Interstellar Grain Alignment Observations

"In theory you can do whatever you want unless you've got numerical agreement"

A. Lazarian (this meeting)

Let's try to do one better and compare to ***observations***…

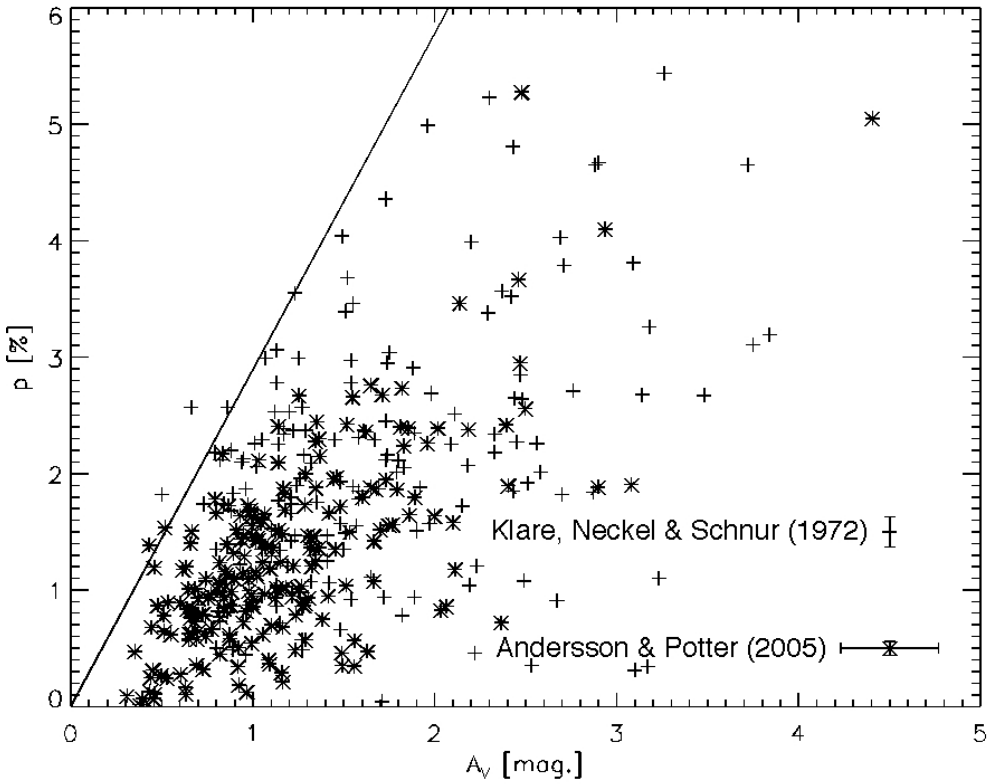
B-G Andersson

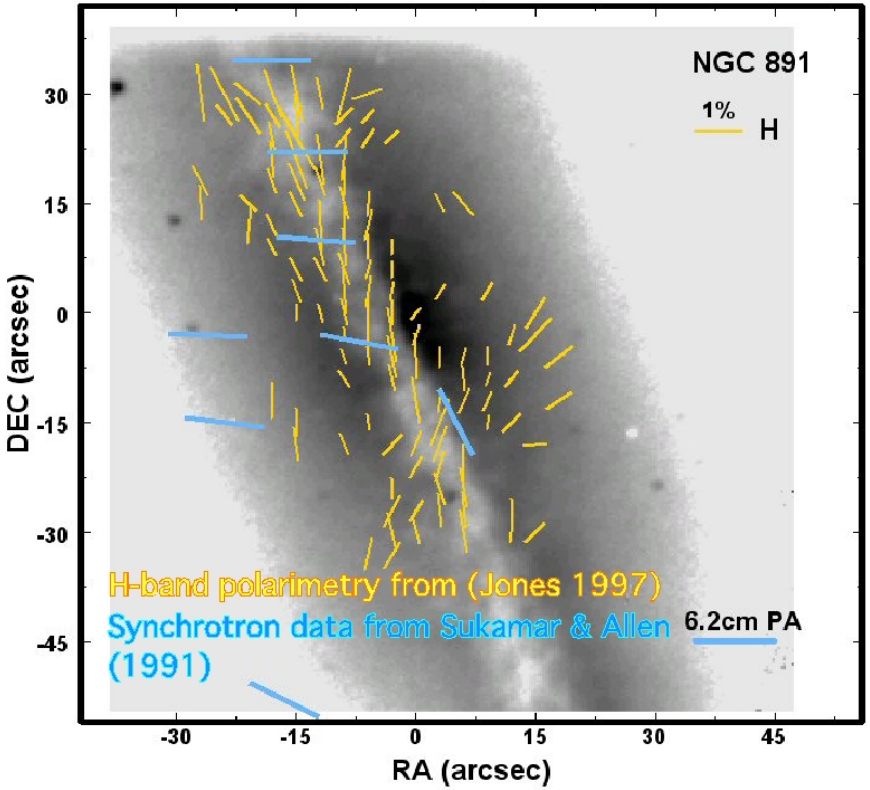
SOFIA Science Center

USRA

Thanks to: S. Potter, J. Vaillancourt, D. Clemens, T.J. Jones, M. Charcos-Llorens, S. Shenoy, V. Piirola, A. Lazarian, T. Hoang, etc.

