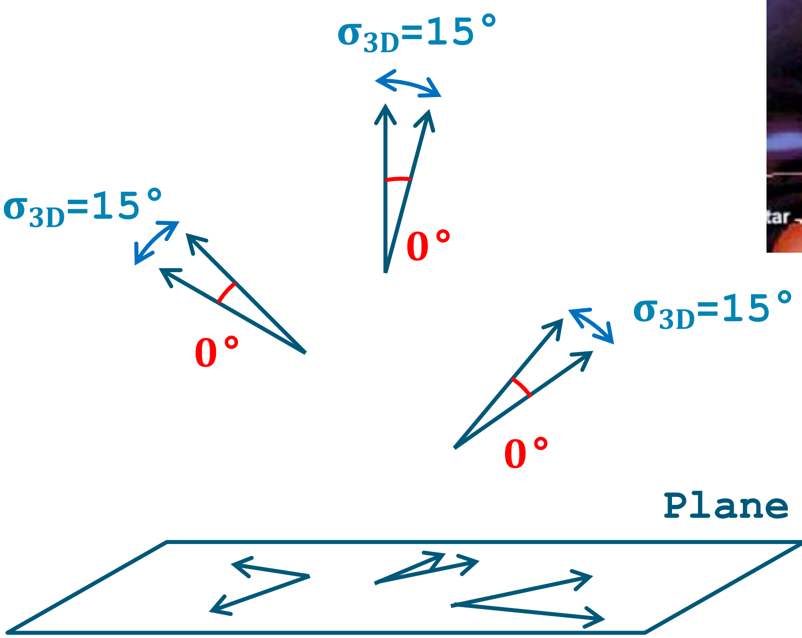
Probability of 2% that the distribution of these angles is drawn from a random distribution

