Grain Alignment and Magnetic Field

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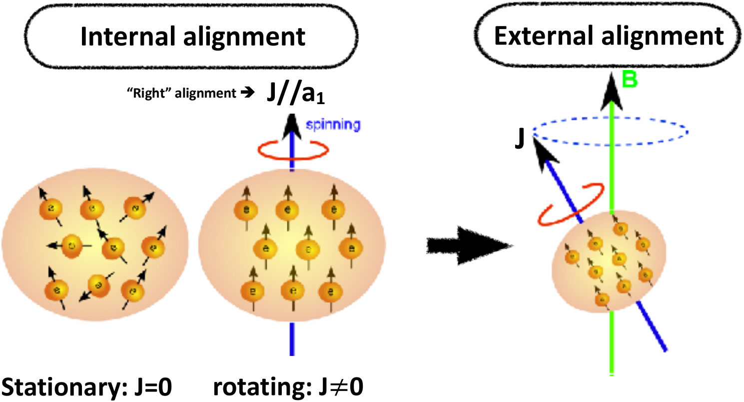
Probing Cosmic Magnetic Fields

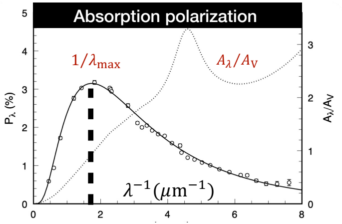
- **Zeemann effect** (radio)
  - Advantage: line-of-sight and position-of-sky B-fields,
    cold gas → star-formation studies
  - Disadvantage: calibration challenge and telescope time.
- **Faraday rotation** (radio)
  - Advantage: line-of-sight B-fields
  - Disadvantage: only for ionized gas → less relevant to SF studies
- **Synchrotron polarization** (radio)
  - Advantage: regular/total B-fields
  - Disadvantage: high-energy particles → less relevant to SF studies
- **Dust polarization** (optical/NIR and FIR/sub-mm)
  - Advantage: position-of-sky B-fields
    dust → star-formation studies
  - Disadvantage: no line-of-sight B-fields.

Alignment Mechanisms[1]



[1]Only considering paramagnetic grains (e.g., astrosilicate)
Disregarding diamagnetic grains (e.g., carbonaceous)

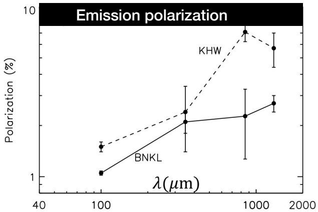
Observed Polarization Features



Whittet 2004 and refs therein

- Absorption pol. degree gets **decreased** at Optical-UV.
- Extinction is higher in this wavelength range.

➡ Small grains are weakly aligned



Vaillancourt 2008 and refs therein

- Emission pol. degree gets **increased** at FIR-Submm.

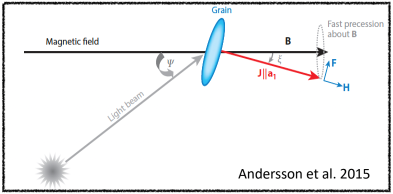
➡ Large grains are effectively aligned.

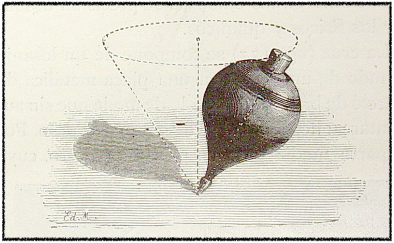
Brief Summary of Alignment Theories

- **Paramagnetic relaxation** (Davis-Greenstein 1951): Grains are spun-up by gas collisions
  - ○ rotating of large grains is effectively damped —> large grains are weakly aligned (Hoang & Lazarian 2016a,b)
- **Pinwheel torques** (Purcell 1979): Superthermally rotation due to the recoil of H_2 desorptions
  - ☑ Overcome the damping
  - ○ torques fixed to grain-body —> alignment is reduced by thermal flipping (Lazarian & Draine 1999) —> not able to align large grains (Weingartner et al. 2021)
- **Radiative Torques** (e.g., Dolginov & Mitrofanov 1976; Lazarian & Hoang 2007a): Grains are spun-up by scattering of photons on irregular grain shape
  - ☑ able to align large grains
- **Stochastic torques** (Gold 1952): Grains are spun-up by stochastic gas collisions
  - ○ inefficient to align large grains (Hoang & Tram 2019)
- **Mechanical torques** (Lazarian & Hoang 2007b; Hoang et al. 2018): Grains are spun-up by regular torques due to gas collisions
  - ☑ more effective than Gold alignment
  - ☑ effectively align grains with sub- and super-sonic incident gas flows

