Grain alignment theory and polarimetry with SPICA: a personal review

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Grain alignment with DG mechanism

- Discovery of polarization in distant stars   Hall 1949, Hiltner 1949
- Alignment with paramagnetic relaxation   Davis and Greenstein 1951
  - Phase lag of magnetization → torque that makes angular momentum J // B
  - Alignment time scale τ_{DG}:   Draine & Weingertner 1996

$$\tau_{DG} = \frac{2\alpha_1 \rho a_{eff}^2}{5K(\omega)B_0^2}$$
$$= 1.5 \times 10^6 \alpha_1 \rho_3 a_{-5}^2 \left[\frac{10^{-13}\ \mathrm{s}}{K(\omega)}\right]\left(\frac{5\ \mu\mathrm{G}}{B_0}\right)^2\ \mathrm{yr}$$

(Davis & Greenstein 1951), where $K(\omega) \equiv \mathrm{Im}[\chi(\omega)]/\omega \approx 10^{-13}$ s for normal paramagnetism at $T \approx 18$ K

  - Rotational damping by gas drag:

$$\tau_{drag,gas} = \frac{\pi \alpha_1 \rho a_{eff}}{3\delta n_H (2\pi m_H kT)^{1/2}} = (8.74 \times 10^4\ \mathrm{yr}) \times \frac{\alpha_1}{\delta} \rho_3 a_{-5} T_2^{1/2} \left(\frac{3000\ \mathrm{cm}^{-3}\ \mathrm{K}}{n_H T}\right)$$

where $\rho_3 \equiv \rho/3$ g cm^{-3}, $a_{-5} \equiv a_{eff}/10^{-5}$ cm, and $T_2 \equiv T/10^2$K.

α_1, δ: shape factor, $\alpha_1 \sim \delta$

  - $\tau_{DG} >> \tau_{drag}$ DG is very slow process.   No alignment?   A "mystery" in 1950-1980s.

Grain alignment by Radiative Torque (RAT)

- Dolginov & Mytrophanov 1976, Draine & Weingartner 1996, 1997, Lazarian et al. many papers
- Irregular Grains rotate rapidly by RAT → magnetized by the Barnett effect

The Barnett magnetic moment is

$$\boldsymbol{\mu} = -\frac{\chi(0)V\hbar}{g\mu_B}\boldsymbol{\omega} ,$$

where V is the grain volume, μ_B is the Bohr magneton, $g \approx 2$ is the gyromagnetic ratio, and $\chi(0)$ is the static susceptibility.

DW 1997

- → Larmor precession around interstellar magnetic field B_0, i.e. directions of J and B_0 is related, with frequency Ω_B

$$\Omega_B = \frac{\mu B_0}{I_1\omega} = \frac{5\hbar\chi(0)B_0}{2\alpha_1 g\mu_B \rho a_{\rm eff}^2} \approx 7.5\ {\rm yr}^{-1} a_{-5}^{-2}\left(\frac{3\ {\rm g\ cm}^{-3}}{\alpha_1\rho}\right)^{1/2}\left[\frac{\chi(0)}{10^{-4}}\right]\left(\frac{B_0}{5\ \mu{\rm G}}\right)$$

where we have set $g \approx 2$. It is therefore clear that interstellar grains will precess around $\boldsymbol{B}_0$ very rapidly compared to all other timescales except the grain rotation period itself.

- Period of the Larmor precession $\tau_B = 1/\Omega_B \sim$ 0.1 year ... very rapid!

Some phrases by authors…

- Cugnon P. (1987)

  "… What concerns coherent derivations of the magnetic field strength, my general impression remains rather pessimistic, but not desperate."

  in the proceedings of "Interstellar Magnetic Fields" ed. Beck & Graeve, pp.100-109

- Draine and Weingartner (1996)

  "... It therefore appears that the longstanding mystery has been solved -- the observed alignment of interstellar grains is due to radiative torques produced by anisotropic starlight!"