Statistical analysis

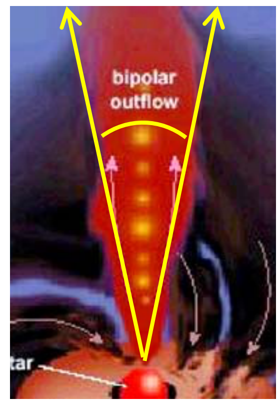
Monte-Carlo simulations

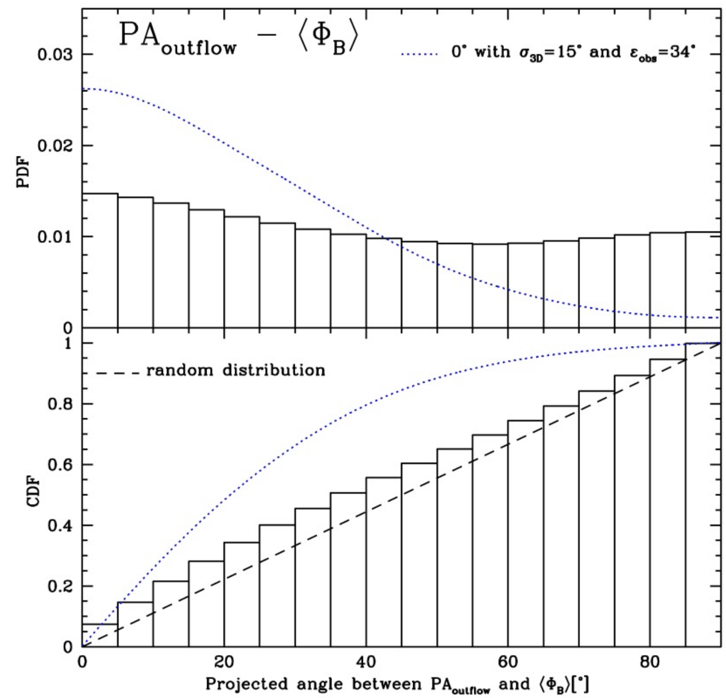
B parallel to outflows

3D space vectors



30°



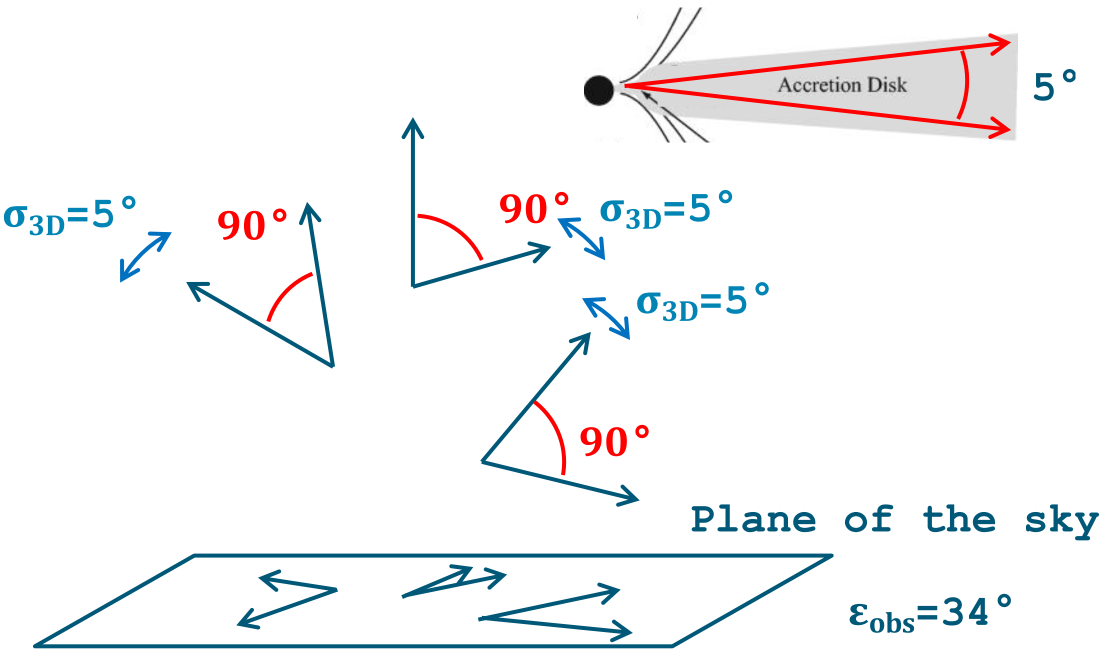


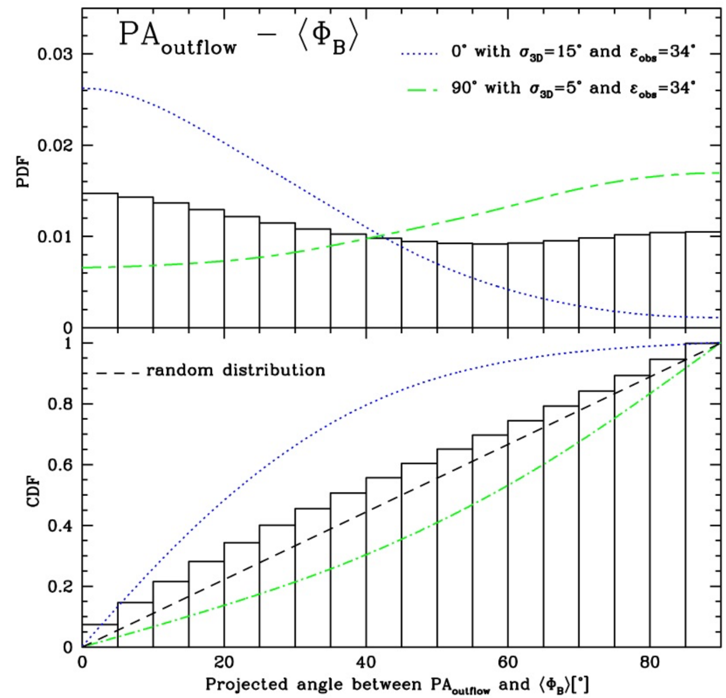
Statistical analysis

Monte-Carlo simulations

B perpendicular to outflows

3D space vectors

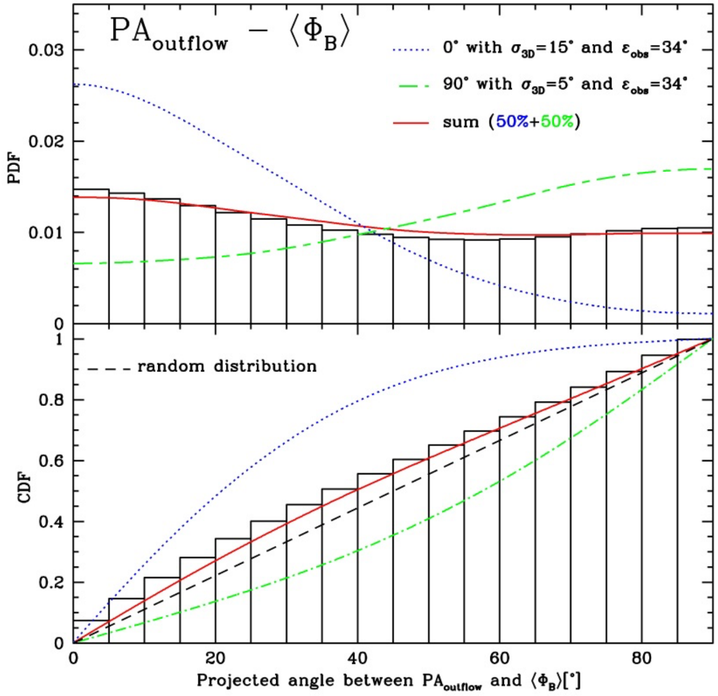




Statistical analysis

Monte-Carlo simulations

50% have B parallel to outflows
+
50% have B perpendicular to outflows



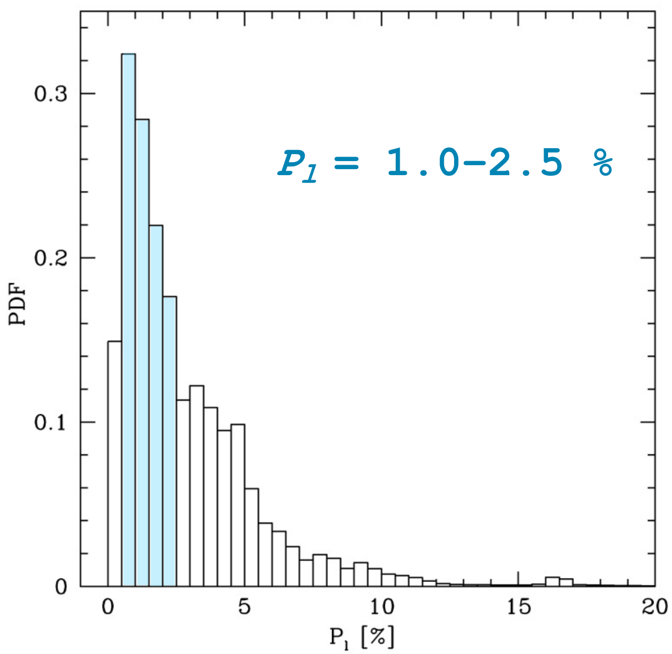
Bimodal distribution might be due to the different evolutionary stages of the YSOs or to where the 6.7 GHz CH_3OH masers arise.

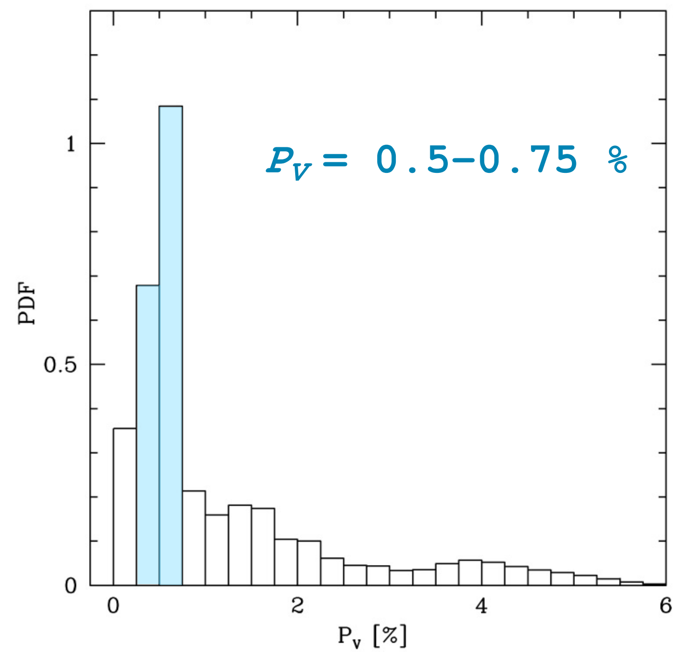
"There are many kinds of delusion." – Michael Ende

Polarimetric characteristics of CH_3OH masers

Toward the 31 sources of the Flux-Limited sample we measured