O/IR continuum polarization is due to asymmetric dust grains, aligned with the magnetic field





- The upper envelope of the polarization is correlated with the column density
- The P.A. of O/IR polarization is related (±90˚) to that of synchrotron radiation

But the detailed physics of the grain alignment has been unsettled

- Does p really trace B?

Three Main Theoretical Candidates

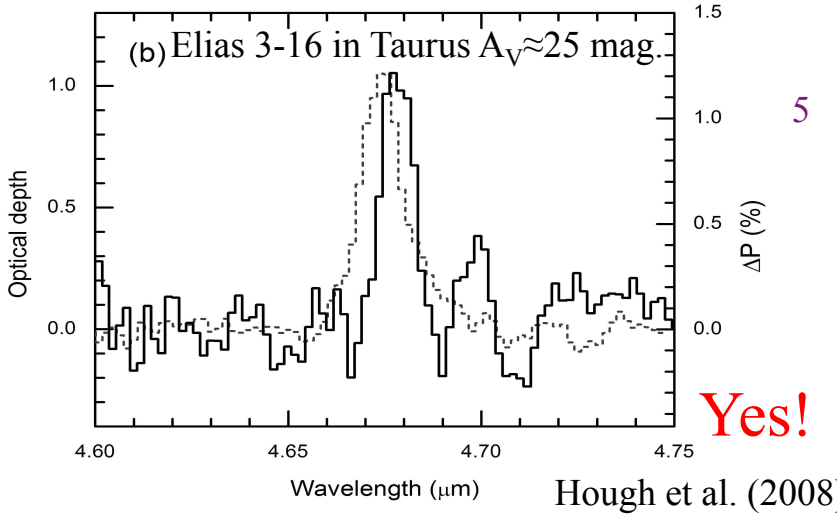
- And what they require

- *Paramagnetic Alignment* (Davis & Greenstein, 1951, Purcell 1979, Mathis 1986)
  - Requires $T_{spin} \neq T_{dust}$ and a **significant magnetic susceptibility** of the dust material (and/or H_2 formation on the grain surfaces) (Jones & Spitzer 1967)
- *Mechanical Alignment* (Gold 1952)
  - Requires Gas-dust flow (won't discuss – but -doesn't work)
- *Radiative Torque Alignment*
  (Dolginov & Mytrophanov, 1976; Drain & Weingartner 1996; Lazarian & Hoang, 2007)
  - Requires anisotropic radiation field with $\lambda < 2a$

"All observers will now agree to ignore all theorists"
R. Crutcher

Paramagnetic Alignment - Fails

- Are dust grains aligned at depths into the cloud where CO ice can survive (A_V>6-10)?
  - At such opacities:
    - $T_{spin}=T_{gas}\approx T_{dust}$ (ignoring RAT)
    - No FUV radiation
      No H_2 formation or photoelectrons



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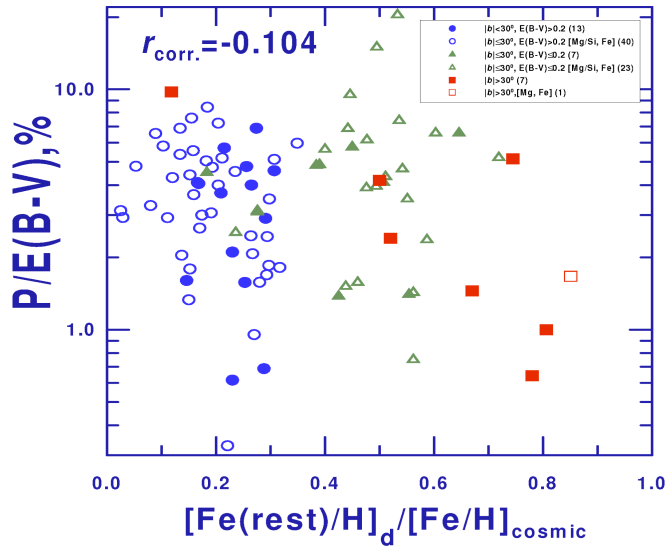
Yes!

