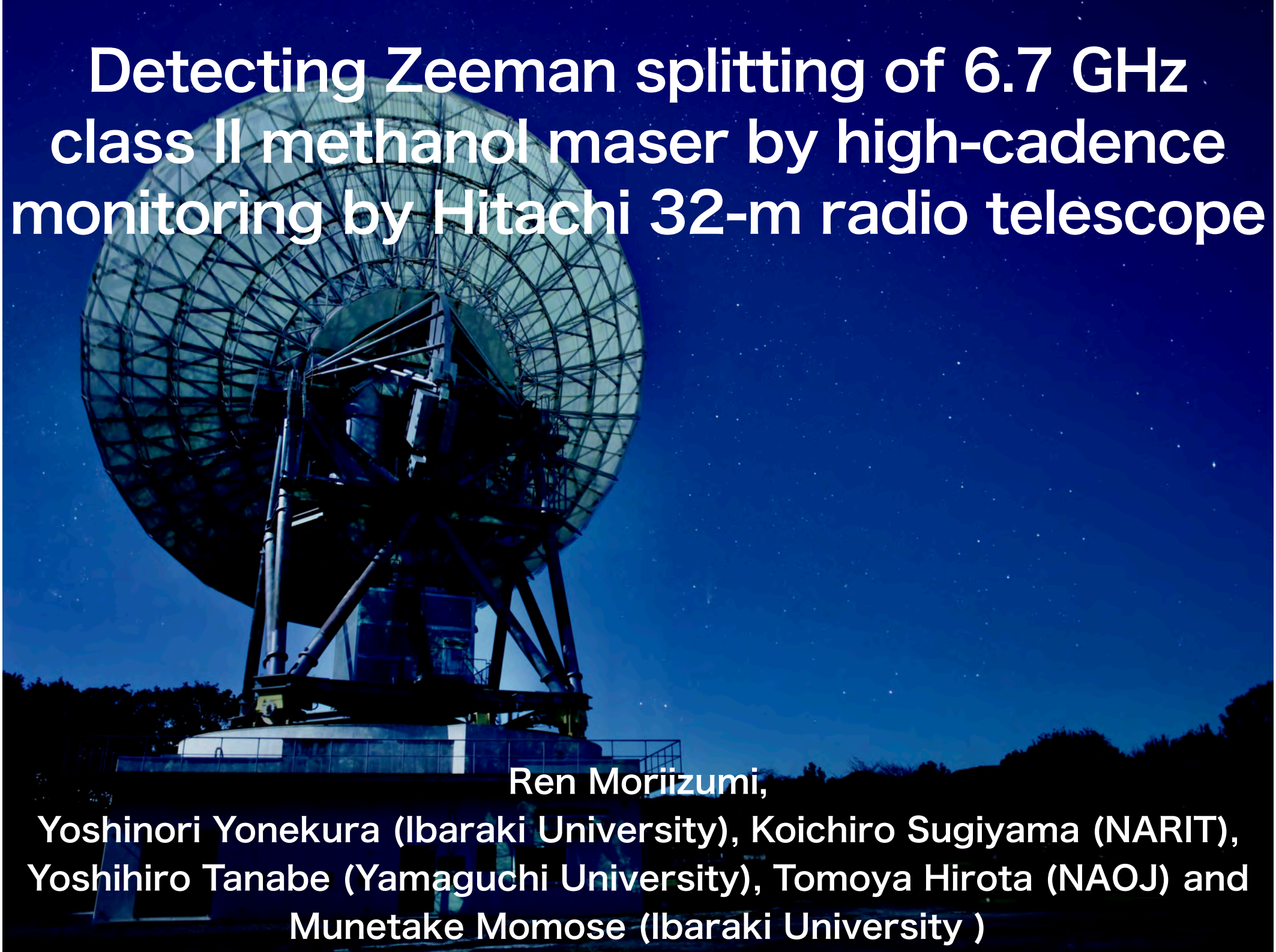


Detecting Zeeman splitting of 6.7 GHz class II methanol maser by high-cadence monitoring by Hitachi 32-m radio telescope

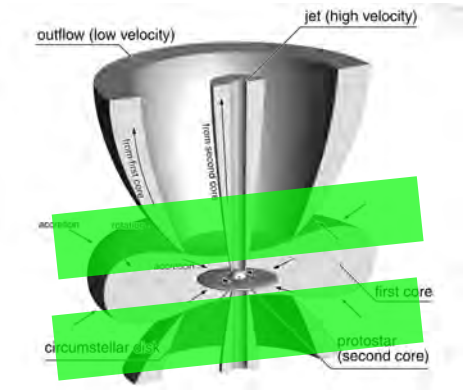
Ren Moriizumi,
Yoshinori Yonekura (Ibaraki University), Koichiro Sugiyama (NARIT),
Yoshihiro Tanabe (Yamaguchi University), Tomoya Hirota (NAOJ) and
Munetake Momose (Ibaraki University)

Introduction

- Massive stars ($M > 8M_{\odot}$) affect to their environment via strong radiation and stellar wind.
- Their forming process is still unknown due to difficulty of observation such as
  - Long distance (~kpc)
  - High optical depth at near—mid IR.
- Several numerical and observational study propose there will be strong magnetic field (~mG) in massive star forming region (e.g., Mckee & Tan 2002, Sanhueza et al. 2025)
- Magnetic fields play important role such as
  - Driving outflow and jet
  - Supporting the molecular cloud against gravity.

Introduction

- Zeeman effects of masers (OH, H_2O, CH_3OH) are useful tools for studying about magnetic fields vicinity of protostar (r $\lesssim$ 1000 au).



Machida et al. (2008)

- Class II methanol maser can trace upper layer of circumstellar disk.

- To detect Zeeman effect of methanol maser, High sensitivity is required. (1 σ < 100 mJy)

- We averaged each circular polarization data of 6.7 GHz methanol maser collected in 2017—2022 by Hitachi 32-m radio telescope to obtain low noise spectral data.

- We use Cross Correlation (CC) method to estimate Zeeman splitting.