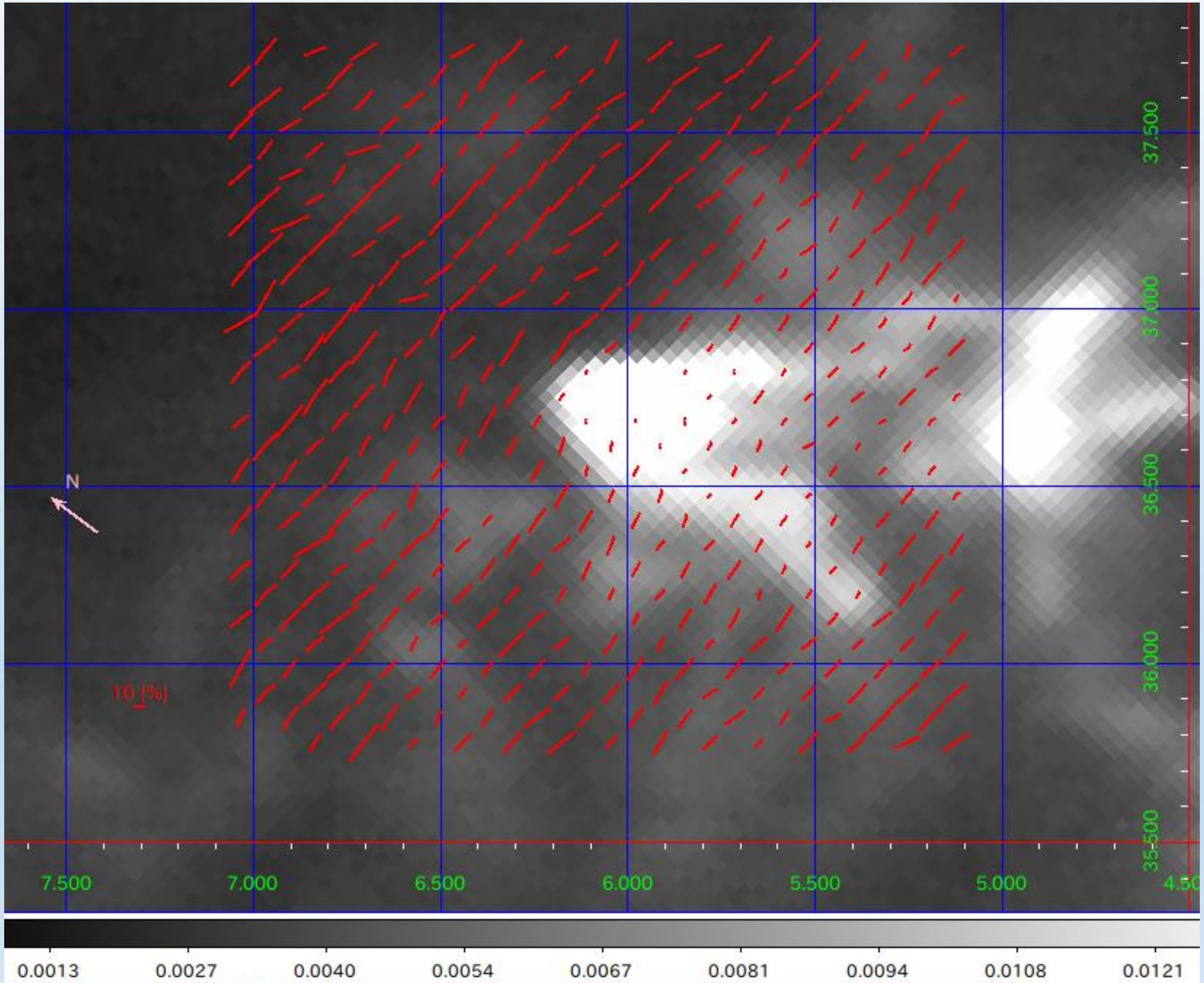
  AAS 189, 1602

Possible plans for observations with SPICA pol.

- RAT alignment seems most probable at present.
- Assuming RAT, what can we expect for observations?

- To understand more about the RAT theory (and other things…) , we may observe the borders where grains are aligned / not aligned by RAT.
  - If radiation field is weak, grains do not rotate by RAT.
    → Grains are not magnetized by the Barnett effect → No alignment
    e.g. Starless cores?
  - If rotational damping by gas drag is strong, i.e. τ_{drag} is small,
    → $\tau_{drag} \ll \tau_B$ i.e. the rotation is damped before precession
    → No alignment
    e.g. Outflow around SF regions?

A Possible Science with SPICA polarimetry: Starless cores



An example:

LDN 183

Planck 353GHz

Resolution for pol.: 6′×6′

Fractional polarization drops in L183,

i.e. polarization hole.

Relation between pol. efficiency p/τ and τ

- In diffuse space, the observed dichroic extinction shows:

$$p/\tau \propto 1 / \tau^{0.5}$$

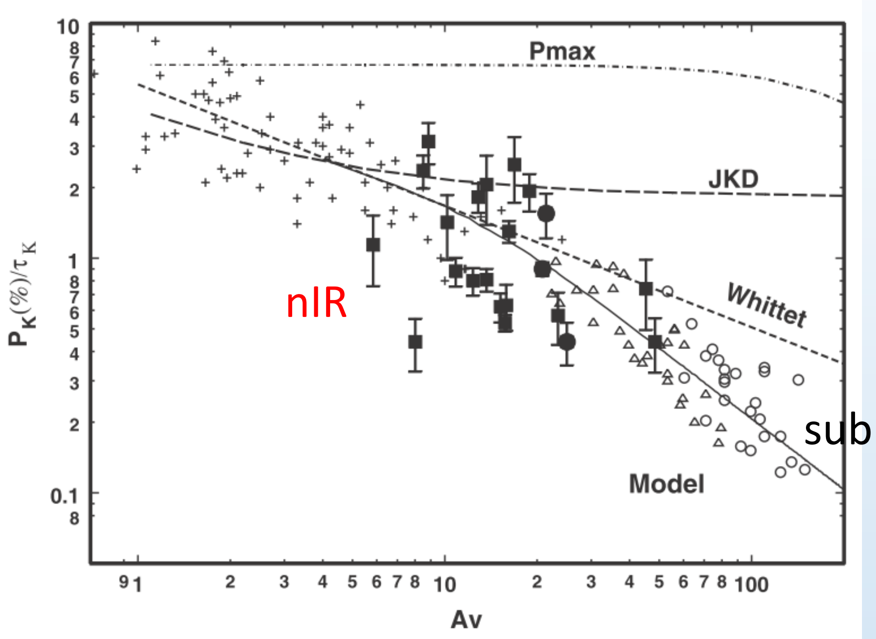
If B is random, then $p \propto \tau^{0.5}$, and p/τ goes as $1 / \tau^{0.5}$

