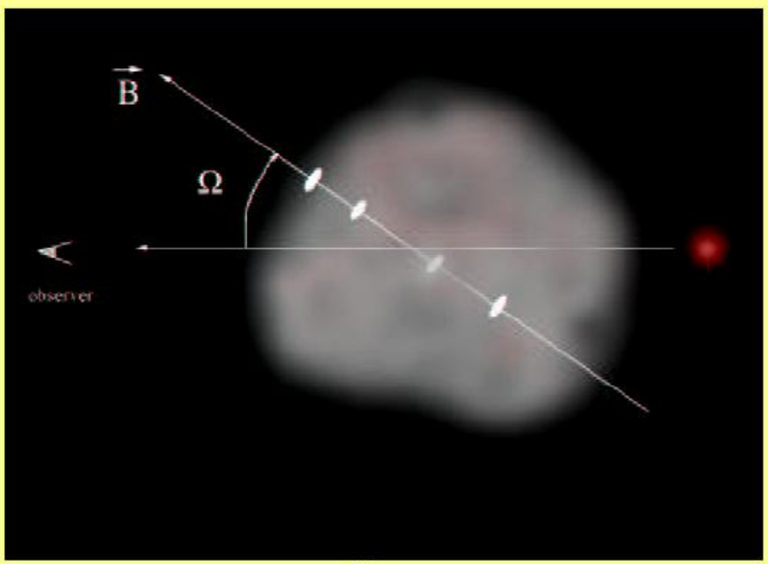
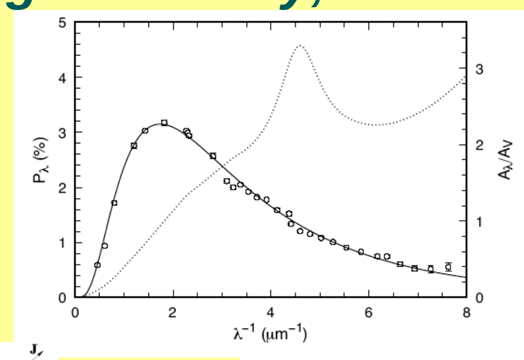
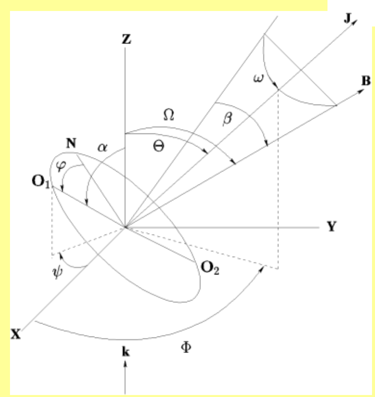
Tracing magnetic fields through interstellar polarization

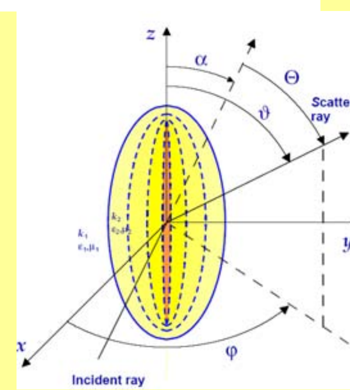
Nikolai Voshchinnikov

Sobolev Astronomical Institute, St. Petersburg University, Russia



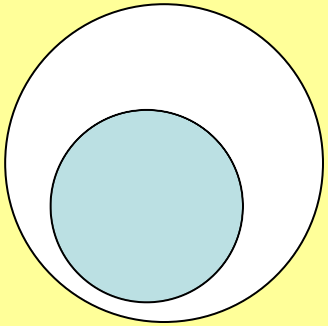






Preliminaries: Sobolev-Chandrasekhar effect

Victor Sobolev (1943/1949)
Subramanian Chandrasekhar (1946)



Electronic (Thomson) scattering in stellar atmosphere

Limb polarization: P~12.5% (11.713%)

How to observe? Eclipsing binaries!

Interstellar linear polarization: discovery

1949 – William Hiltner, John Hall, Victor Dombrovskii (searching for Sobolev-Chandrasekhar effect)

SCIENCE

FEBRUARY 18, 1949

RHYTHMIC BEHAVIOR OF THE NERVOUS SYSTEM
HUDSON HOAGLAND

POLARIZATION OF LIGHT FROM DISTANT STARS BY INTERSTELLAR MEDIUM
W. A. HILTNER

OBSERVATIONS OF THE POLARIZED LIGHT FROM STARS
JOHN S. HALL

ՀԱՅԿԱԿԱՆ ՍՍՌ ԳԻՏՈՒԹՅՈՒՆՆԵՐԻ ԱԿԱԴԵՄԻԱՅԻ ԶԵԿՈՒՅՑՆԵՐ
ДОКЛАДЫ АКАДЕМИИ НАУК АРМЯНСКОЙ ССР
X 1949 5

АСТРОФИЗИКА

В. А. Домбровский

О поляризации излучения звезд ранних спектральных типов

(Представлено В. А. Амбарцумяном 11 VII 1949)

В 1944 г. В. В. Соболев (1) показал, что в том случае, когда в атмосфере звезды рассеяние света обусловлено в основном свободными электронами, излучение, выходящее из звезды под углом Θ, должно быть поляризовано так, что плоскость поляризации будет совпадать с меридиональной плоскостью, а степень поляризации будет меняться, для случая чистого рассеяния, от 0 при $\Theta = 0^\circ$ до $12{,}5\%$ при $\Theta = 90^\circ$.