Summary of observation

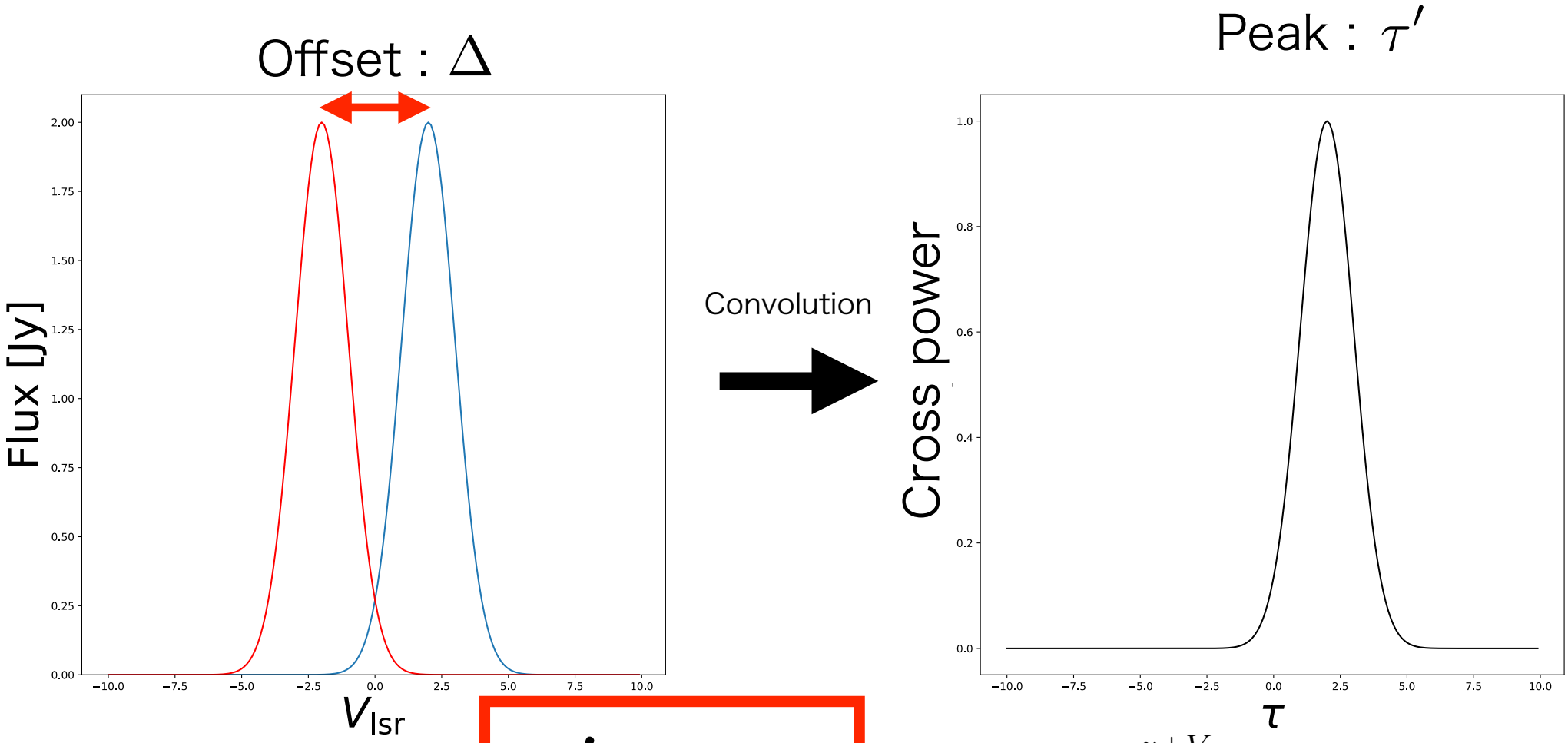
Frequency	6.664 — 6.672 GHz
Beam size	4.6 arcmin
Velocity resolution	0.0439 km/s
Noise level (1 σ)	~ 0.5 Jy (300 s scan) ~ 20 mJy (averaged data)
Observed polarization	RHCP, LHCP
Observing period	2017. 11 — 2022. 12



Hitachi 32-m radio telescope

CC-method (Modjaz et al. 2005)

Idea : offset =the peak of correlation function



$$\tau' = \Delta$$

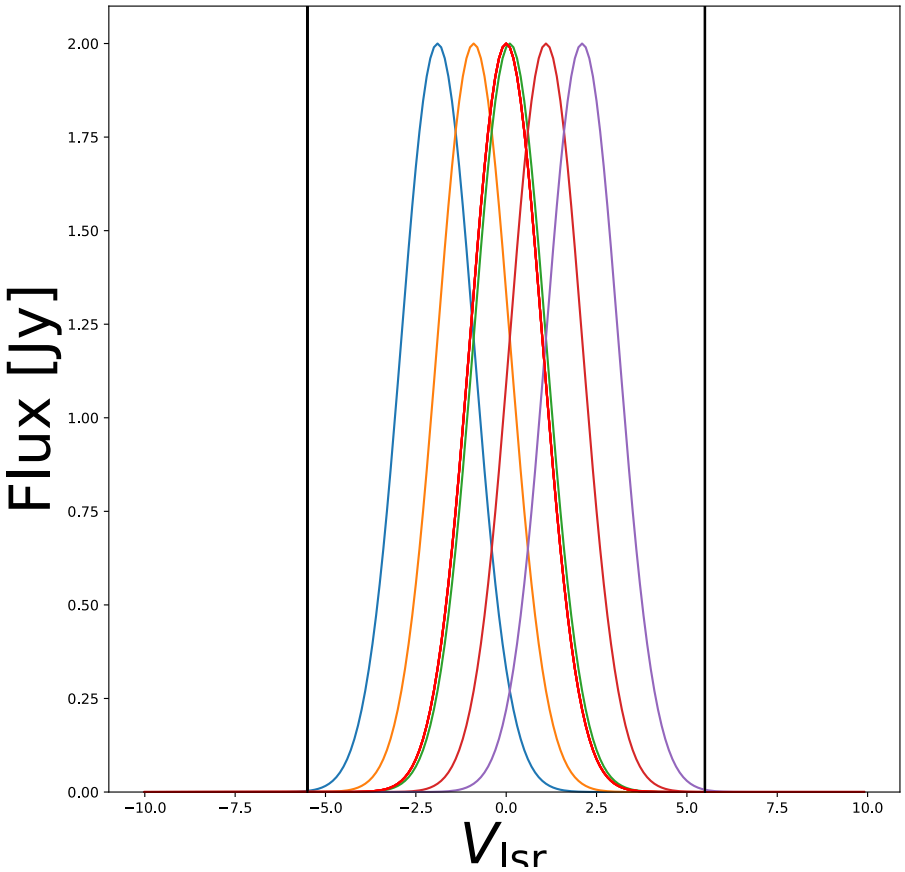
$$C_v(\tau) = \int_{v-V}^{v+V} S_{\mathrm{R}}(v') S_{\mathrm{L}}(v' - \tau) \mathrm{d}v'$$

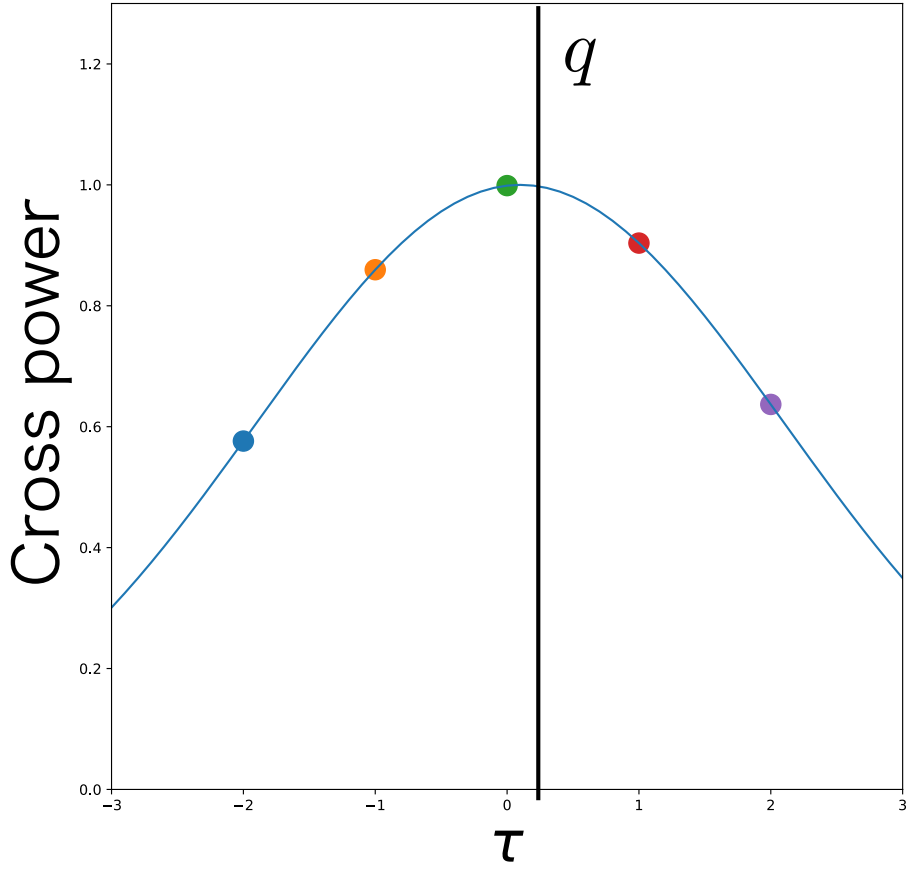
Cross Correlation (CC) method

$\tau = 2$

Integration range

$$C_v(\tau) = \int_{v-V}^{v+V} S_{\mathrm{R}}(v') S_{\mathrm{L}}(v' - \tau) \mathrm{d}v'$$





Purple : LHCP

Red : RHCP

$$f(\tau) = A \exp\left(-\frac{(\tau - q)^2}{\sigma^2}\right)$$

CC-method (integration interval)

Integration interval of correlation function must be determined carefully to avoid extrapolation from

- 'Wings of emission'
- Noise of correlation function

So we determined integration interval as smallest range within 5 σ_v which showed robust solution.