RATs are expected to dominate over METs in most conditions (Lazarian & Hoang 2021)

Radiative Torque (RAT) Alignment theory

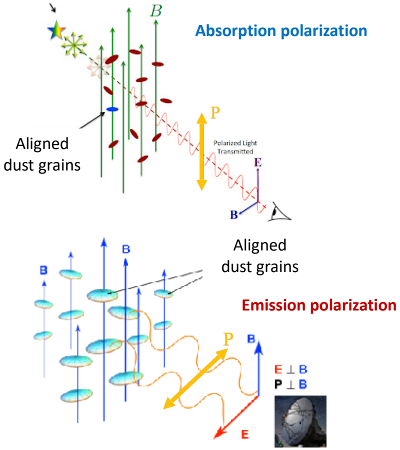




- Anisotropic radiation field causes irregular grains to rotate (Dolginov & Mitrofanov, 1976).
- Rotation damped by gas collisions and dust re-emission
- Internal alignment due to Barnett relaxation (Barnett, 1909)
- Alignment with external B-field due to Larmor precession

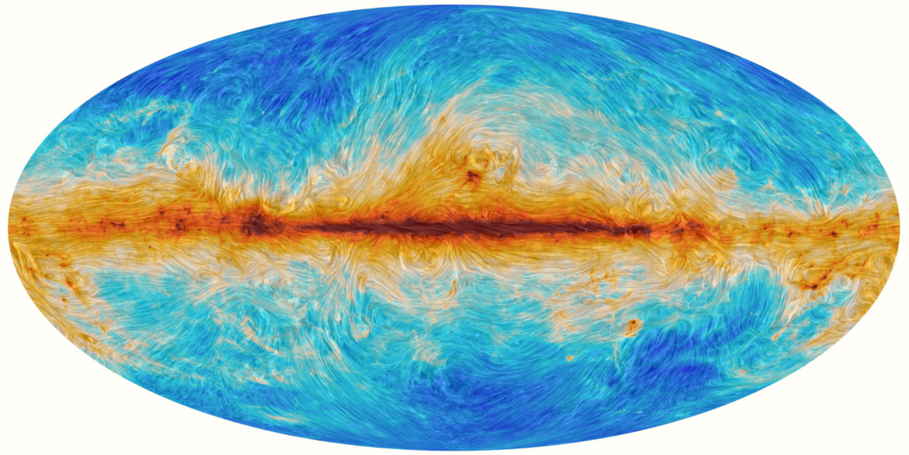
- For ISRF, alignment efficiency $\approx 50\%$
- ➡ RAT's predictions are successfully tested by observations (e.g., Andersson et al. 2015)

Radiative Torque (RAT) Alignment Theory



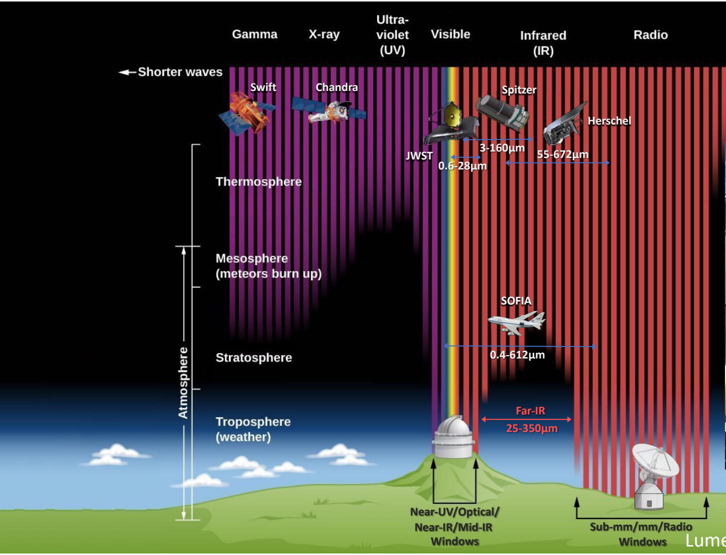
- Absorption pol. is parallel to B-fields
  - Pol. vectors → B_{POS} morphology
  - Observable at UV-NIR wavelengths
- Emission pol. is perp. to B-fields
  - Rotating the pol. vectors by 90^{o} → $B_{\rm POS}$ morphology
  - Observable at FIR-Submm wavelengths
- B-strength:
  - "Tradition"
    - Davis 1951; Chandrasekhar-Fermi 1953
  - "Improvement"
    - Falceta-Gonçalves et al. 2008
    - Hildebrand et al. 2009; Houde et al. 2009
    - Skalidis & Tassis 2021
    - Lazarian et al. 2022