- **Linear polarization fraction (P_l) in 233 6.7-GHz CH_3OH maser features**
- **Circular polarization fraction (P_V) in 33 6.7-GHz CH_3OH maser features**

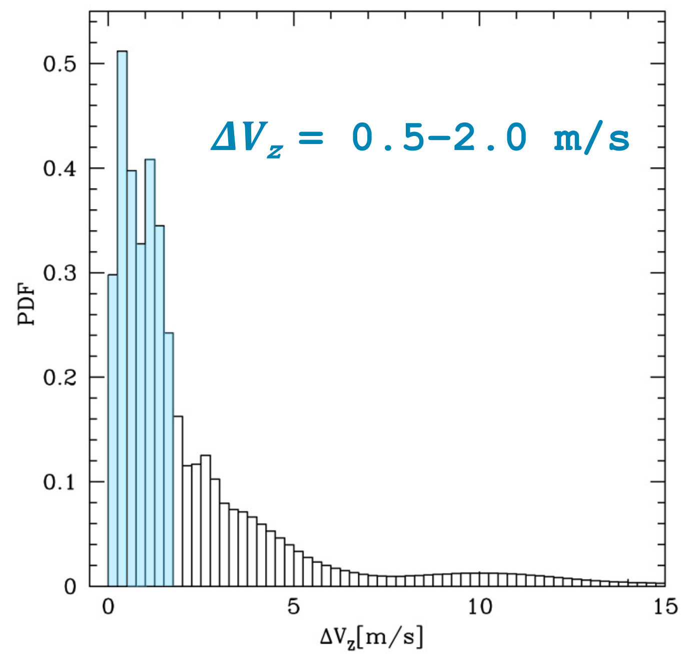




Polarimetric characteristics of CH_3OH masers

Toward the 31 sources of the Flux-Limited sample we measured

- Zeeman splitting of the maser line (ΔV_Z)
  Circular polarization fraction (P_V) (in 33 6.7-GHz CH_3OH maser features



if F = 3 ⟶ 4

9 mG < |B//| < 40 mG

Conclusions

We observed and analysed the linearly and circularly polarized emission of 6.7-GHz CH_3OH masers toward a sample of 31 massive YSOs.

- The statistical analysis revealed a bimodal distribution of the 3D angles $|PA_{outflow} - \langle \Phi_B \rangle|$, where the magnetic field is in the 50% of sources parallel to the outflows and in the other 50% perpendicular.