σ_v: line width

Robust solution are defined as

- The solution doesn't change if integration interval is shifted for v_{ch} and - v_{ch}
- The solution doesn't change if integration interval is extended by 0.5 σ_v

CC-method (error analysis)

The error of Zeeman splitting should come from fitting and noise.

$$\sigma_{\rm fit} = \text{fitting error}$$

$$\sigma_{\rm noise} \sim \sigma_q^2 = \sum_{j=1}^{N} \left(\frac{\partial q}{\partial x_j}\right)^2 \sigma_x^2 + \left(\frac{\partial q}{\partial y_j}\right)^2 \sigma_y^2 + 2\frac{\partial q}{\partial x_j}\frac{\partial q}{\partial y_j}\sigma_{xy}.$$

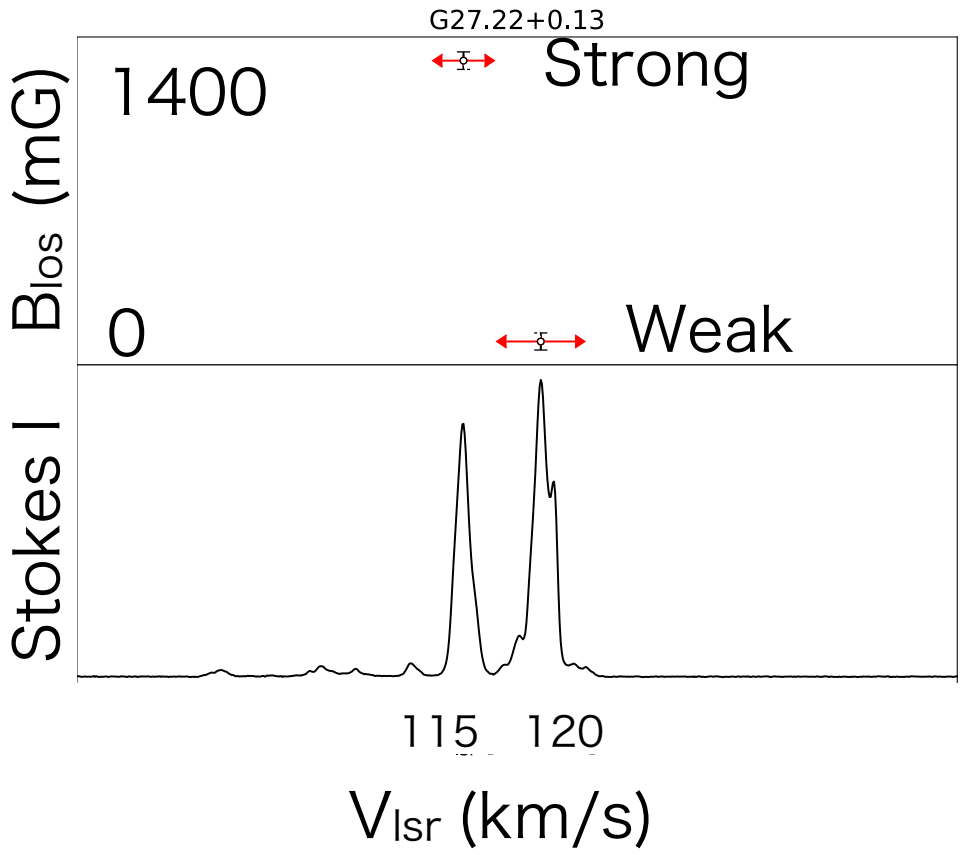
Modjaz et al. (2005)

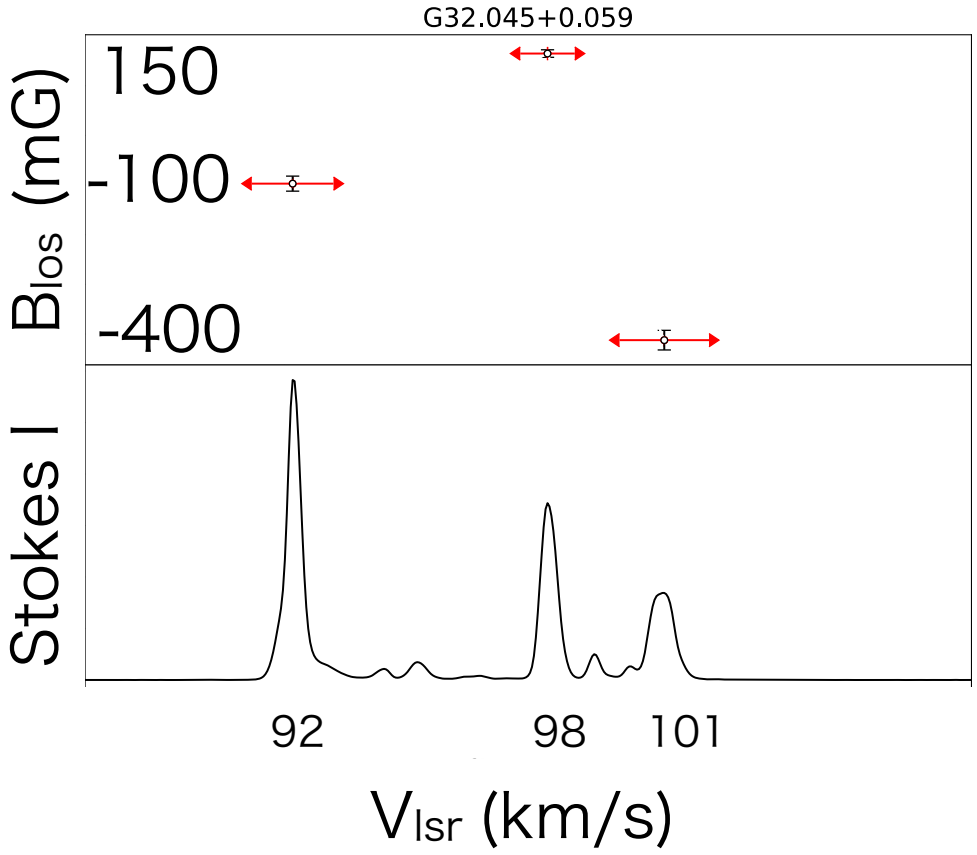
$$\sigma_q = \sqrt{\sigma_{\rm fit}^2 + \sigma_{\rm noise}^2}$$

Result

We analyzed 104 sources with SNR exceeding 500 and successfully detected the Zeeman splitting in 63 sources.

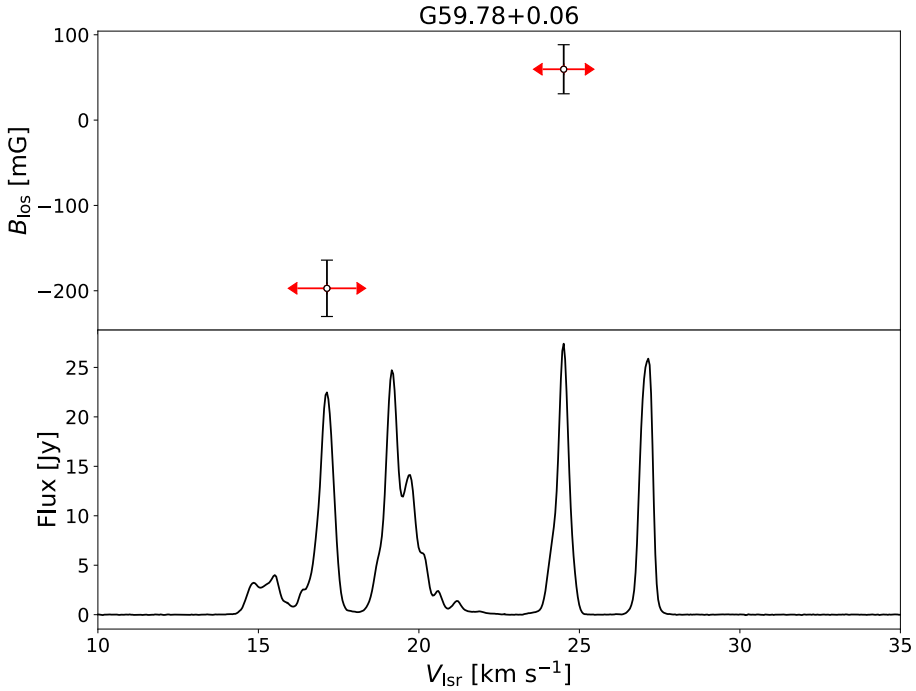
We use Zeeman splitting coefficient calculated by Takagi et al. (2022)