Galactic Magnetic Fields @5' with Planck



https://www.ias.u-psud.fr/soler/planckhighlights.html

Stratospheric Observatory for Infrared Astronomy (SOFIA)



Adapted from Lumen Learning/STScI/JHU/NASA

Cosmic Magnetic Fields with SOFIA/HAWC+

Orion Nebula

Serpens South

30 Doradus

Milky Way Center

NGC 1068

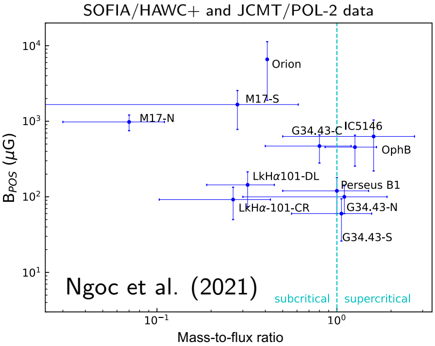
M82

M51

There are many more …

Credit: NASA/SOFIA

Star Formation in Strong B-fields

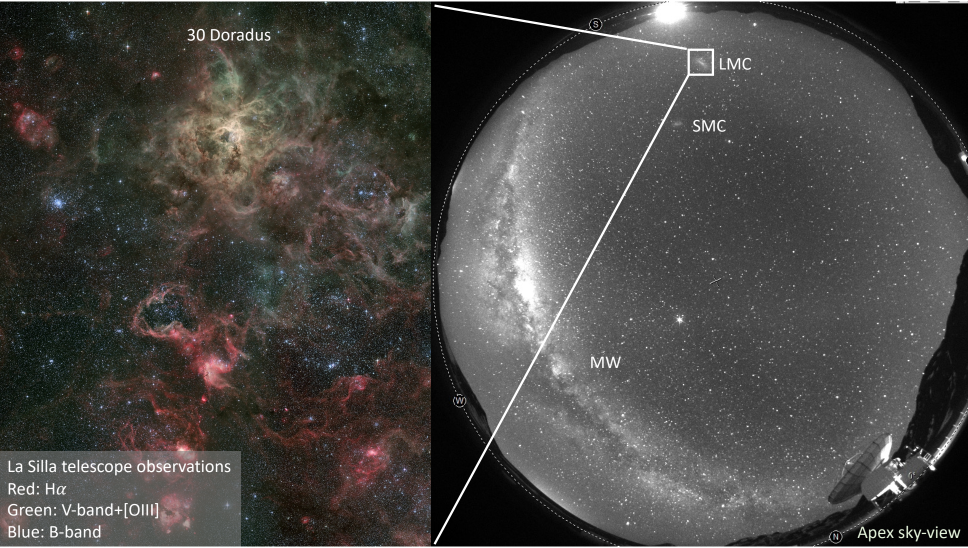


- Observations of some near-by star-forming regions showed $\lambda < 1$
- Star formed in strong B-fields?