Hough et al. (2008)

- There is no correlation between the amount of "magnetic **solid** iron" on the line of sight and fractional polarization



Voshchinnickov et al. (2012)

Radiative Alignment Torque (RAT) Alignment

- Fundamental prediction:

Grains are aligned if exposed to an anisotropic radiation field with $\lambda<2a$

c.f. T. Hoang's talk for details

- Observational predictions:
  - The alignment efficiency will vary with radiation field intensity
  - The size distribution of aligned grains will vary with the radiation field
    - For the general ISM grain alignment will fail for $a < 912Å/2$
    - For moderate opacities the polarization curve will move to the red with A_V
    - For deep star-less cores there will be a depth beyond which no alignment takes place
    - If the grains (in cores) are both heated and aligned by the radiation then FIR polarization will show a minimum in the 50-500μm range
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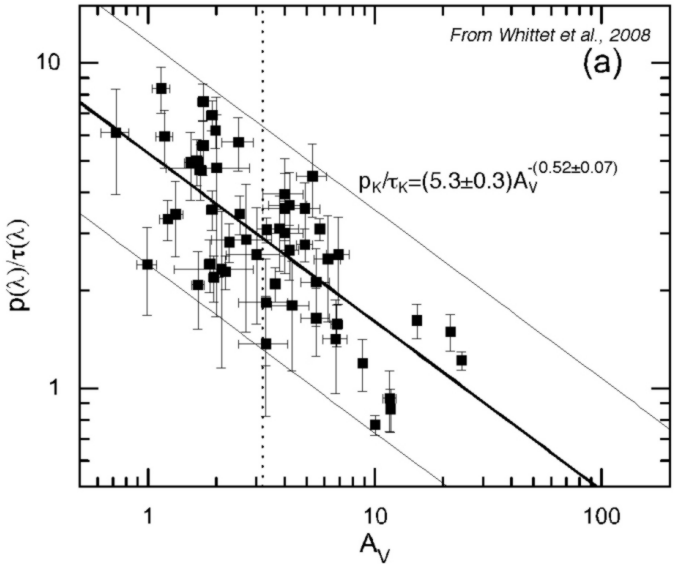
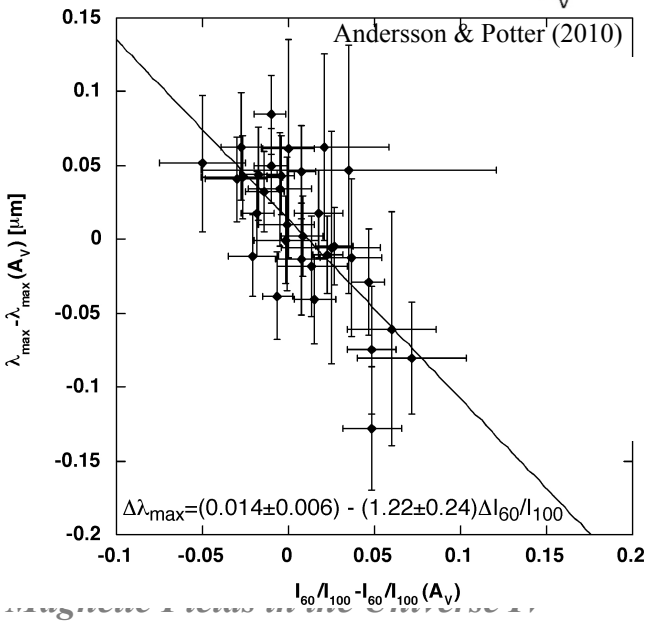
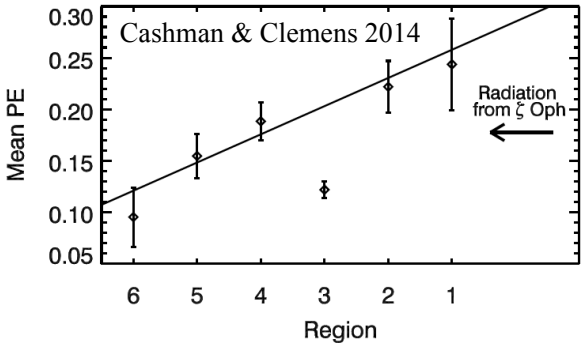
The grain alignment varies with radiation field strength

- The fractional polarization (p/τ) drops with opacity (Jones, Klebe & Dickey, 1992 (JKD); Whittet et al., 2008)
  - While magnetic field topology can explain much of this drop-off (JKD), models show observations are consistent with RAT