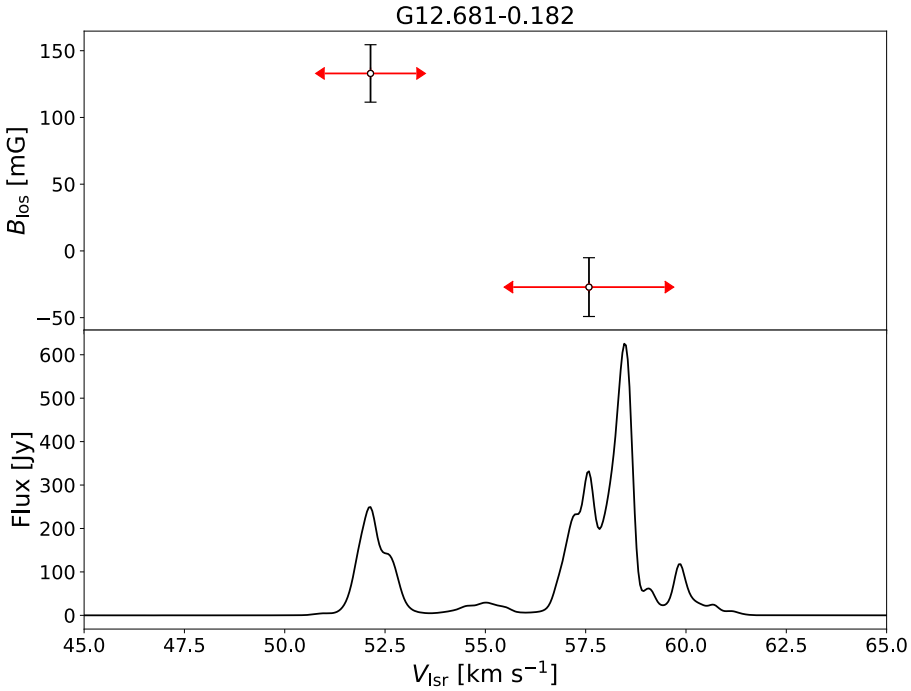


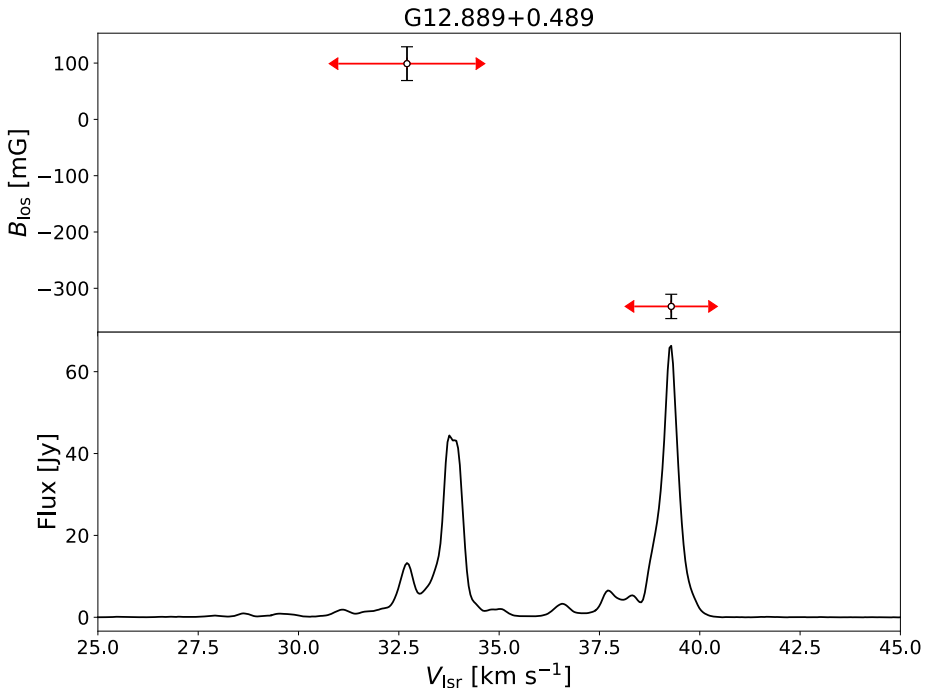


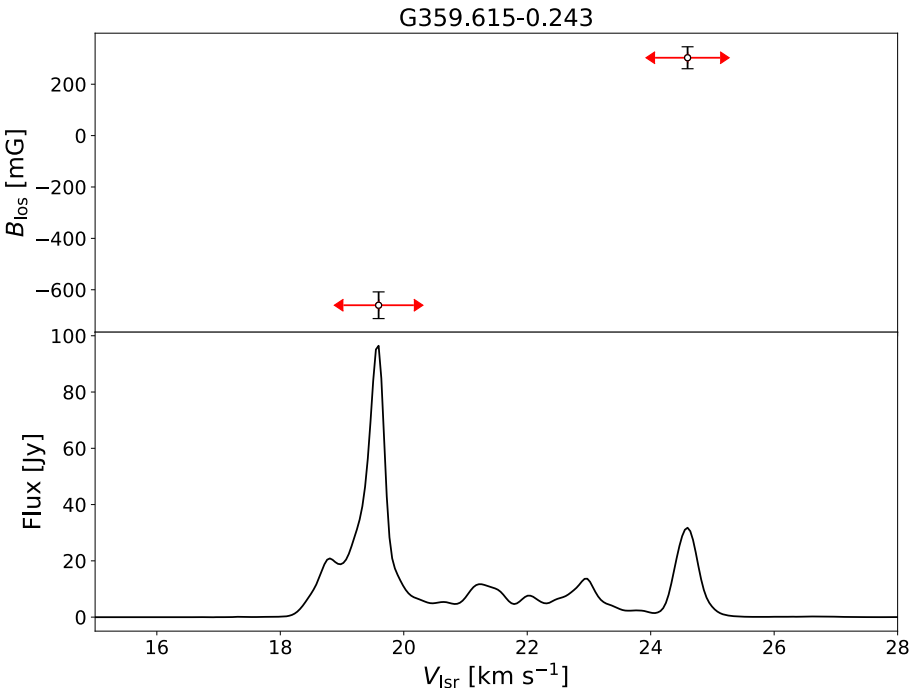
18 sources appear different strength of magnetic fields between different velocity component.