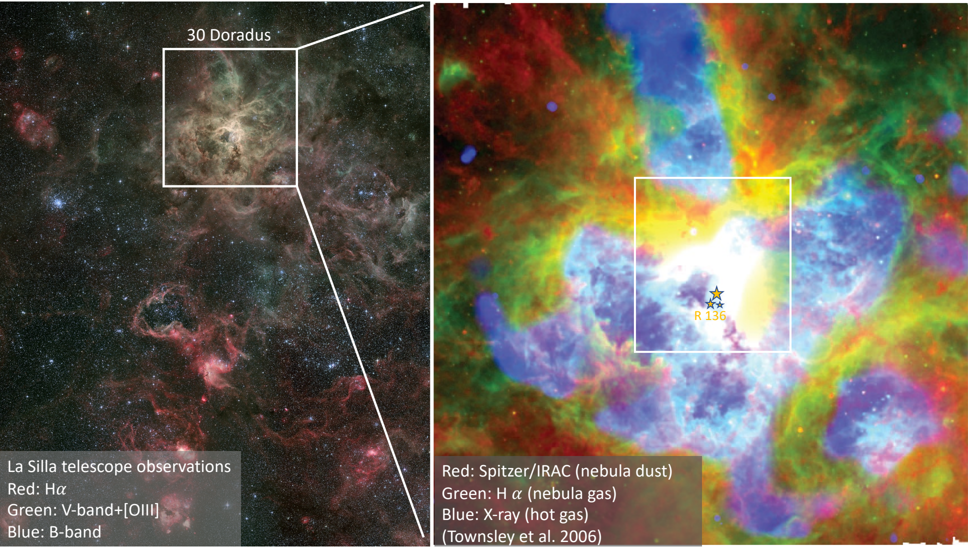
Gravity, B-fields, and turbulence are keys to studying star-formation

- Alfvénic Mach number ($\mathcal{M}_\mathrm{A}$) ("turbulence/B-fields")
  - $\mathcal{M}_\mathrm{A} > 1$: super-Alfvénic (strong turbulence)
  - $\mathcal{M}_\mathrm{A} < 1$: sub-Alfvénic (strong B-fields)
- Mass-to-flux ratio (λ) ("gravity/B-fields")
  - $\lambda > 1$: super-critical (gravity dominant)
  - $\lambda < 1$: sub-critical (strong B-fields)