- The grain alignment is observed to be enhanced close to illuminating star





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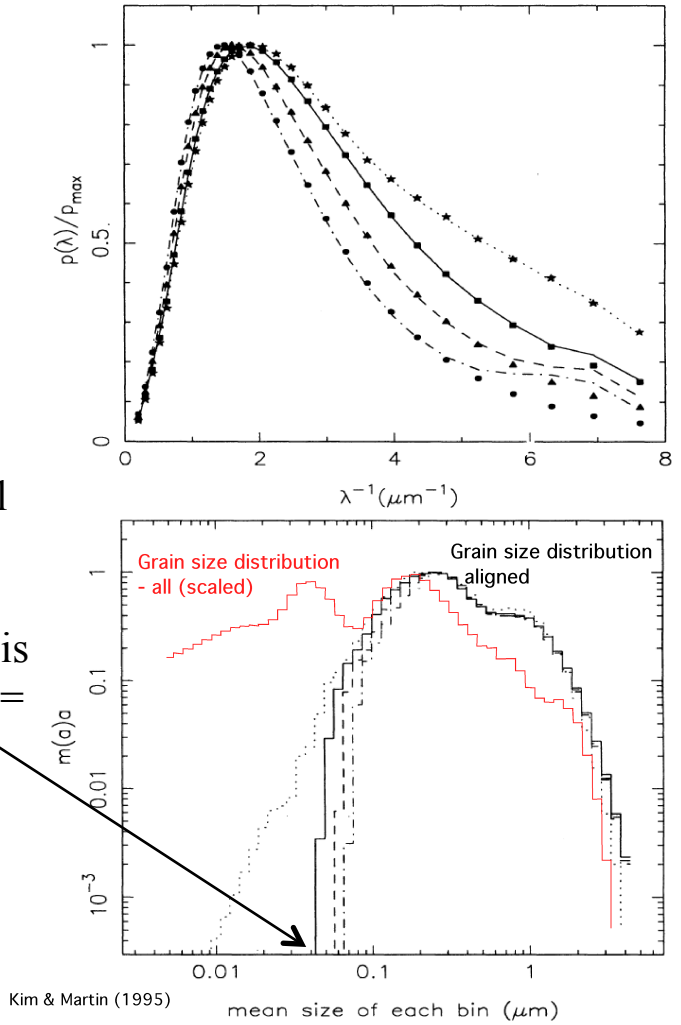
The size distribution of aligned grains will vary with the radiation field

- Modeling of the extinction and polarization curves show that only the larger grains are aligned and that the peak of the polarization curve varies with the small cut-off in the aligned grain sizes

- λ_{max} (the location of the peak of the polarization curve) can be used to measure the variations in the alignment – immune to l.o.s turbulence effects

For the general ISM the small size cut-off in aligned grains is at $a \approx 0.045\mu m$ = 912Å/2



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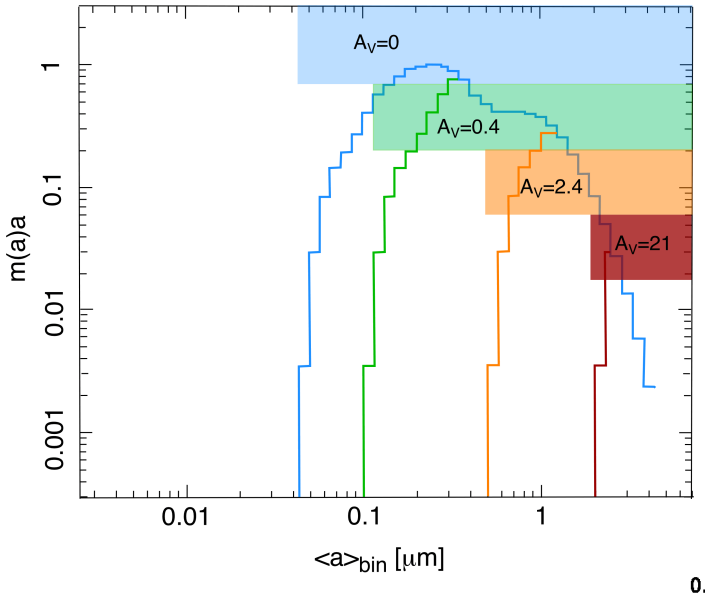
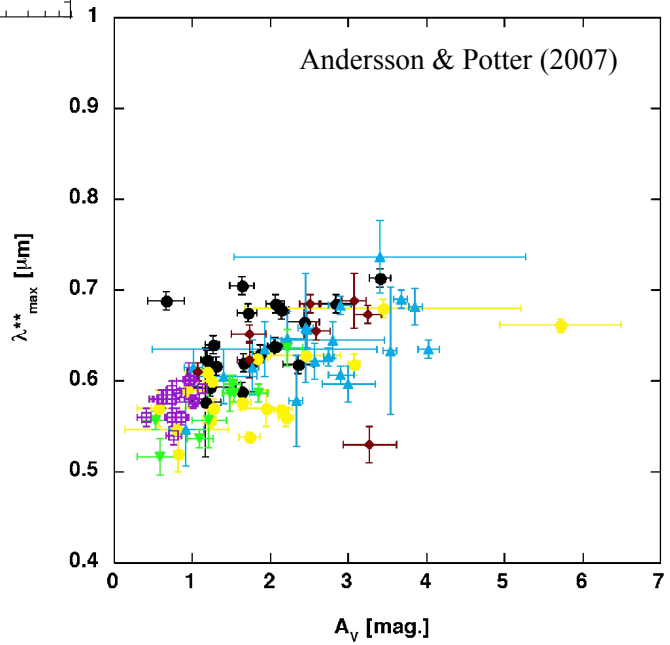
The polarization spectrum depends on the opacity

- As the radiation field reddens into the cloud, the small size cut-off of aligned grains – in RAT alignment - should increase and λ_{max} should grow.