- If we see a uniform B-field, i.e. not random, $p \propto \tau$, and then,

$$p/\tau \propto \tau^{0} \sim \text{const}$$

- In very dense region where radiation is weak, e.g. starless cores, grains do not rotate by RAT. Then they are not magnetized, and not aligned.
As a result, p does not increase as τ, and is constant:

$$p/\tau \propto 1 / \tau$$

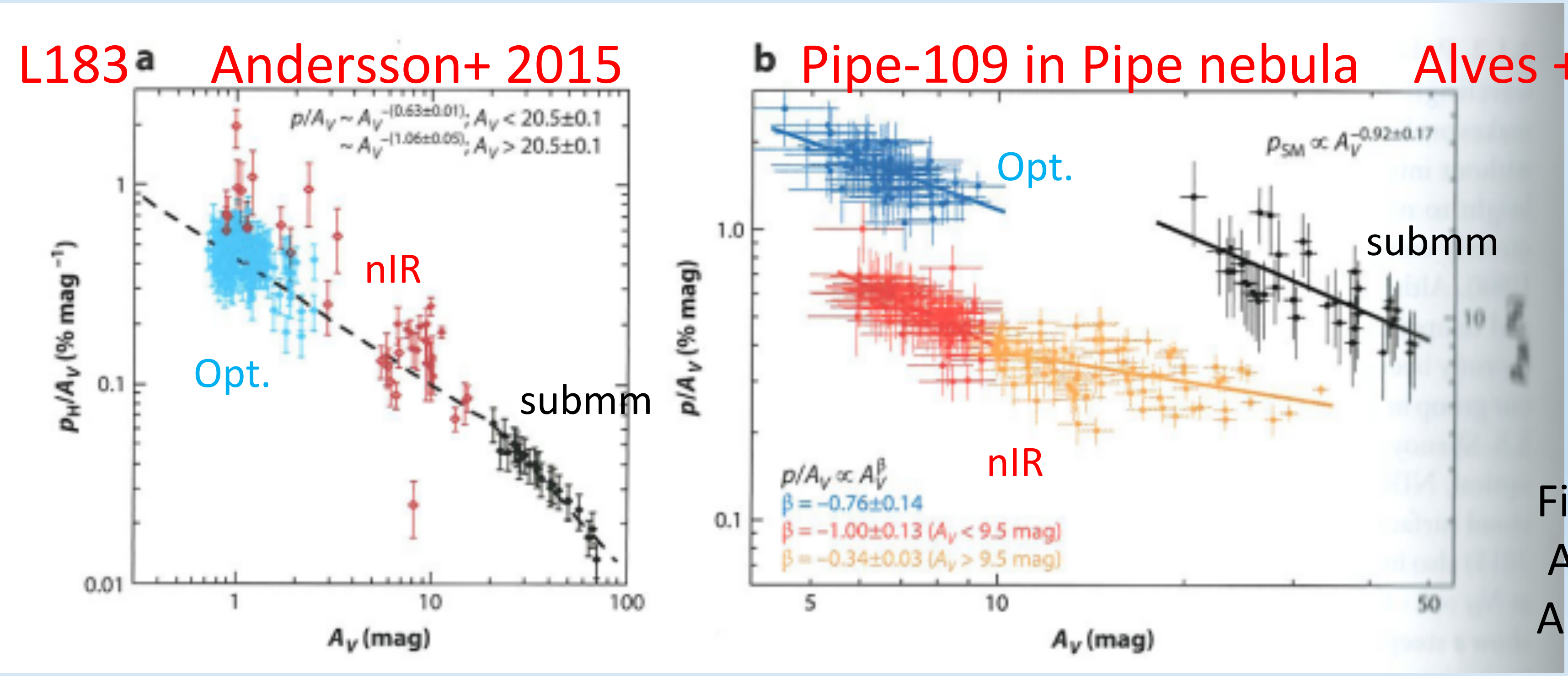


L183 & L43. Jones + 2015

$p/\tau \propto 1/\tau$ for $A_V > 20$ mag.