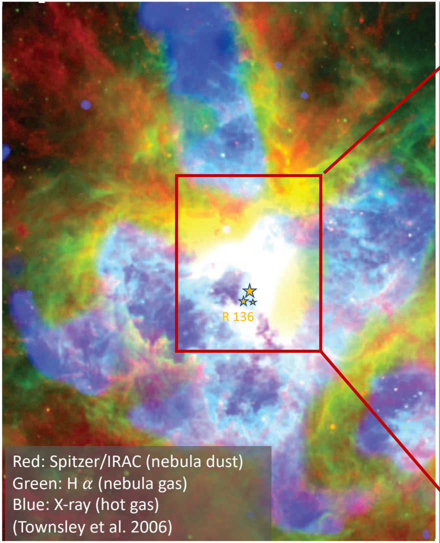
A Case Study of 30 Doradus



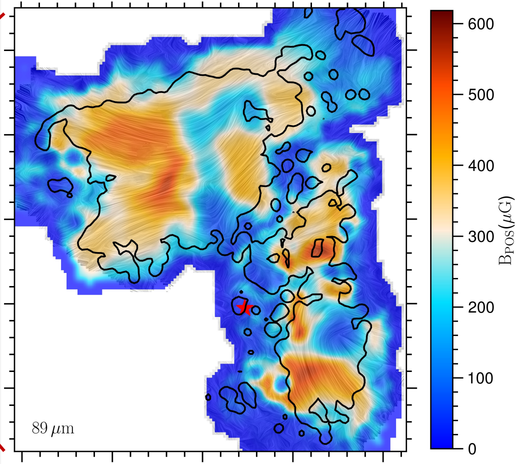
A Case Study of 30 Doradus



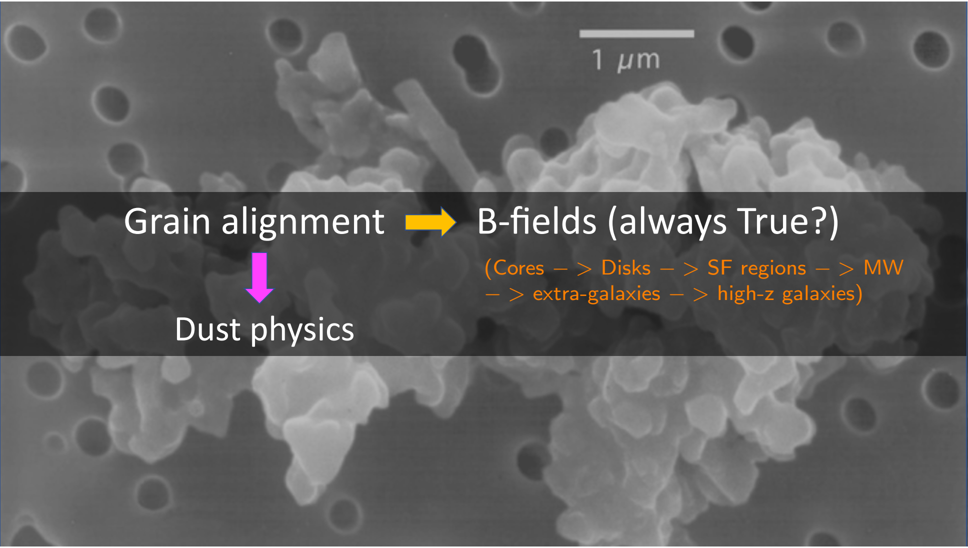
A Case Study of 30 Doradus



Tram et al. (2023)



Role of B-fields: Ngoc's talk on Thursday



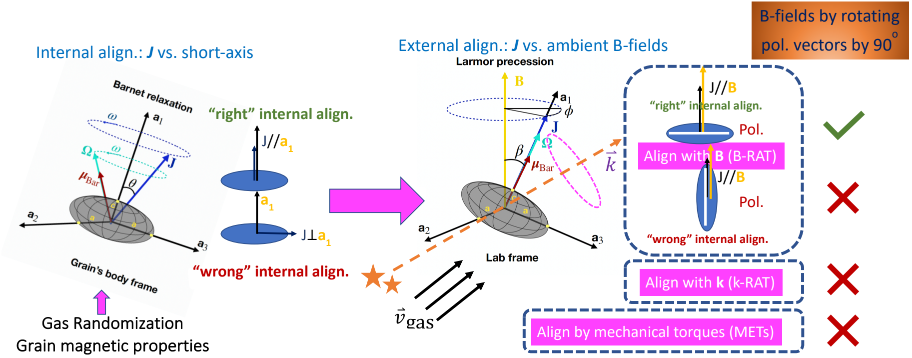
Grain alignment → B-fields (always True?)

(Cores – > Disks – > SF regions – > MW – > extra-galaxies – > high-z galaxies)

↓

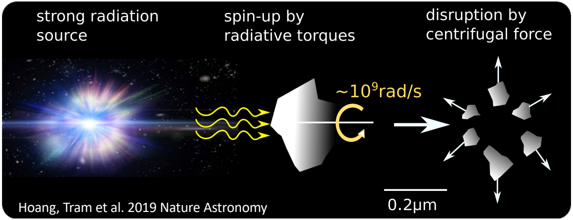
Dust physics

Dust Polarization vs. Magnetic Field



- Dust polarization does not always trace B-field
  - Diffuse + MC: likely a reliable tracer
    (reviewed in Andersson+2015; Tram & Hoang 2022)
  - Cores/Disks: unlikely a reliable tracer [warning!]
    (details in Hoang, Tram et al. 2022)
- Dust polarization → B-field with caution

Radiative Torque Disruption (RAT-D) Mechanism



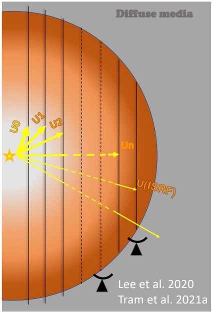
- Large grains exposed to a strong radiation field (or high $T_{\rm d}$ as a proxy) can be spun up to very fast rotation by RATs.
- Induced centrifugal force can exceed the binding force that holds the grain's structure $\rightarrow$ Disruption the large grain into smaller species (RATD mechanism)
- Disruption efficiency depends on the gas density, radiation strength, and grain porosity
- Disruption affects on the largest grains $\rightarrow$ modification of the grain-size distribution

RAT paradigm: RAT-A theory + RAT-D mechanism

(Other application: see Hirashita's talk on Thursday)