- When we correct for different [total] grain size distributions in different clouds a universal λ_{max} vs. A_V relation is observed



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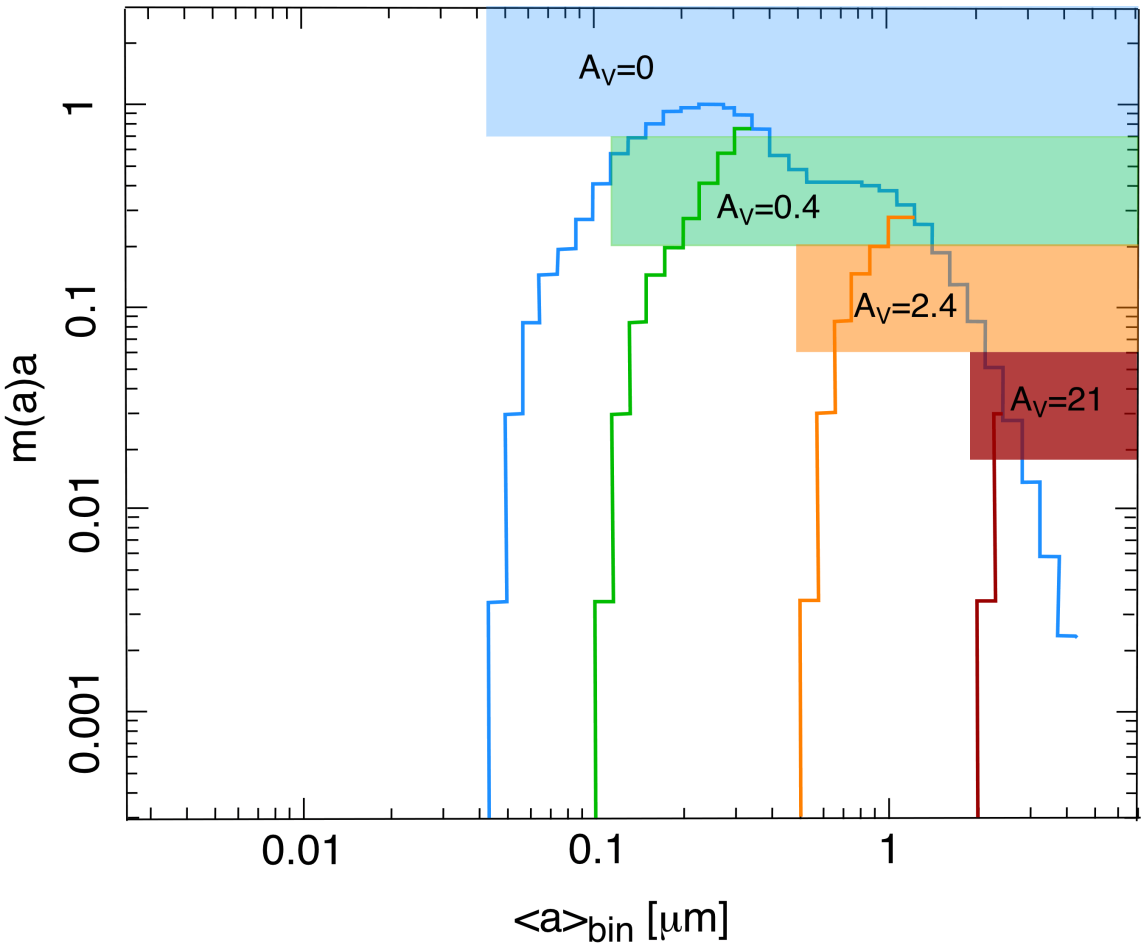
    - For deep star-less cores there will be a depth beyond which no alignment takes place

Grain alignment is lost deep into star-less clouds

- Because of [refractory] elemental abundance limitation, an upper grain size cut-off at ~1-2μm is expected (poorly constrained)
- For star-less cores this should mean that at some opacity, [almost] no grains are present that can couple to the remaining radiation field. When this happens $p/A_V \sim A_V^{-1}$
- In L183 we see an indication of this effect