Result

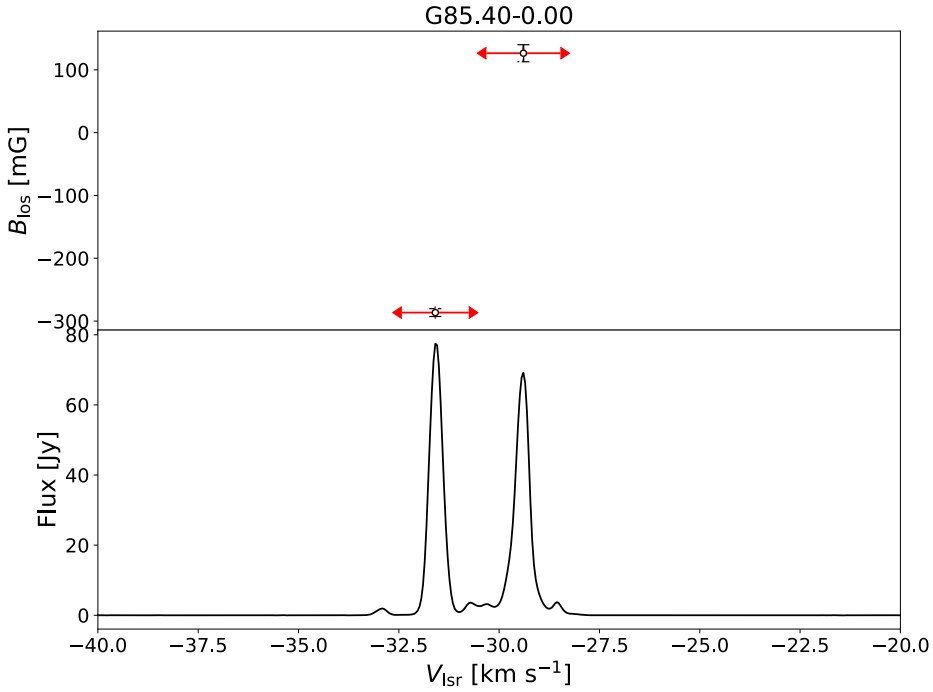

G59.78+0.06
B_{los} [mG]
Flux [Jy]
V_{lsr} [km s^{-1}]

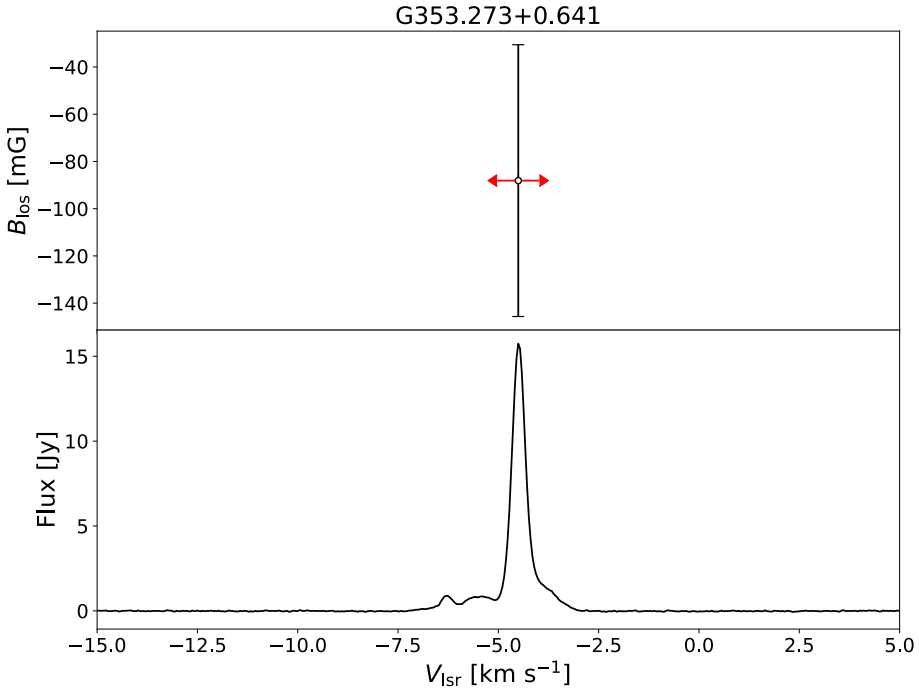

G12.681-0.182
B_{los} [mG]
Flux [Jy]
V_{lsr} [km s^{-1}]

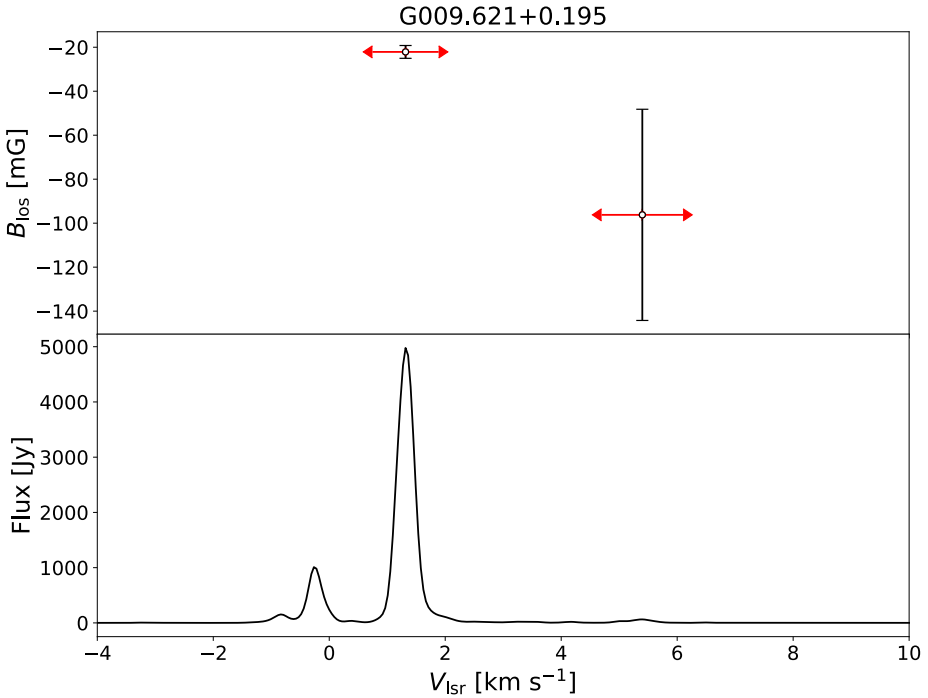

G12.889+0.489
B_{los} [mG]
Flux [Jy]
V_{lsr} [km s^{-1}]

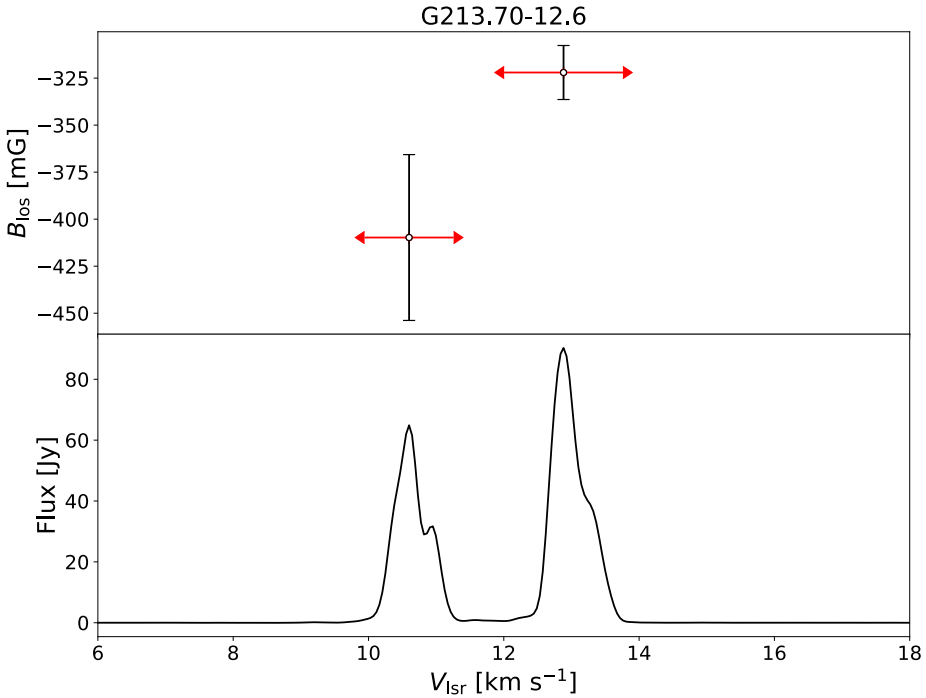

G359.615-0.243
B_{los} [mG]
Flux [Jy]
V_{lsr} [km s^{-1}]