Simplified modeling: DustPOL

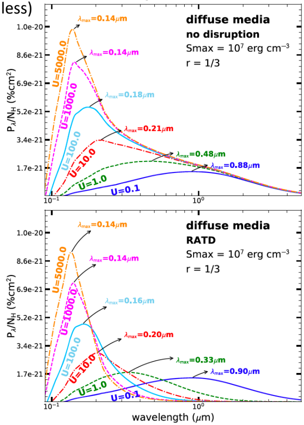
$U = u_{rad}/u_{ISRF}$ radiation strength (dimensionless)



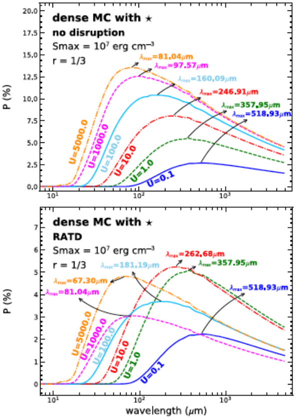
❖ Starlight + thermal dust pol.
❖ RAT + RAT-D
❖ Uniform B-fields
❖ Perfect internal alignment

Lee et al. (2020)
Tram et al. (2021a)

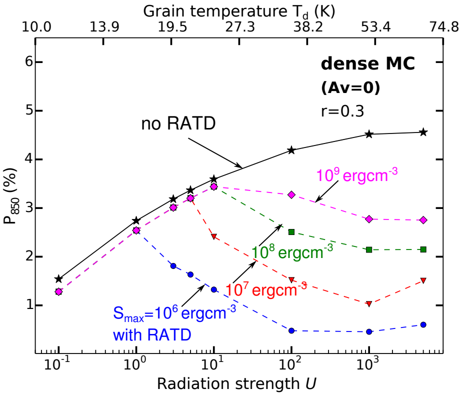
abs. polarization



emi. polarization



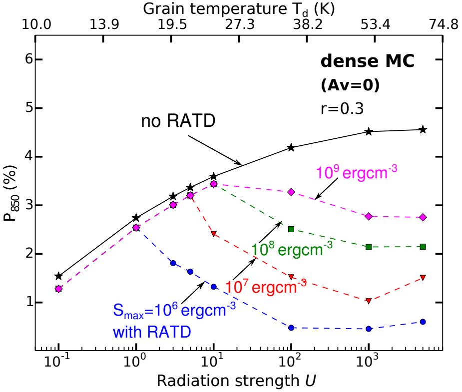
Simplified modeling: DustPOL



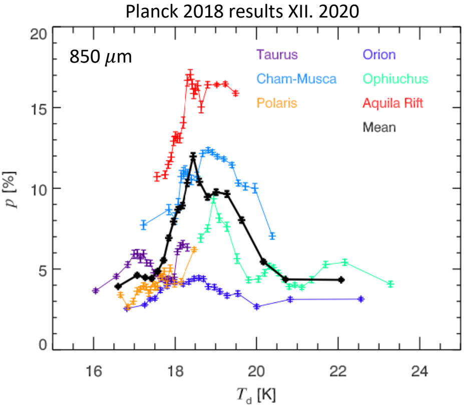
Lee et al. (2020)

- Only RAT:
  monotonic increase of $p(\%)$ with $T_{\rm d}$
  → classical RAT
- With RAT+RATD:
  - "small" $T_{\rm d}$: no disruption
    → $p(\%)$ increases → classical RAT
  - "high" $T_{\rm d}$: disruption
    → $p(\%)$ decreases
    → opposite to classical RAT
  - $T_{\rm d,\,crit}$ depends on
    - ambient prop.: U, $n_{\rm H}$, $T_{\rm gas}$, ...
    - grain prop.: size, shape, ...
    - hardness: $S_{\rm max}$