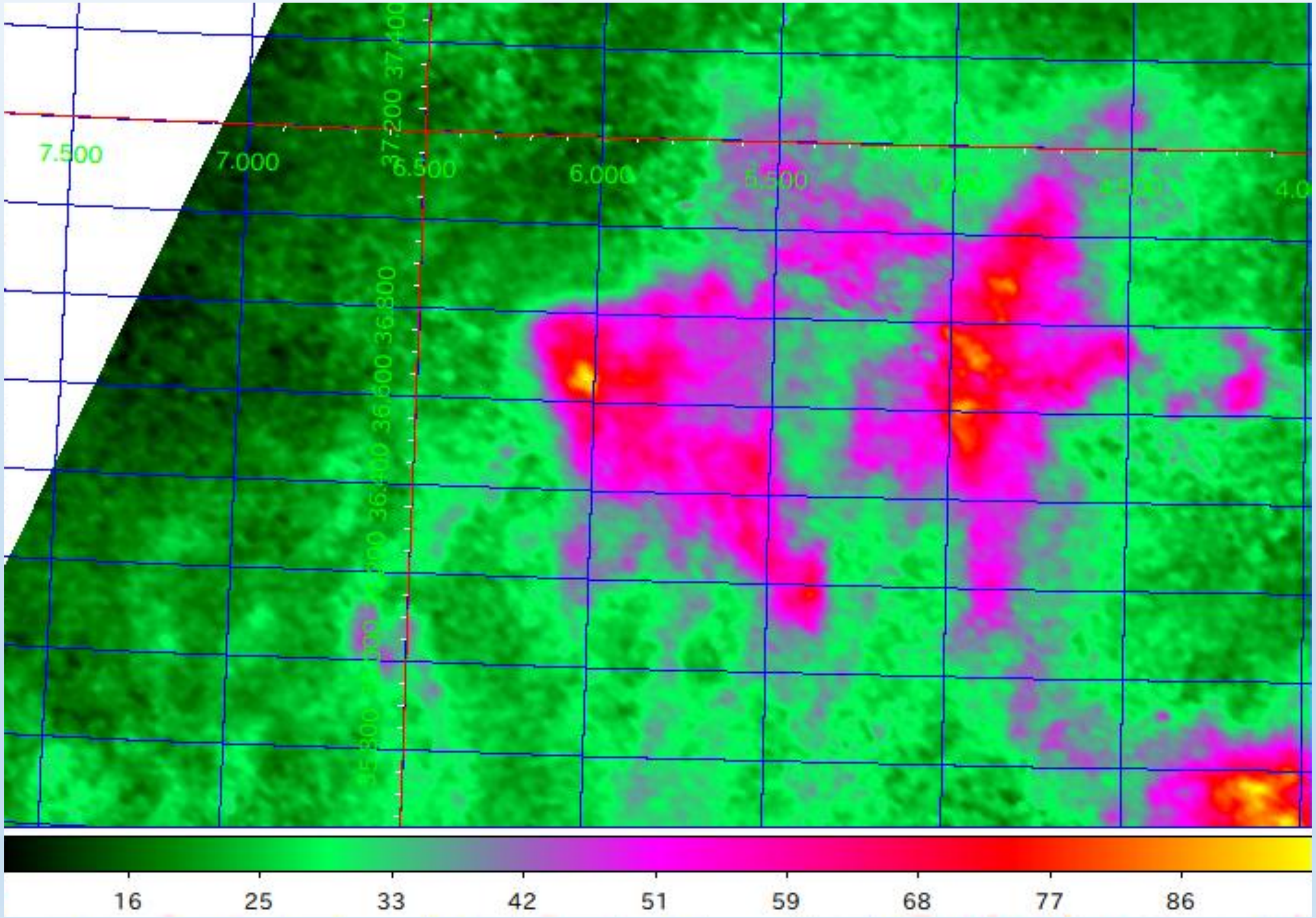
→ They suggest that grains are not aligned in $A_V > 20$ mag.

But, systematic difference exists between observational methods?