Result

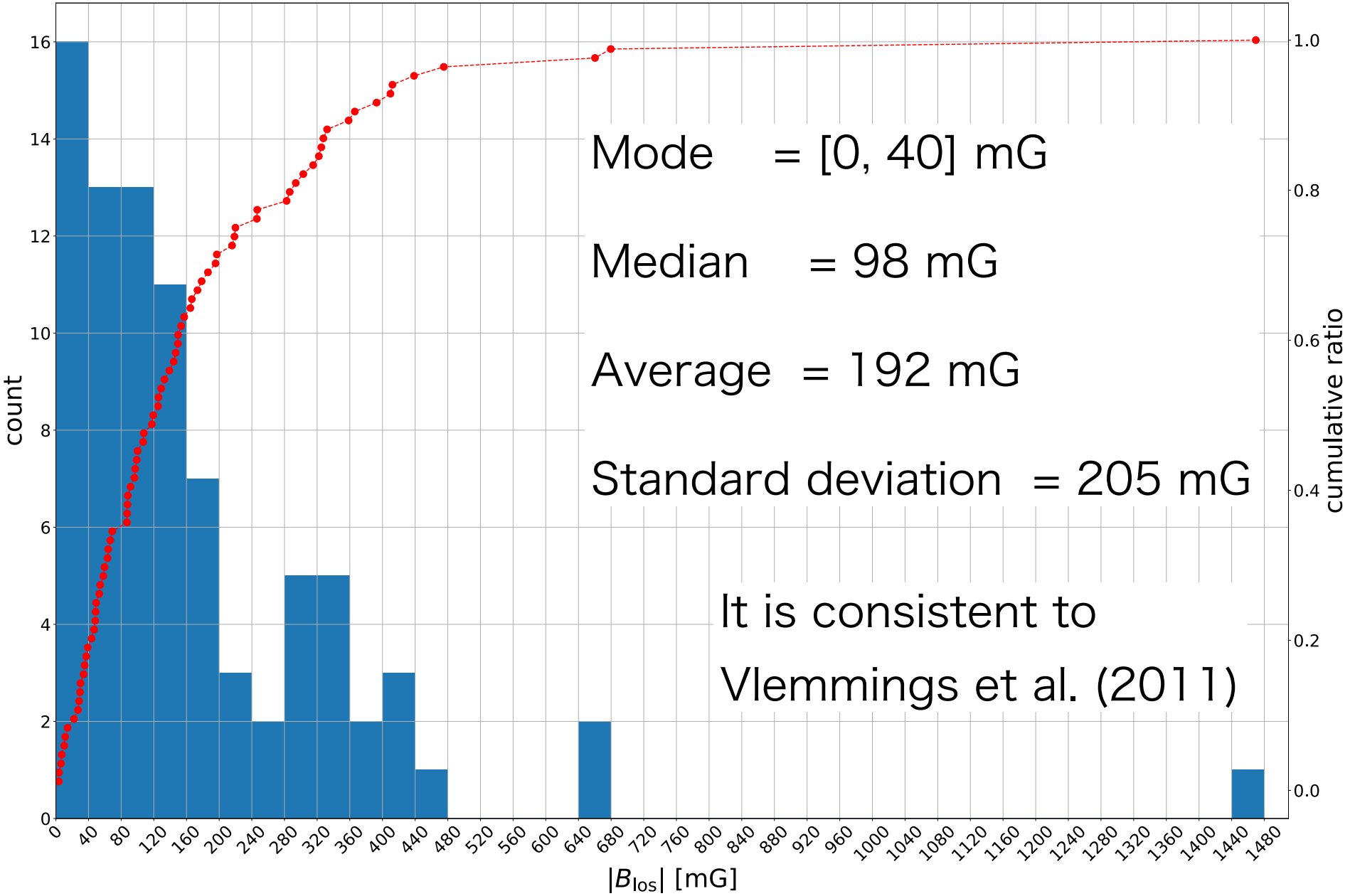

G85.40-0.00
B_{los} [mG]
Flux [Jy]
V_{lsr} [km s^{-1}]


G353.273+0.641
B_{los} [mG]
Flux [Jy]
V_{lsr} [km s^{-1}]


G009.621+0.195
B_{los} [mG]
Flux [Jy]
V_{lsr} [km s^{-1}]


G213.70-12.6
B_{los} [mG]
Flux [Jy]
V_{lsr} [km s^{-1}]

Result (histogram of $|B_{\rm los}|$)



Discussion

Difference of sign or strength of magnetic fields between different velocity component can come from …

- Frozen-in of magnetic fields

- Hyperfine of methanol

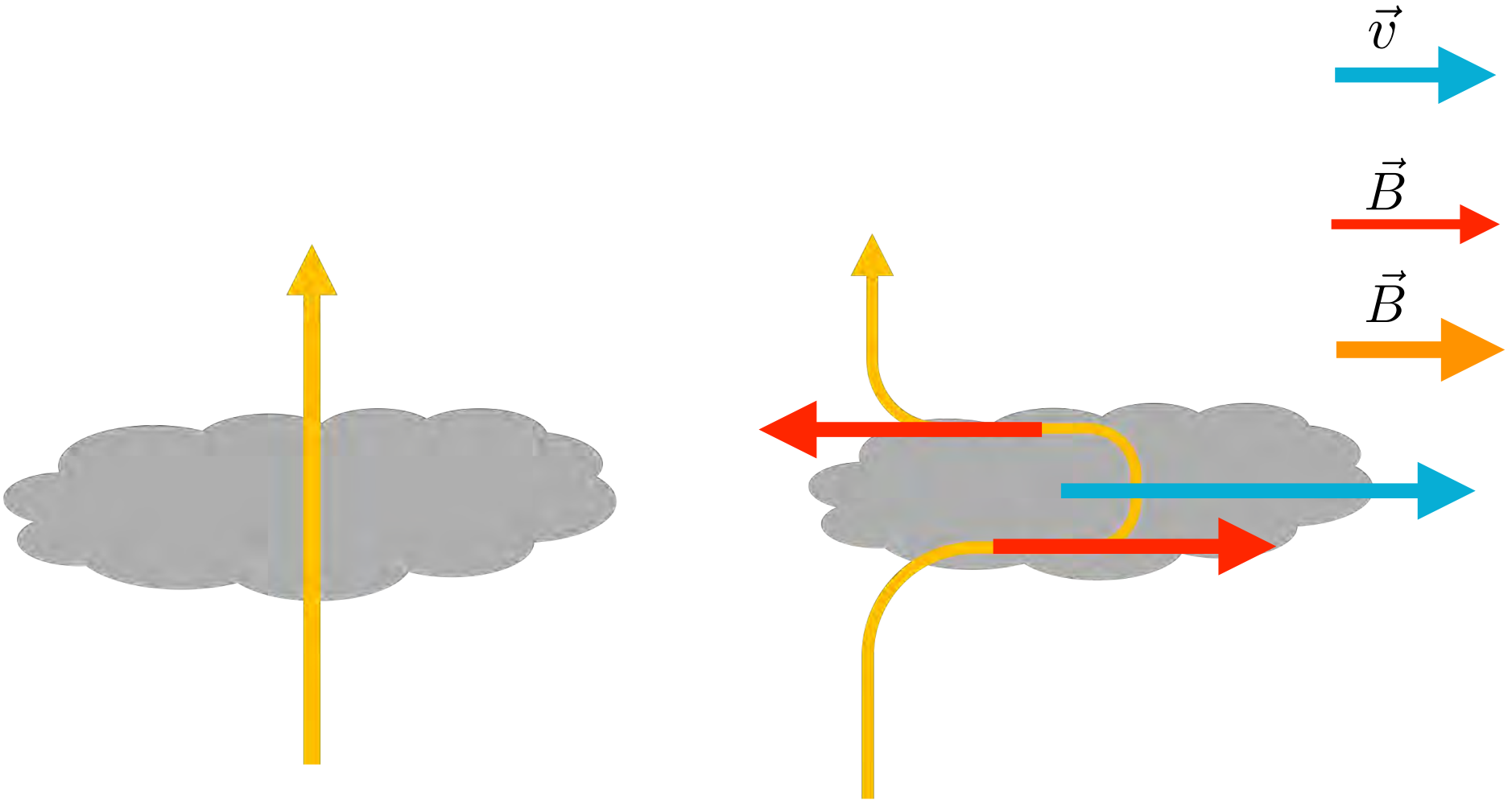
Discussion

Difference of sign or strength of magnetic fields between different velocity component can come from …