- We determined that typical linear polarization fraction of 6.7-GHz CH_3OH maser is P_l = 1.0 - 2.5%

- We determined that typical circular polarization fraction of 6.7-GHz CH_3OH maser is P_V = 0.5 - 0.75%

- We determined that a typical Zeeman splitting for 6.7-GHz CH_3OH maser is in the range 0.5 m/s and 2.0 m/s.

Surcis et al. 2022, A&A, 658, A78

22 GHz Water Masers

W75N: 6 years monitoring

Monitoring Project (total = 48 hours)

4 epochs separated by 2 years
@K-band in full polarization mode

Epoch 1: 17th June 2014 — ***analysed***

Epoch 2: 12th June 2016 — ***analysed***

Epoch 3: 10th June 2018 — ***analysed***

Epoch 4: 25th October 2020 — ***analysed***

Surcis et al. 2023, A&A, in prep. (first draft at 80%)

"But that is another story and shall be told another time."
- Michael Ende

THANK YOU

"If you stop to think about it, you'll have to admit that all the *papers* in the world consist essentially of twenty-six letters. The letters are always the same, only the arrangement varies. From letters words are formed, from words sentences, from sentences *sections*, and from *sections papers*."

- Michael Ende

Extra 1

Magnetic field vs outflow in low-mass protostars

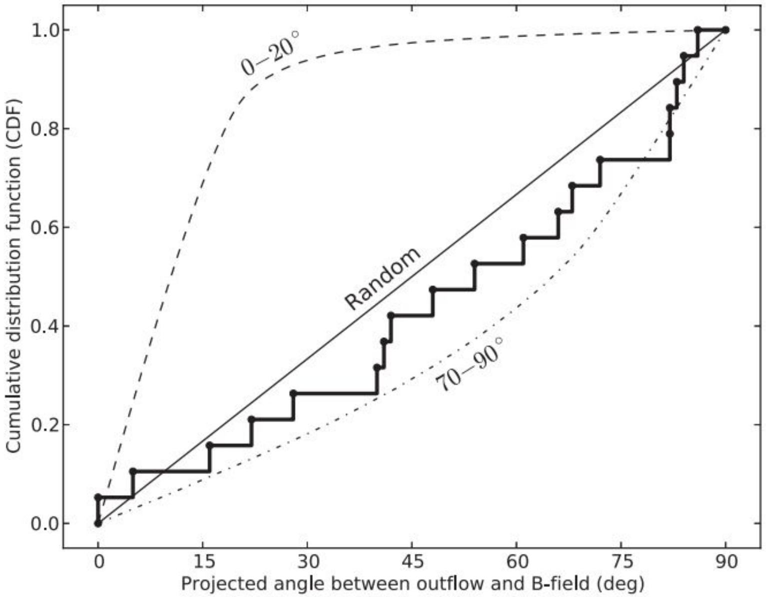


Figure 2. Thick solid curve shows the cumulative distribution function (CDF) of the (projected) angles between the mean magnetic field and outflow directions for the sources in Table 1. The upper dashed curve is the CDF from a Monte Carlo simulation where outflow and *B*-field directions are oriented within 20° of one another (tightly aligned). The lower dot-dashed curve is the CDF from a simulation where outflow and *B*-field directions are separated by 70°–90° (preferentially misaligned). The straight line is the CDF for random orientation.

Hull et al. 2013, ApJ, 768, 159

Hull et al. 2013

based on 17 sources (CARMA obs; 2′′.5)

K-S -> 0°-20° = 0.0000003 %

-> 70°-90° = 79 %

-> random = 64 %

no alignment between outflows and *B*

Chapman et al. 2013

based on 7 sources (SHARC-II obs; 10′′)

alignment between outflows and *B* at a confidence level of ~97%

Extra 2a

Full radiative transfer method (FRTM)

Nedoluha & Watson 1992, ApJ, 384,185

- Intrinsic thermal linewidth (ΔV_i)
- Emerging brightness temperature ($T_b\Delta\Omega$)
  - Unsaturated masers

    Stimulated emission rate(R)<< Decay rate(Γ)