DustPOL vs. Observations

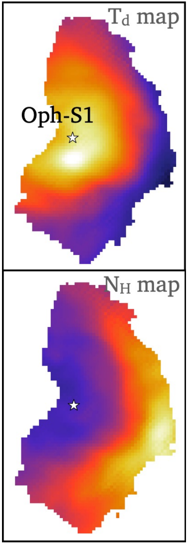


Planck data @40′



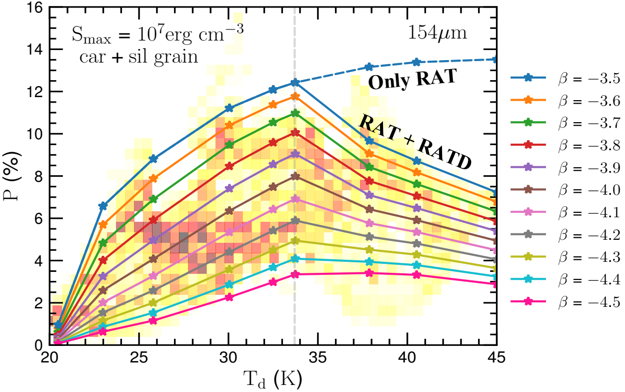
DustPOL vs. Observations

ρ Oph-A cloud



Santos et al. (2019)

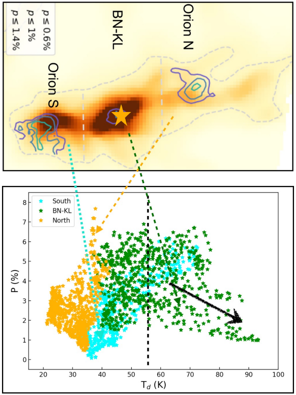
SOFIA/HAWC+ @14''



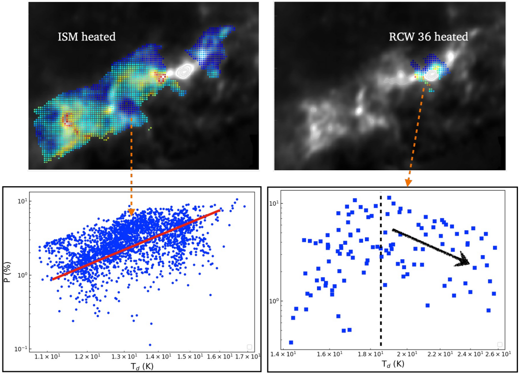
Tram et al. (2021a)

DustPOL vs. Observations

OMC-1 (SOFIA/HAWC+)
(Ngoc et al. in prep.)



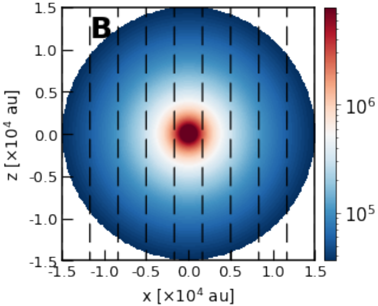
Vela-C (BLASTPol)
(Fissel et al. 2016)

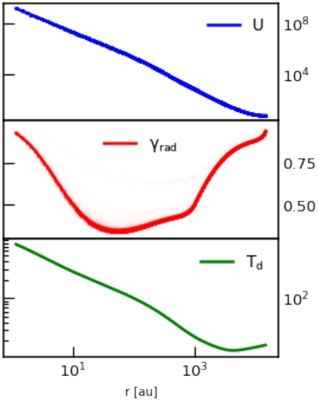


many more observational pieces of evidence ...

e.g., 30 Dor (Tram et al. 2021c)
M17 (Hoang et al. 2021)
NGC 6334 (Arzoumanian et al. 2021)

Synthetic Simulation: updated POLARIS





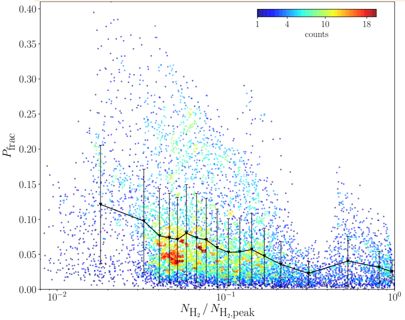
- 3D Monte-Carlo Radiative Transfer code
- RAT + MRAT[2] + RATD
- "Realistic" internal alignment
- "Realistic" external alignment

- POLARIS: Reissl et al. (2016)
- POLARIS Plus: Giang, Hoang, Kim & Tram (2023)

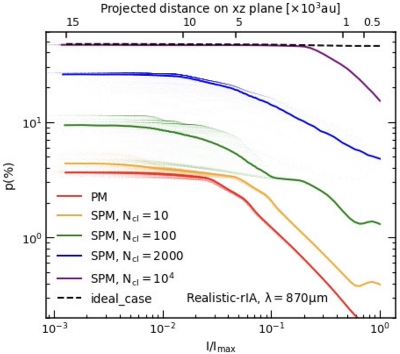
[2] Magnetically Enhanced Radiative Torque Alignment