- Frozen-in of magnetic fields

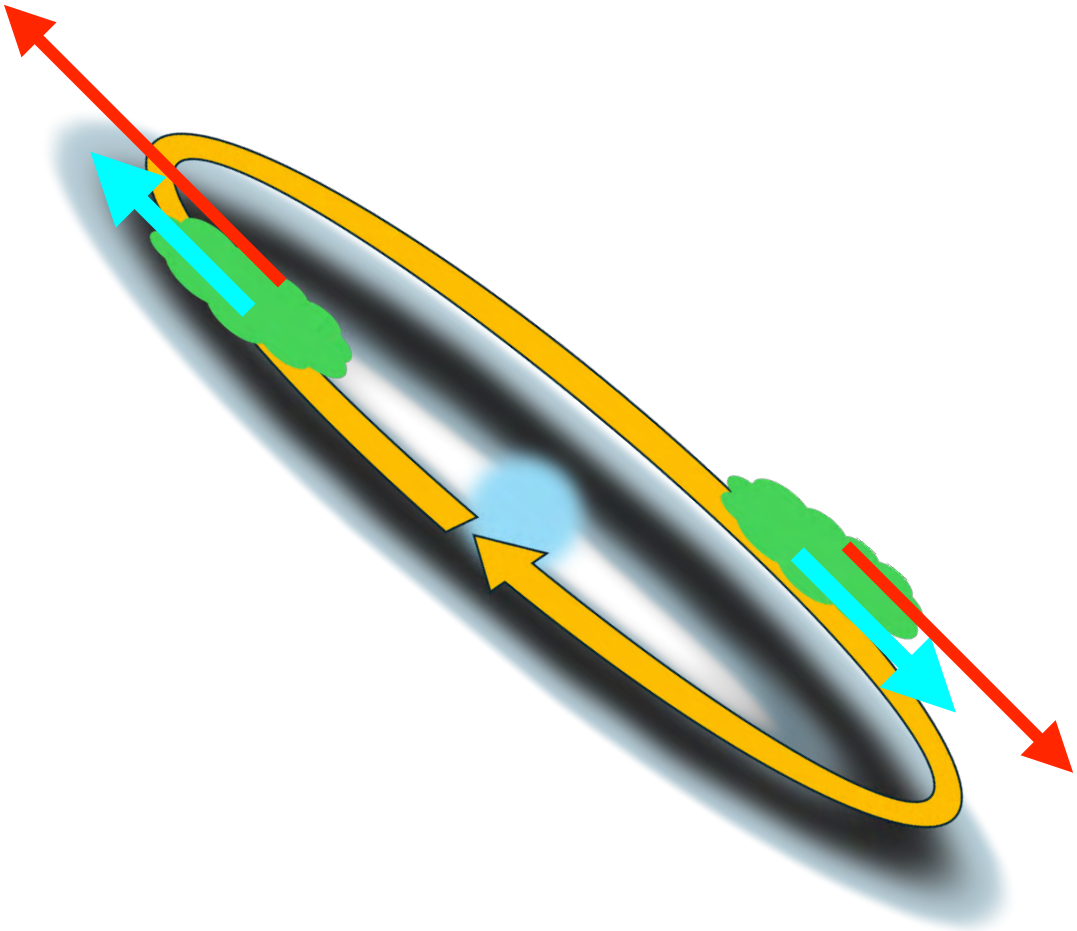
- Hyperfine of methanol

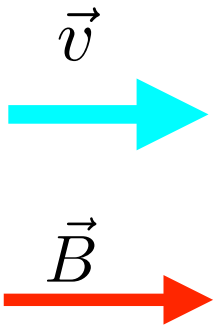
Discussion

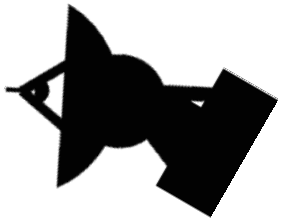


If magnetic fields are frozen-in, magnetic fields will be dragged by gas motion.

Discussion

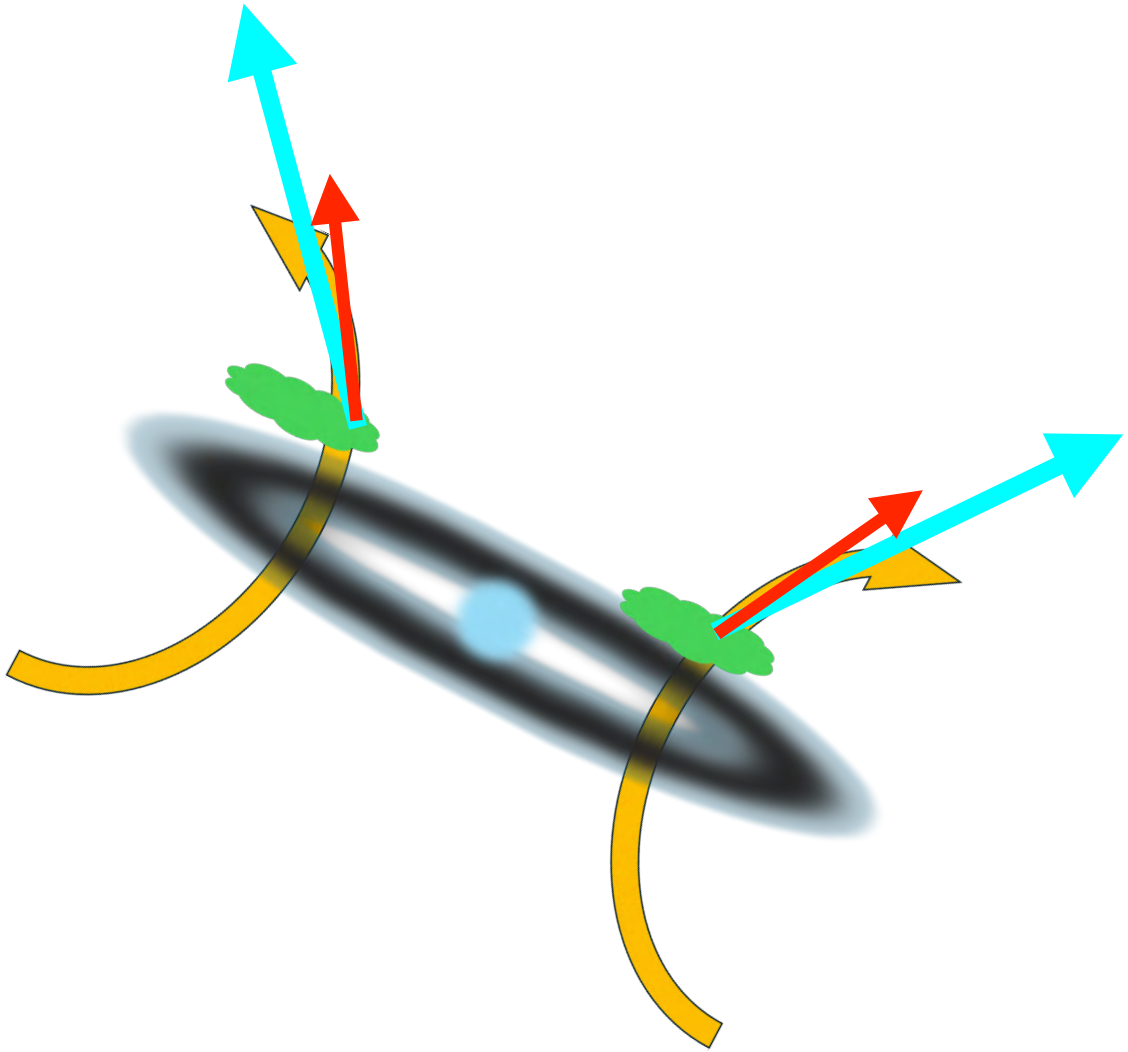


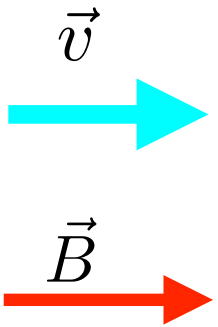


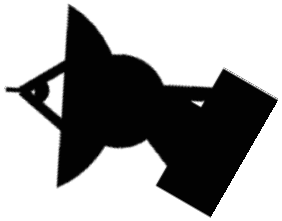


If magnetic fields are frozen-in, magnetic fields will be dragged by gas motion. Such as rotating, expanding and rotating + expanding.