Figs are from Andersson+ 2015 ARAA 53, 501

LDN 183 in Akari Wide-L band



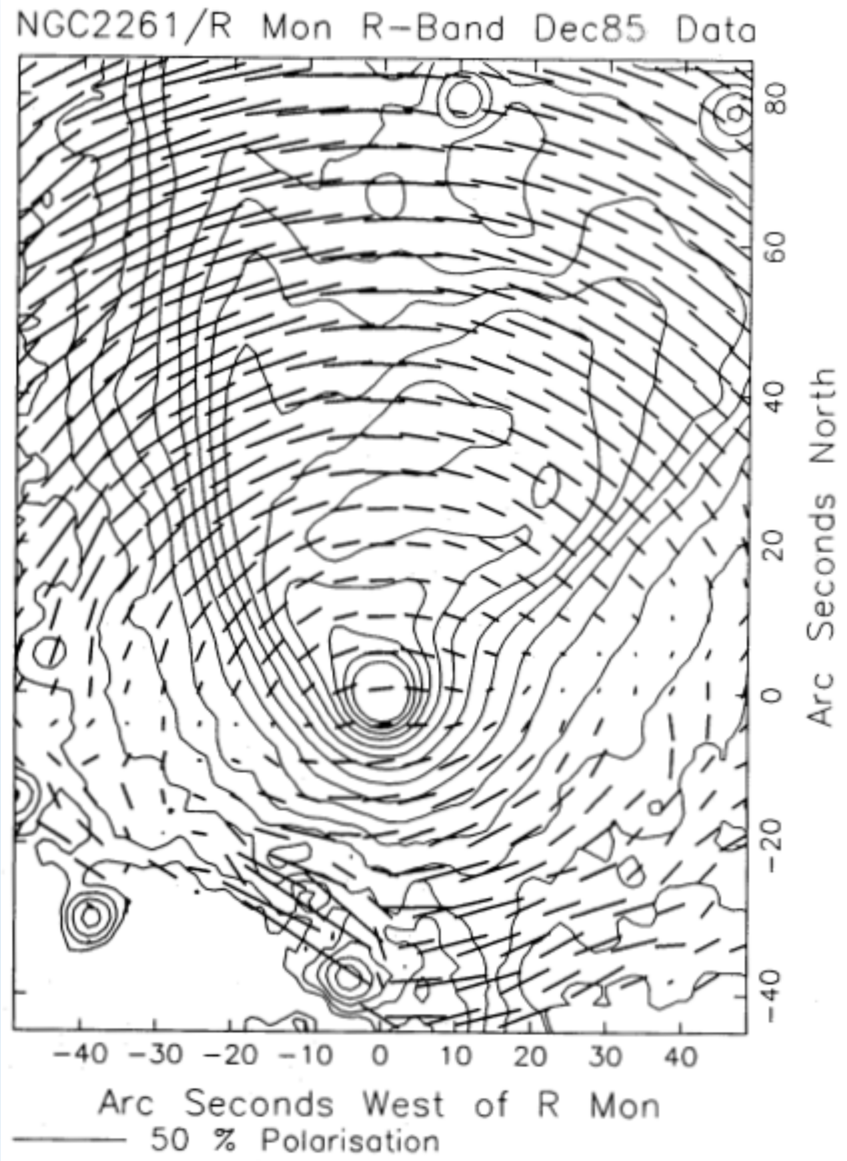
Max: ～90 MJy/Sr

Min: ～13 MJy/Sr

It seems the flux is strong enough to observe with SPICA polarimeter.

Since SPICA has large dynamic range > 8000, such observations should be feasible and important.

Another Possible Science with SPICA polarimetry: YSO



- An example: R Mon … a Herbig B star
  Scarrott + 1989 MNRAS 237 621
- Two features in polarization map:
  - (1) <u>"Aligned Pattern"</u> near star
    → interpretations in 1980-1990s:
    - extinction by aligned nonspherical grains (Scarrott et al. 1989) ... since the DG time is long, it was questioned.
    - multiple scattering by grains (Bastien et al. 1990)

    → Recent submm/mm linear pol. & circular pol. obs.
    suggest <u>both</u> ext. & multiple scat. by aligned grains

    → SPICA pol. may observe grain alignment (=B fields)!
  - (2) <u>"Centro-symmetric Pattern"</u> in outer region
    - Single scattering by non-aligned grains seems OK, but some evidence of alignment