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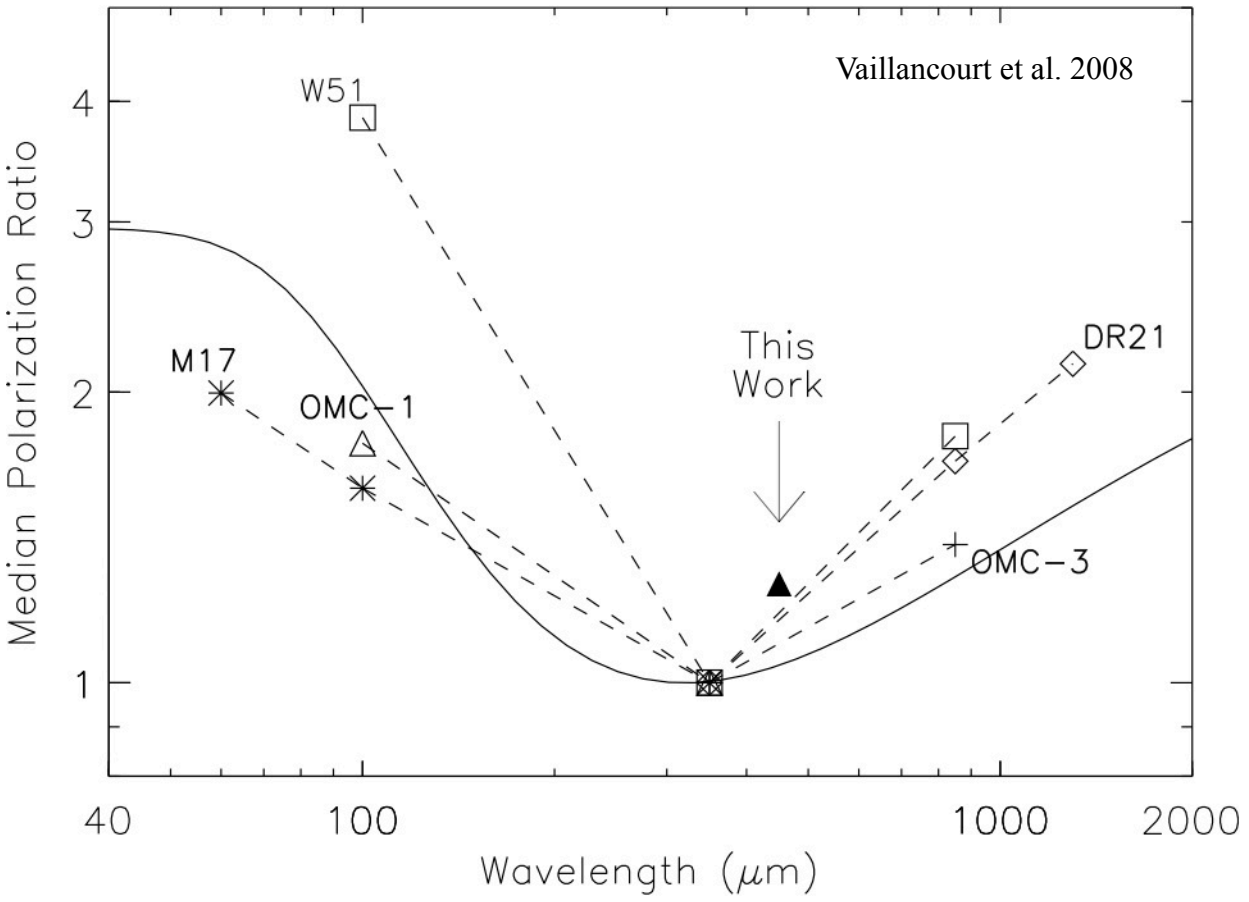
FIR/sub-mm wave polarization also supports RAT alignment

- The FIR/sub-mm wave polarization spectrum is best explained if radiation heats AND aligns the grains

- The FIR/sub-mm wave polarization spectrum requires – at least – two temperature populations



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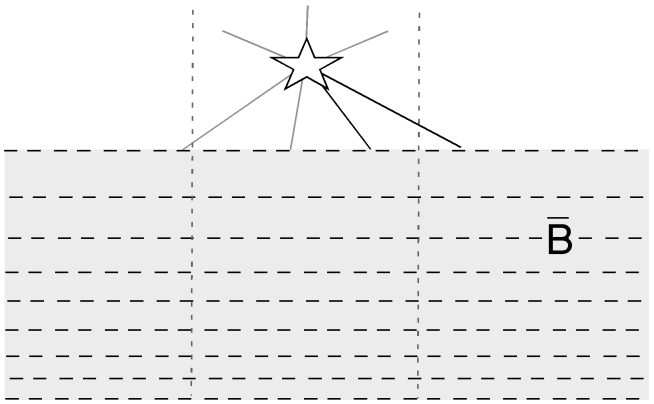
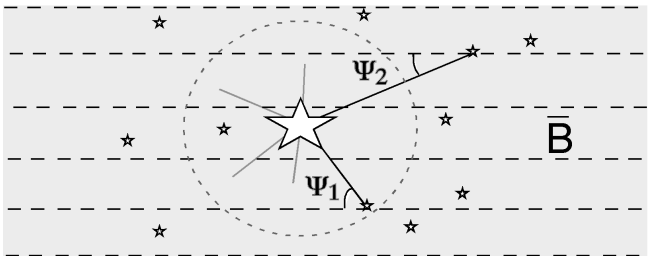
  - The alignment will depend on the angle between the magnetic and radiation field anisotropy