POLARIS vs. Observations

A sample of Class 0 protostellar cores



Le Gouellec et al. (2020)



Giang, Hoang, Kim & Tram (2023)

- SPM: super-paramagnetic grain
- PM: Paramagnetic grain
- N_{cl}: number of iron cluster

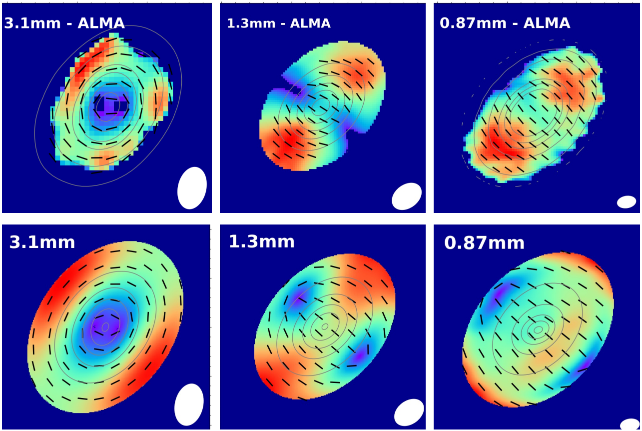
- ALMA: $p(\%)$ could be up to 40%[3]
- We need:
  - SPM with "amount" of iron!? and/or
  - Strong-Bfield

[3] Planck: $p(\%)$ up to 20%

POLARIS vs. Observations: HLTAU Protoplanetary Disk

Observations (ALMA)

Simulations (POLARIS+)

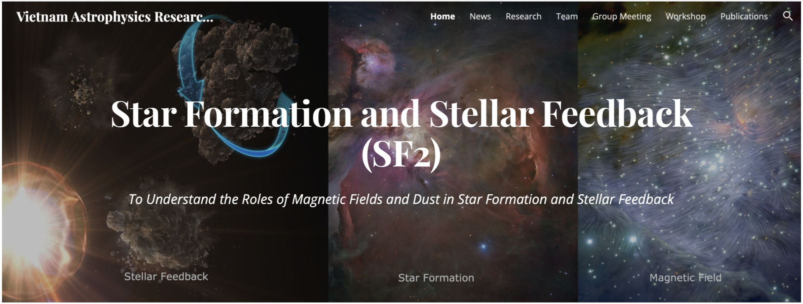


Alignment mechanisms

- Magnetically aligned dust grain with wrong IA
- Self-Scattering

Thang et al. in prep.

Vietnam Astrophysics Research Network (VARNET)



- PIs: Prof. Thiem Hoang (Korea), Prof. Diep Pham (Vietnam), Dr. Tram Le (Germany)
- Goals: train young students and foster collaboration among Vietnamese researchers
- Community: 22 members (10 researchers - 6 grad students - 6 undergrad students)
- First impressions:
  - 6 undergrad students were fully funded to the grad programs: Korea, France, USA, UK
  - Organize 3 international workshops
  - >15 publications on Q1 journals
- Supports: Simons Astrophysics Group at ICISE (SAGI)

Conclusion and perspective

Conclusions

1. Polarization orientations could infer B-field (but need to be verified)
2. Polarization percentage allows to study of the basic dust physical properties (e.g., shape, mineralogy, helicity, internal structure, size distribution)
3. RAT paradigm: RAT/MRAT alignment theory and RAT-D mechanism is essential for observation interpretations
   - Numerical modeling: DustPOL (https://github.com/lengoctram/DustPOL)
   - Numerical simulation: POLARIS+ (publicly available soon)
4. Multiple-wavelength dust polarization is essential! (e.g., synthesizing SOFIA/HAWC+, APEX/A-MKID, CCAT-P, JCMT/POL-2, IRAM/NIKA-2)

Perspectives

1. Alignment of diamagnetic (e.g., carbonaceous) grains (Hoang, Minh & Tram subm.)
2. Grain alignment by Mechanical Torque (MET) (Tram & Hoang in prep.)
   - → DustPOL: RAT-based and MET-based
   - → POLARIS: RAT-based and MET-based