Deviations from symmetry

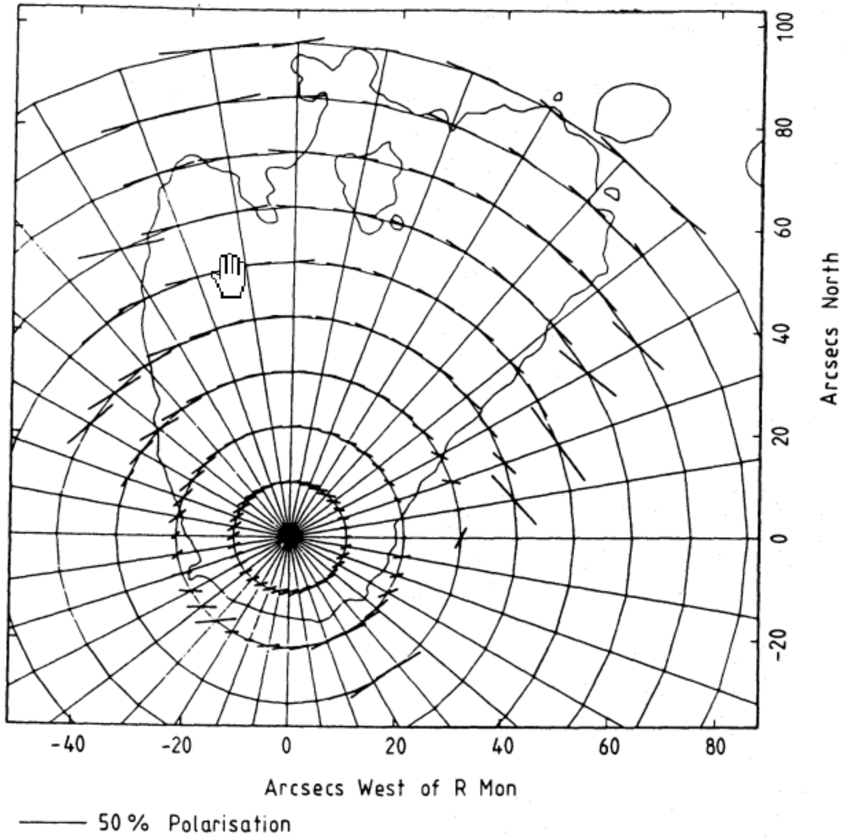
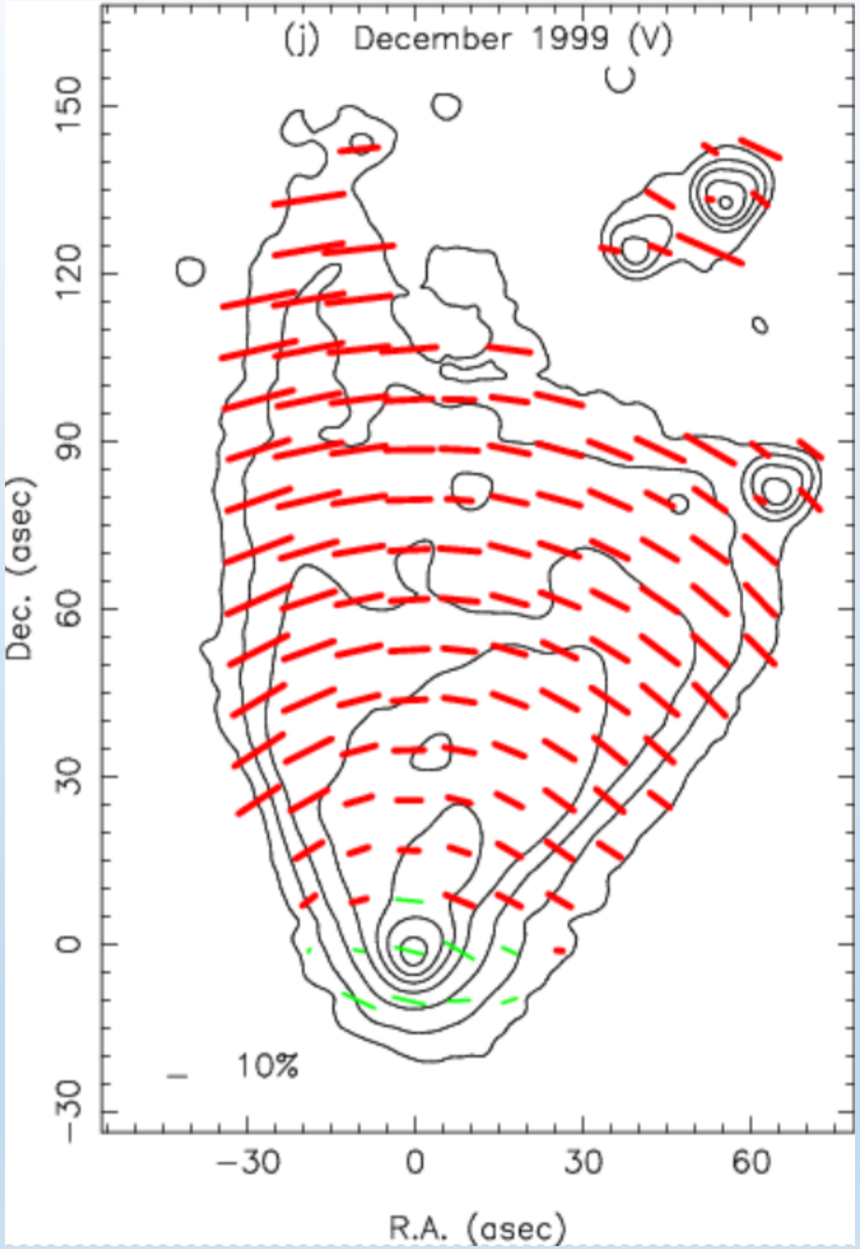


Figure 11. The *I* data used in Fig. 10 but plotted so as to highlight the deviations from the circular symmetry expected for a simple reflection nebula. The centres of measurements of polarization parameters are equally spaced on circles concentric about R.Mon. For a simple reflection nebula all vectors should be tangential to the circle on which it is drawn. Note the drastic deviations in the central regions; this is the polarization disc. To the north of R.Mon there is the expected centro-symmetric pattern representing the optically thin reflection nebula. On the eastern and western peripheries of this region the pattern is distorted.

R Mon: Scarrott + 1989 MNRAS 237 621



R Mon: Matsumura et al. unpublished (not yet?)

A Model of Single Scattering by Aligned Grains

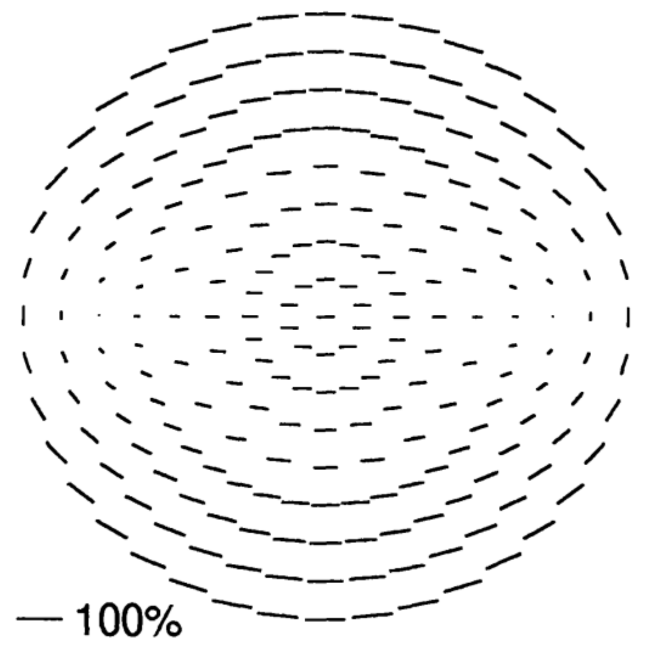


Figure 2. Linear polarizations by oblate (2:1) grains (left) and those by spherical grains (right).