The alignment seems to depend on the angle of illumination

- Because the alignment of the grains with the magnetic field occurs through continual radiative torques during Lamor precession, the alignment is predicted to vary with the angle between the magnetic field and the radiation field anisotropy

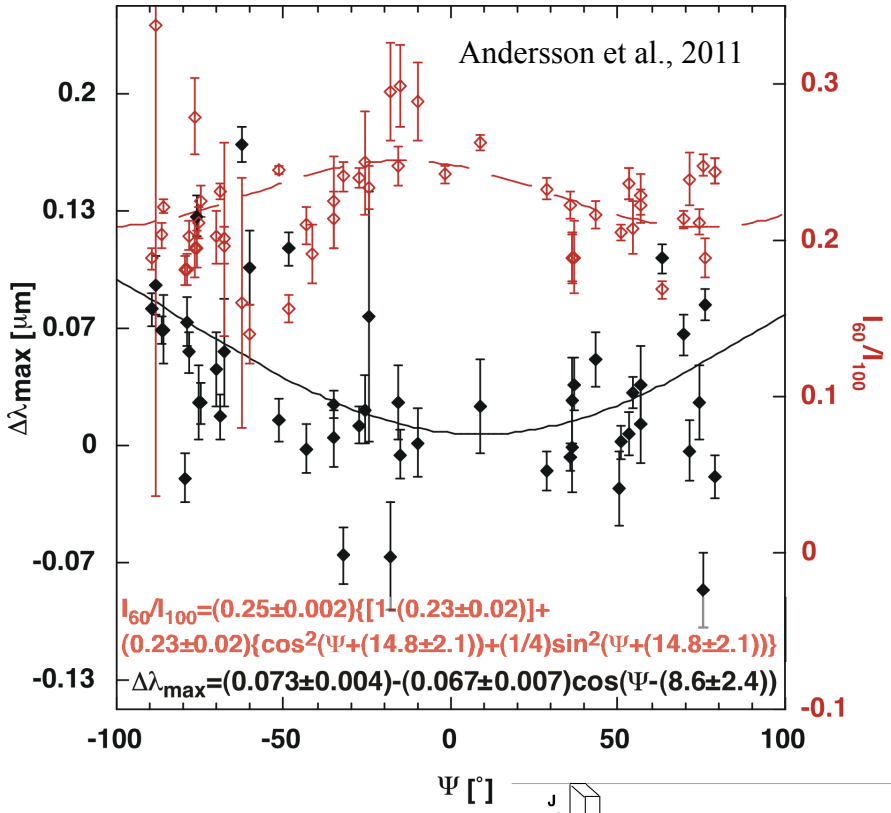


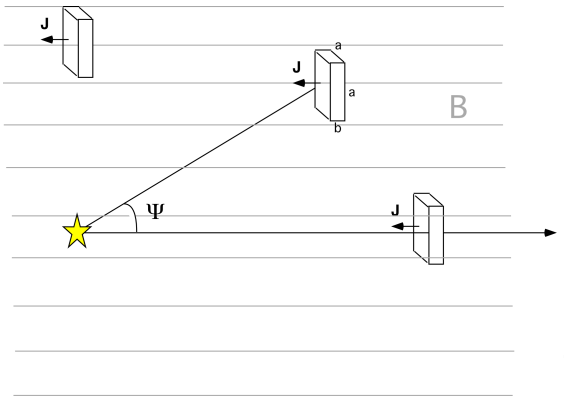
- Observing the polarization of background stars around a star illuminating the surface of a cloud can probe for this effect.