    maser grows exponentially

FRTM code

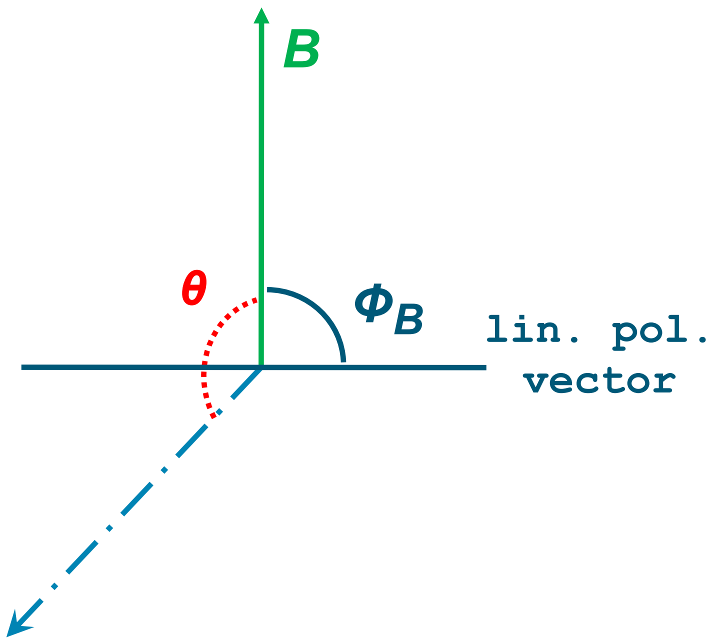
observed spectra

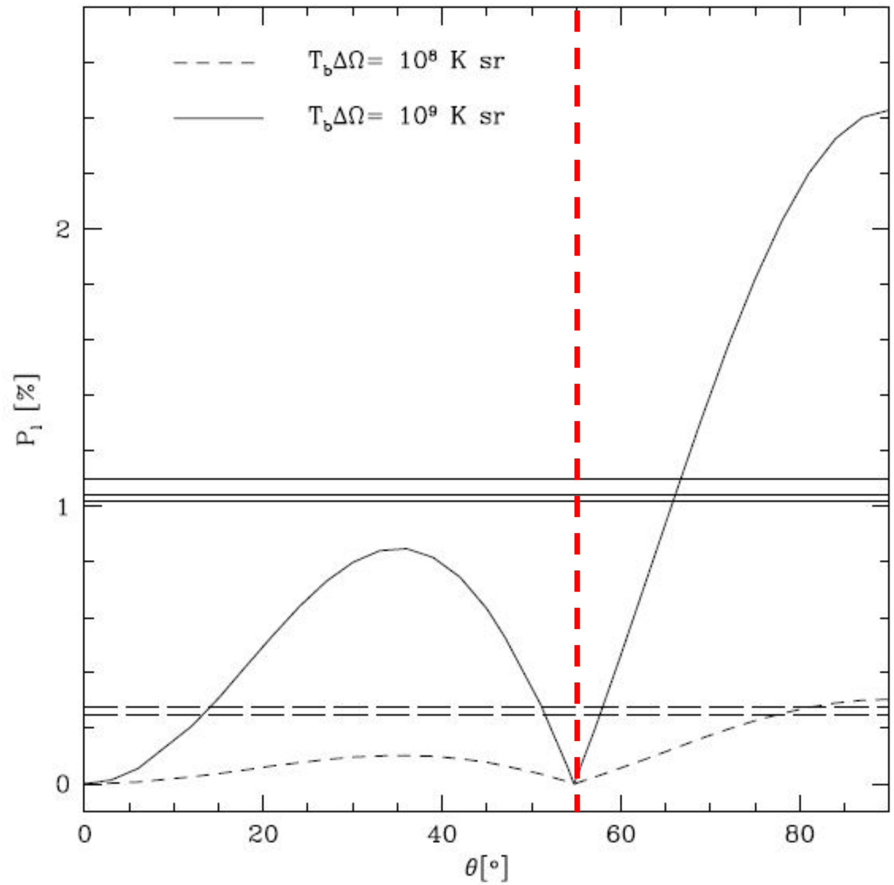
Total intensity → $T_b\Delta\Omega$ + P_l → θ