Matsumura & Seki 1996, ASPC 97, 63

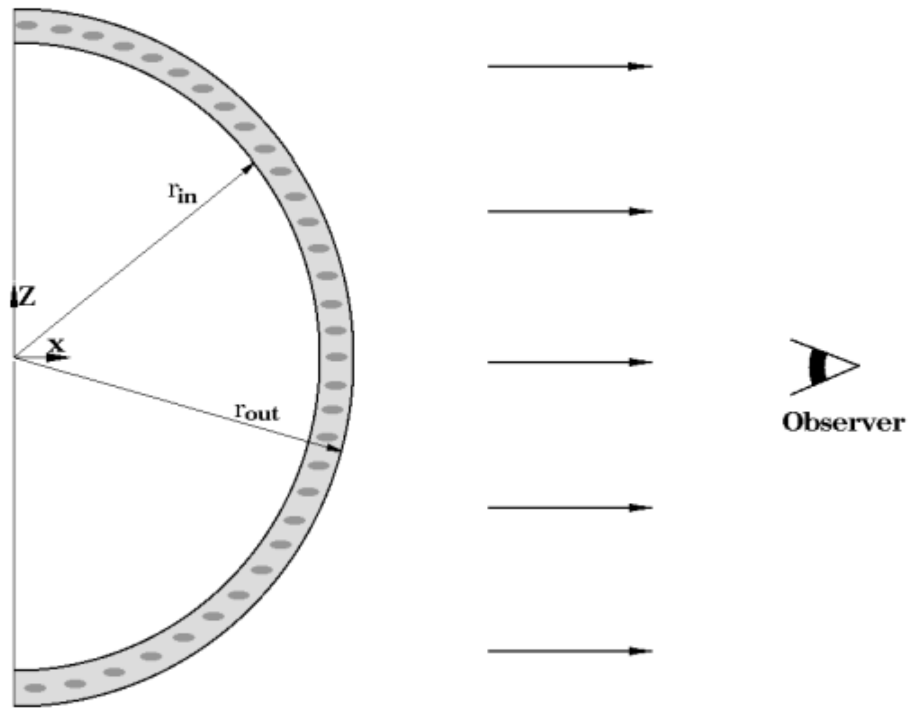
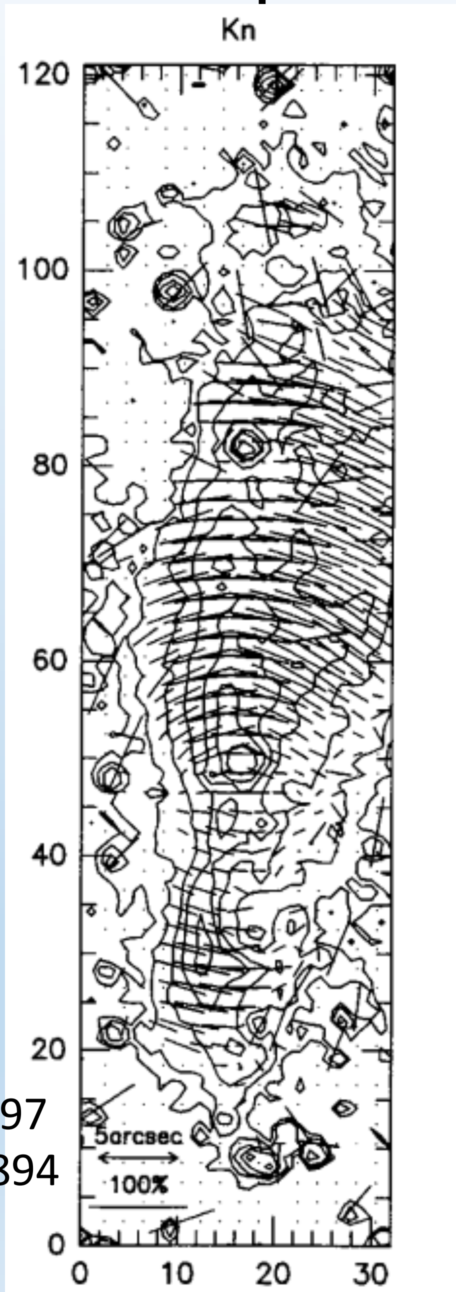