The alignment seems to depend on the angle of illumination II

- Observations of the polarization around HD97300 in Chamaeleon I indicates that grains **are** better aligned along the field lines than across.
- The (60/100mm) color temperature of shows a behavior consistent with alignment along the field, with an amplitude consistent with RAT theory





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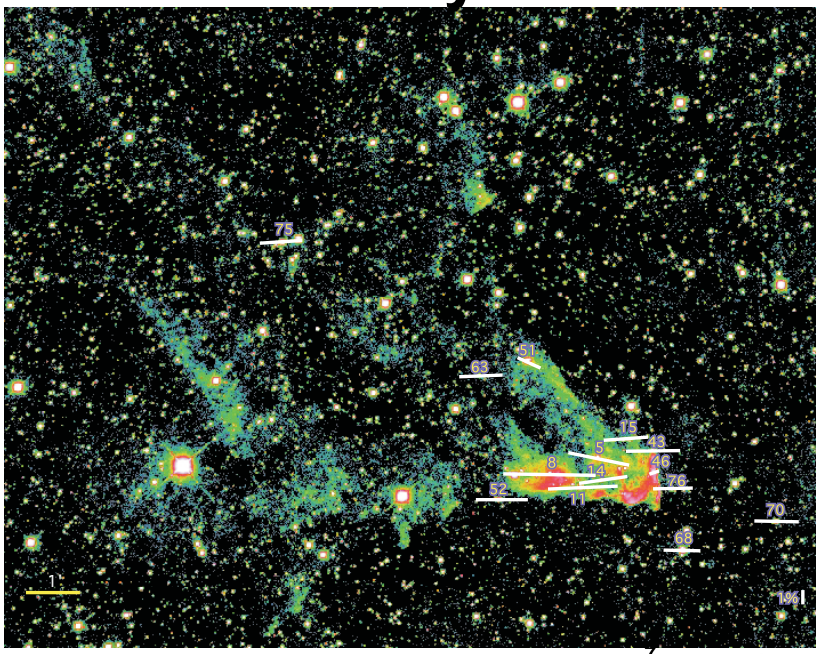
Purcell alignment has a – secondary – role in RAT alignment

- By providing additional angular momentum to the grains, Purcell rockets (H_2 formation impulses) can lift grains out of "low-J traps" and enhance the alignment.



IC 63:
H_2 1-0 S(1)
and optical pol. vectors

Note: If SPM active, H2 torques should not matter!!

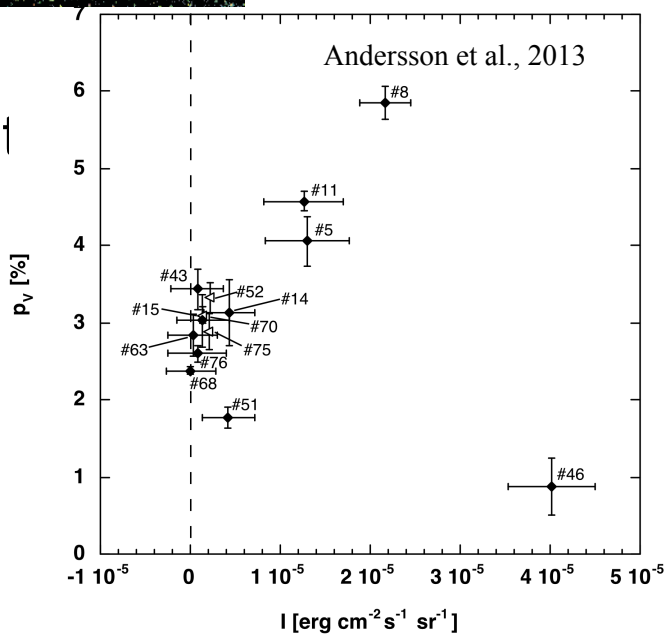
- Because H_2 destruction is initiated through line absorption and

  $t_{PDR} >> t_{photo\text{-}processes}$

  =>

  $I_{fluorescence} \sim R(H_2\ formation)$

H_2 formation enhances alignment in the reflection nebula IC 63, consistent with RAT predictions.



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But: Spoiler alert! (?)

- RAT works in all cases we've tried – except that:
  - The 2175Å "bump" is almost never polarized
    - Only in 2 l.o.s. out of 30 (Anderson et al. 1996 – that's **not** me)
  - The 3.4μm lines (CH aliphatic bond stretch) are not polarized (Chiar et al. 2006)
  - So carbonaceous grains are not aligned - ?
  - Why?
    - Are **all** carbonaceous grains very small?
      - Not thought to be the case
    - Do carbonaceous grains not possess helicity?
    - Are carbonaceous grains all round?
    - Do none of [large] the amorphous carbon grains have CH surface groups?

Summary

- Several lines of observational and theoretical inquiry indicates that paramagnetic or mechanical alignment cannot contribute significantly to the dust grain alignment in the ISM
- Radiative Torque Alignment (RAT), theory provides a number of specific – observationally testable – predictions
  - So far, all the ones that have been tried, support RAT alignment
  - BUT; what about carbonaceous grains?
  - Next step is to go from qualitative tests to quantitative comparisons between theory and observations
- A observationally supported grain alignment theory will not only allow reliable measures of the magnetic field geometry and strength but also of the micro-physics of the dust grains.