Linearly polarized intensity → ΔV_i

Vlemmings, W.H.T. et al. 2006, A&A, 448, 597

Extra 2b





Goldreich, P et al. 1973, ApJ, 179, 111

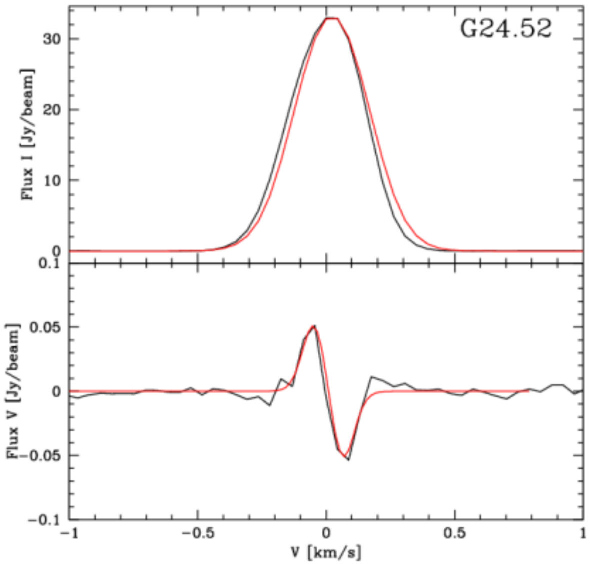
$\Phi_B = 0°$ $\Phi_B = 90°$

Extra 2c

Zeeman splitting & Magnetic field strength

FRTM code + $T_b \Delta\Omega$ + ΔV_i

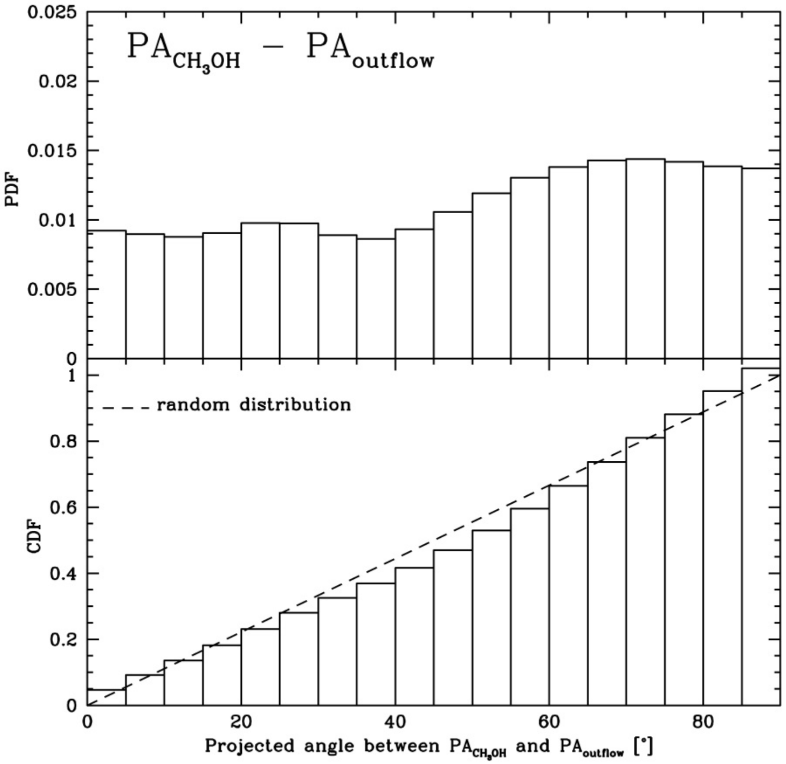
$B \cdot \cos\theta = B_{||}$

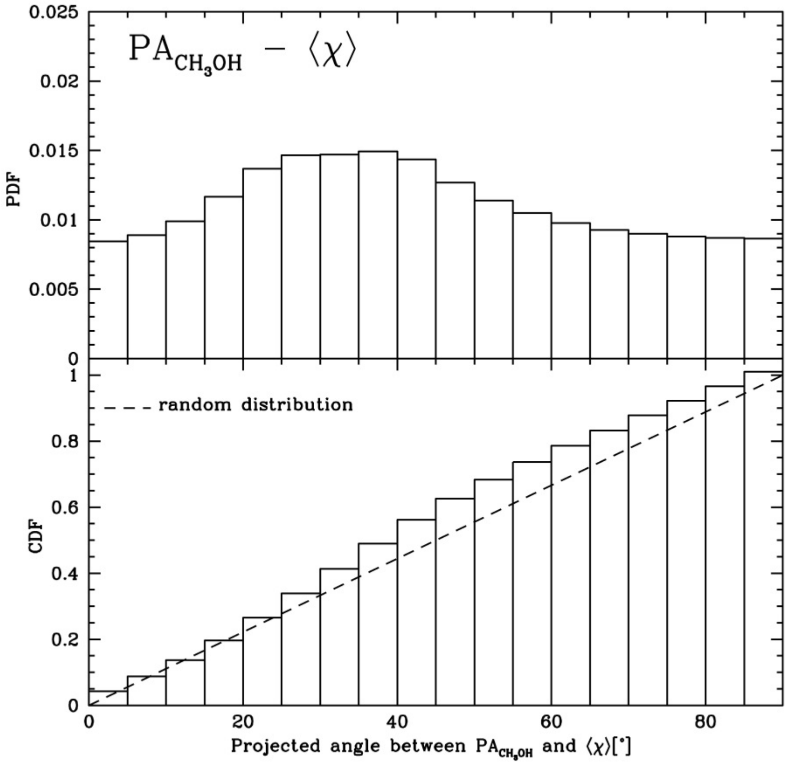


For the g-factors of methanol maser trantisions see:

Lankhaar, B. et al. 2018, Nature Astronomy, 2, 145

Extra 3





Surcis et al. 2022, A&A, 658, A78

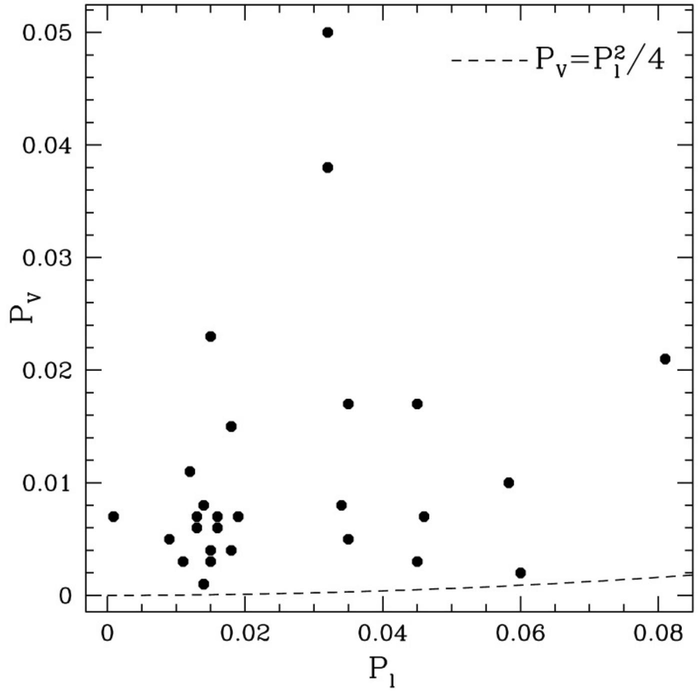
Extra 4

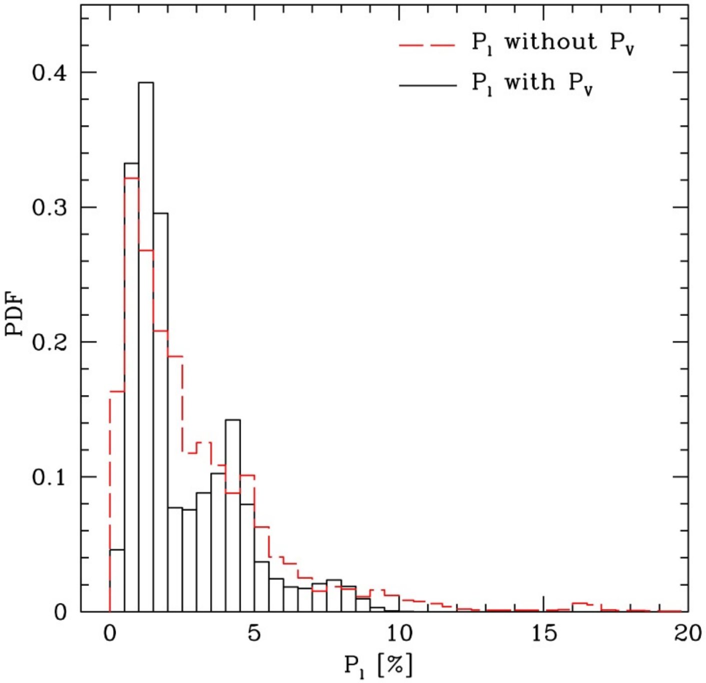
Non Zeeman-effects

Wiebe & Watson 1998, ApJ, 503, L71

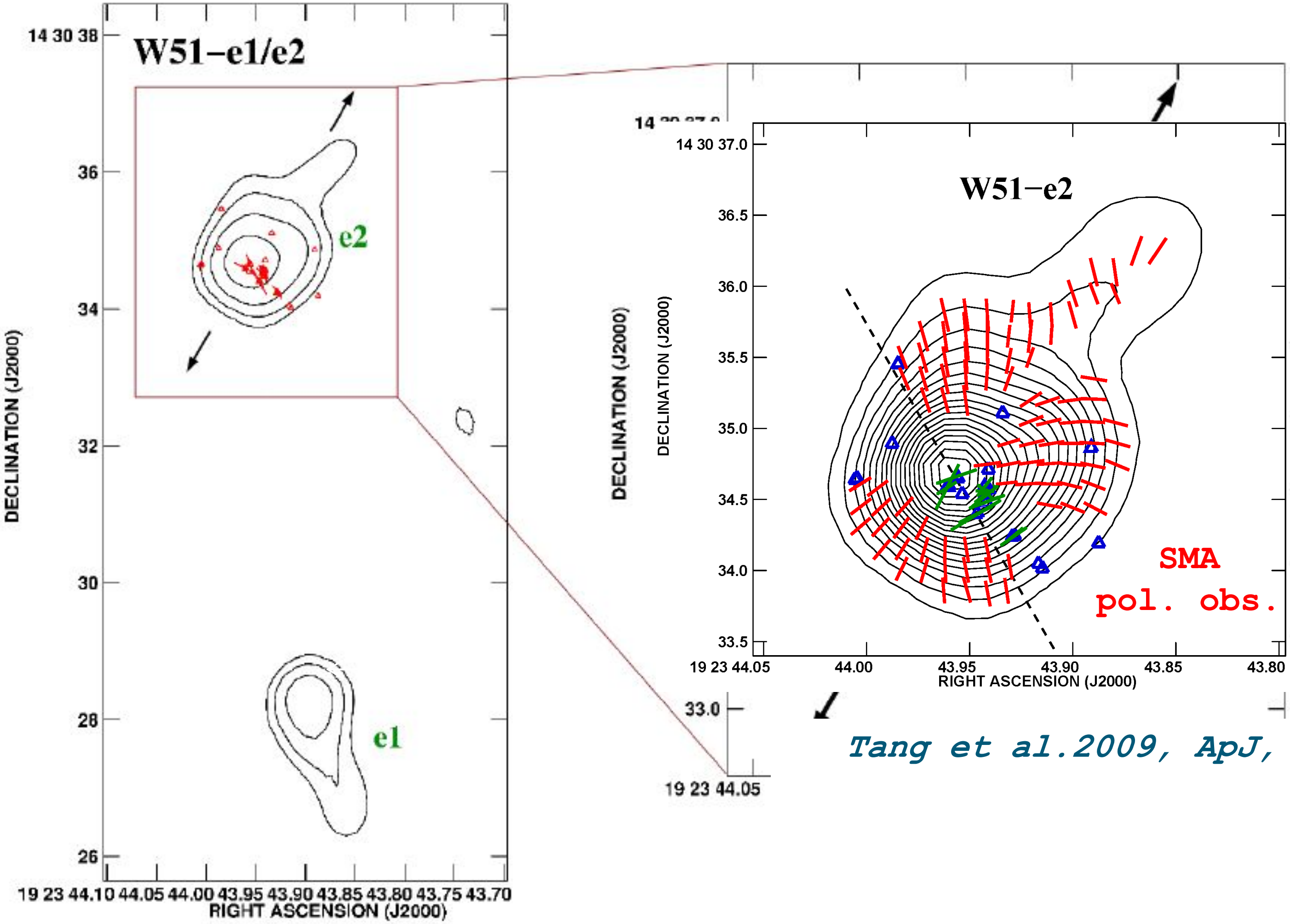
Rotation of the magnetic field along the maser path, which converts P_l into P_V.