Discussion

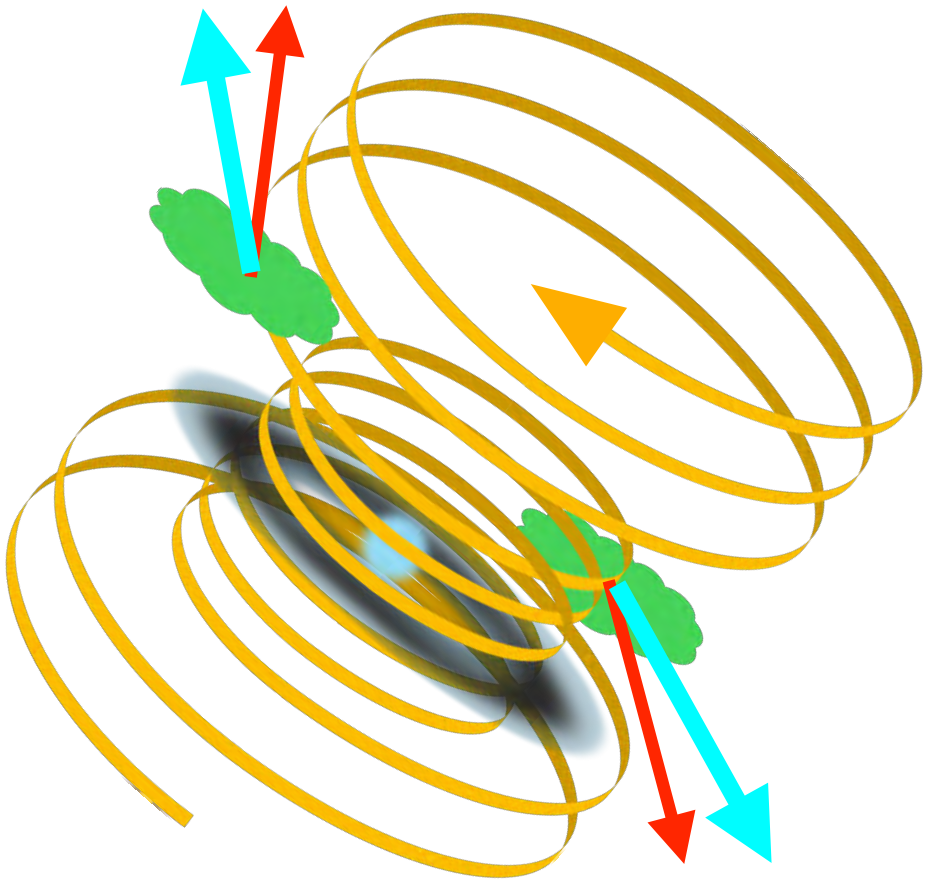


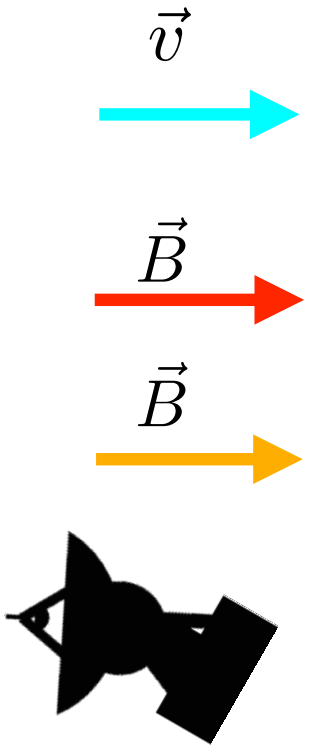




If magnetic fields are frozen-in, magnetic fields will be dragged by gas motion. Such as rotating, expanding and rotating + expanding.

Discussion





If magnetic fields are frozen-in, magnetic fields will be dragged by gas motion. Such as rotating, expanding and rotating + expanding.

Discussion

Assuming effect of ambipolar diffusion. Ambipolar diffusion resistivity can be written as

$$\eta_{\rm AD} = \frac{B^2}{\gamma_{\rm AD}\rho\rho_{\rm i}}$$

$\gamma_{\rm AD}$: drag coefficient

(related to efficiency of collision between ion and molecules)

and the Faraday's induction equation is

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left[\mathbf{v}\times\mathbf{B} + \frac{\eta_{\rm AD}}{\mathbf{B^2}}[(\nabla\times\mathbf{B})\times\mathbf{B}]\times\mathbf{B}\right]$$

So, magnetic Reynolds number can be written as

$$R_m = \left|\frac{\mathbf{v}\times\mathbf{B}}{\frac{\eta_{\rm AD}}{\mathbf{B^2}}[(\nabla\times\mathbf{B})\times\mathbf{B}]\times\mathbf{B}}\right| = \frac{VL}{\eta_{\rm AD}} = \frac{\frac{L^2}{\eta_{\rm AD}}}{\frac{L}{V}} = \frac{t_{\rm diff}}{t_{\rm dyn}}$$

If magnetic field is frozen-in, $R_m \gtrsim 1$

Discussion

Diffusion time of upper layer of circumstellar disk can be estimated as

$$t_{\rm diff} = \frac{R^2}{\eta_{\rm AD}} = 1.3 \times 10^4 \left[\frac{R}{1000\ {\rm au}}\right]^2 \left[\frac{B}{98\ {\rm mG}}\right]^{-1} \left[\frac{\rho}{10^{-16}\ {\rm g\ cm^{-3}}}\right]^2 \left[\frac{\chi}{5.0 \times 10^{-6}}\right]\ {\rm yr}$$

And dynamical timescale $t_{\rm dyn}$ should be rotation time of disk. $t_{\rm dyn} \sim 10^4$ yr at $M_* \sim 10 M_\odot$ and $r \sim 1000$ au

So

$$R_m = \frac{1.3 \times 10^4}{10^4} \approx 1$$

R : typical size of circumstellar disk

ρ : typical density of maser cloud (Cragg et al. 2005.)

B: median of strength of magnetic fields (in this work)

χ : degree of ionization (e.g., Cabedo et al. 2023.)

B is Frozen-in weakly at upper layer of circumstellar disk???

Discussion

Difference of sign or strength of magnetic fields between different velocity component can come from …

- Frozen-in of magnetic field
- Hyperfine of methanol

Discussion

Lankhaar et al. (2018) proposed favored hyperfine transition should exist and Zeeman splitting coefficient should be different for each transition.

It means : Even though strength of magnetic fields traced by maser cloud were same, Zeeman splitting can be different from each other due to existence of hyperfine transition.

To verify the favored hyperfine exist or not, Zeeman splitting of other transition of methanol (e.g., 12 GHz) should be observed.

Favored hyperfine	**Not exist**	**Exist**
Estimated B at several transitions of maser by using α_z from Takagi et al.	Same within error range	Different

Summary

- Typical value of strength of magnetic fields is ~ 100 mG
- Magnetic fields in massive star forming region will be frozen-in weakly at upper layer of circumstellar disk.
- But the strength of magnetic fields have uncertainty due to hyperfine. Therefore, we should observe Zeeman splitting of other transition of methanol maser such as 12 GHz too.


Photo : Ren Moriizumi