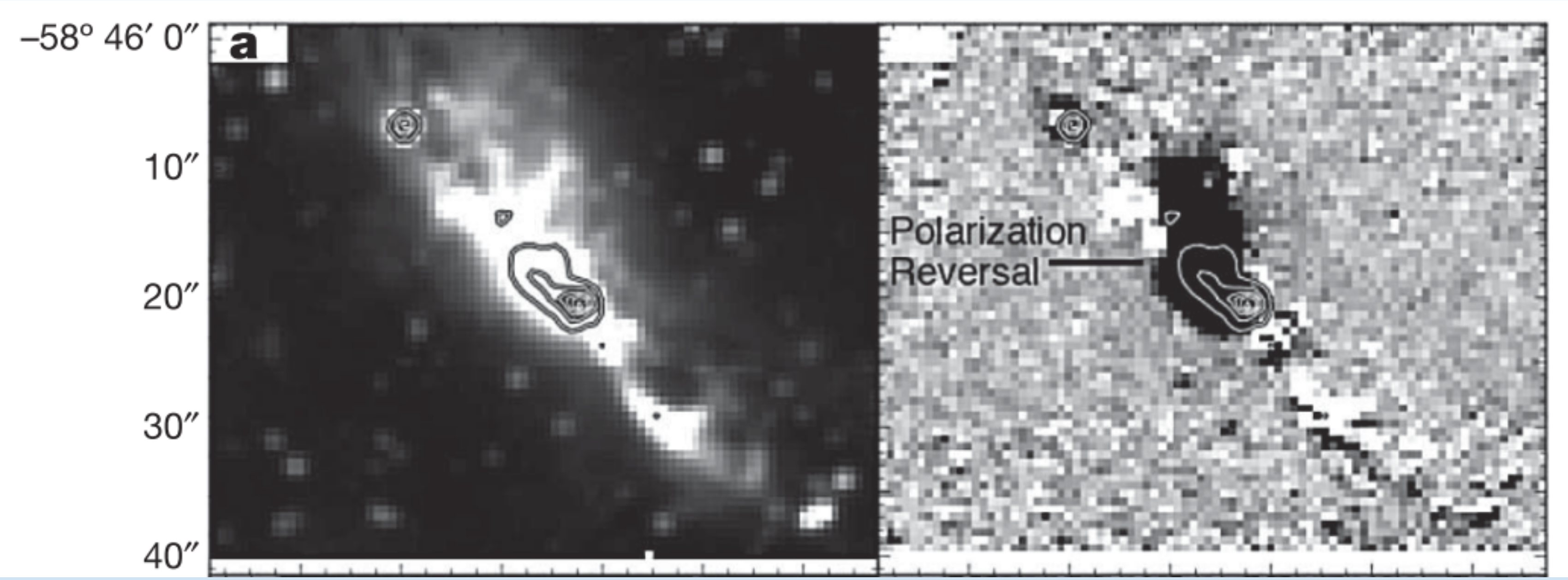
Fig. 4. Model configuration for comparison with the results of Matsumura & Seki (1996). It consists of a thin dust layer at the surface of a hemisphere. The ratio of the inner radius to the outer one amounts to $r_{\rm in}/r_{\rm out} = 0.99$. The shell contains oblate grains, whereby their rotation axes (b) are oriented parallel to the z-axis. The dark grey oval pattern symbolizes the aligned grains. The configuration is shown for $y = 0$ (xz-plane, the azimuthal angle $\Phi = 180°$). An observer sees the radiation at the scattering angles $\Theta = 0°–90°$. In this case the condition $\Theta + \alpha = 90°$ is satisfied in all points of the dust layer.

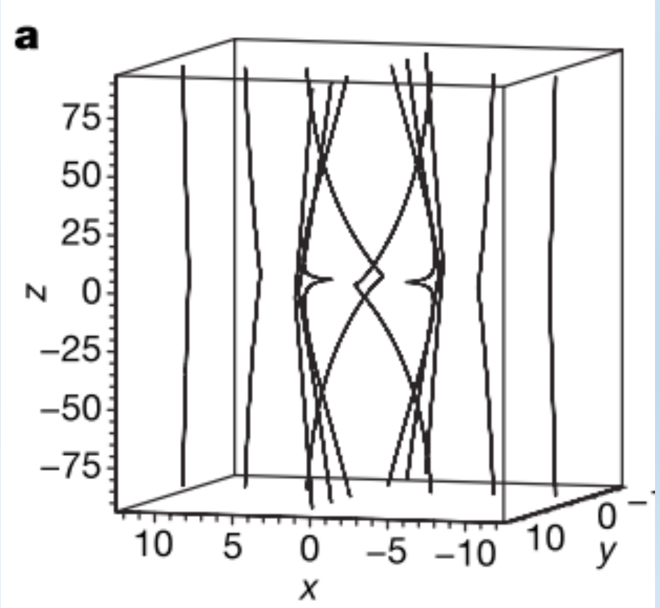
Wolf et al 2002, AA 385, 376

Circular polarization in outflow of HH135-136



Tamaura + 1997
MNRAS 287, 894





Left: intensity (Kn-band)
Right: circular polarimetry (Kn-band)
Black: negative, white: positive CP
Minimum Pc = -8%.
Chrysostomou + 2007 Nature 450, 71

Pinched magnetic field is proposed.
If nonspherical grains are aligned, and
ligt is scatterd by them, PC will appear.

Grain Alignment is common in outflow region?

- Large circular polarization is only in massive star-forming regions?:
  - 15% (H) in R CrA (Clark et al 2000)
  - 15% (K) in OMC1 (Bailey et al. 1998; Chrysostomou et al. 2000; Buschermoehle et al. 2005)
  - 23% (K) in NGC6334V (Menard et al. 2000, Kwon et al. 2013)

… Grain alignment may be common in the massive SFRs? But only massive SFRs?

- If this is the case, why?
  - Strong B in massive SFRs? and/or Grains strongly illuminated by star(s)? → Those make RAT alignment more effective.
  - B fields in massive SFRs are simpler than those in lower ones?
  - Or we just overlooked large PC in less massive SFRs?

  - → Systematic Observation of YSOs with SPICA will answer such questions.

That’s it!   Thank you!