Surcis et al. 2022, A&A, 658, A78





Extra 5



Tang et al.2009, ApJ, 700, 251

Extra 6

IRAS20126+4104 B0.5 with a mass~7 M_{sun}

D = 1.64 ± 0.5 kpc

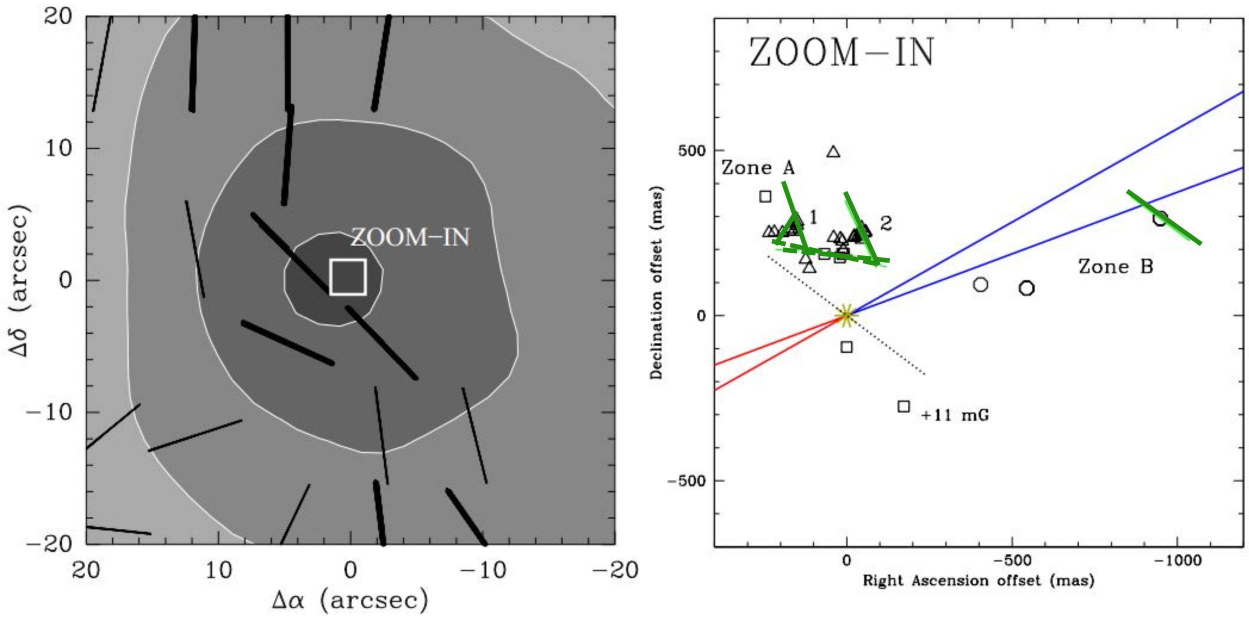


Fig. 4. Left panel: modified version of Fig. 3(b) of Shinnaga et al. (2012). The white box indicates the position of the right panel. The black bars represent the magnetic field direction determined from the polarized dust emission at 350 μm, whose continuum emission is in the background. Right panel: CH_3OH (triangles), OH (squares) (Edris et al. 2005), and H_2O (octagons) masers in IRAS20126+4104. The gold asterisk represents the B0.5 protostar (α_{2000} = $20^h14^m26^s.0498$ and δ_{2000} = 41°13′32″.443, MCR11), while the dotted line represents the Keplerian disk of ~1000 au (PA_{disk} = 53° ± 7°, Cesaroni et al. 2005). The red and blue lines indicate the red- and blue-shifted lobes of the jet, respectively, with a PA_{jet} = 115° and an opening angle of 9° (MCR11). The thick green segments represent the magnetic field direction determined from the polarized CH_3OH and H_2O maser emissions. The green dashed segments represent the magnetic field direction determined from the linearly polarized emission of OH masers (Edris et al. 2005). The foreground Faraday rotation at 1.6-GHz is probably not negligible and needs to be taken into account when interpreting the image (see Sect. 5.2).

Surcis, G. et al. 2014, A&A, 563, 30