166 SCIENCE February 18, 1949, Vol. 109

Observations of the Polarized Light From Stars

John S. Hall

U. S. Naval Observatory, Washington, D. C.

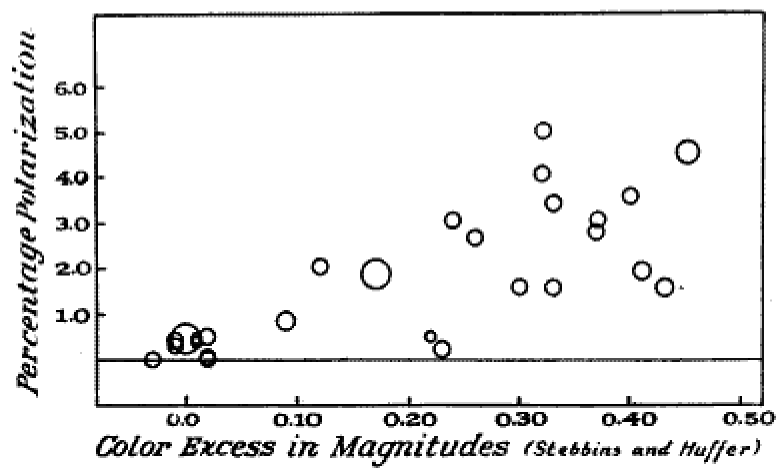


FIG. 3. Observational evidence of a correlation between color excess and percentage of polarization for early-type stars. The size of the circle indicates the weight of the observations.

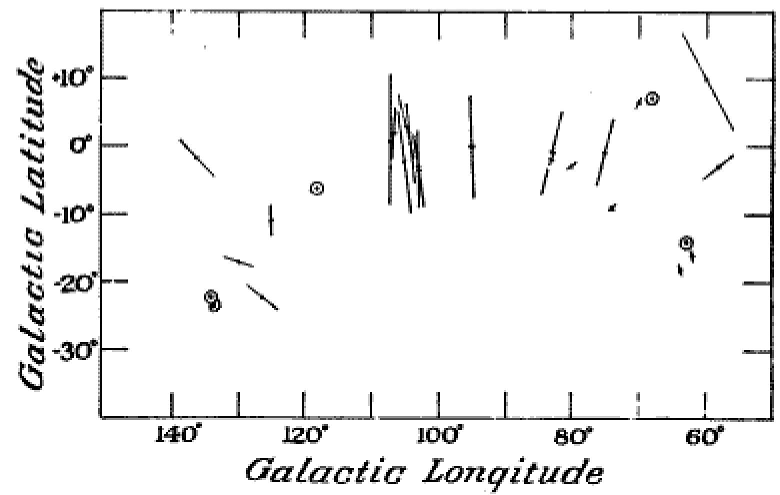
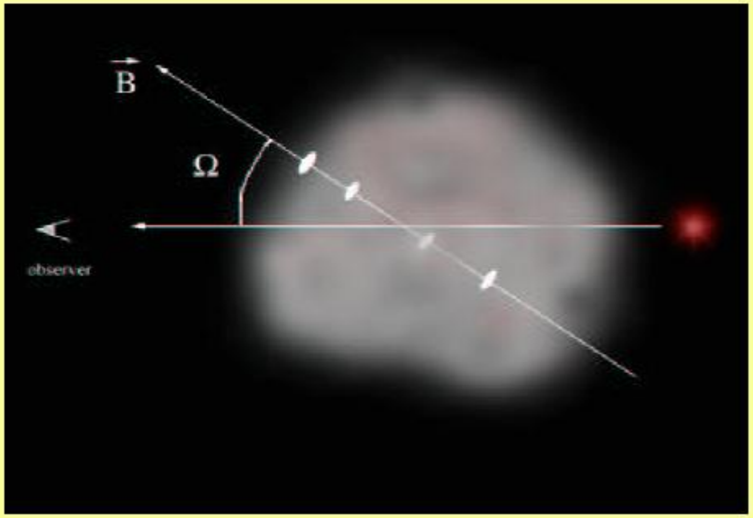


FIG. 4. Observational evidence that there is no one preferential orientation of the plane of polarization. Stars showing no polarization are represented by circles.

Interstellar polarization: observations



$\vartheta || B_{\perp}$

Mechanism

Linear dichroism

medium with aligned non-spherical grains

- polarization degree P ($0 \leq P \leq 100\,\%$) and positional angle ϑ

Polarization is related to some direction in the plane of sky (perpendicular to the direction of observations); (not scattering plane!).

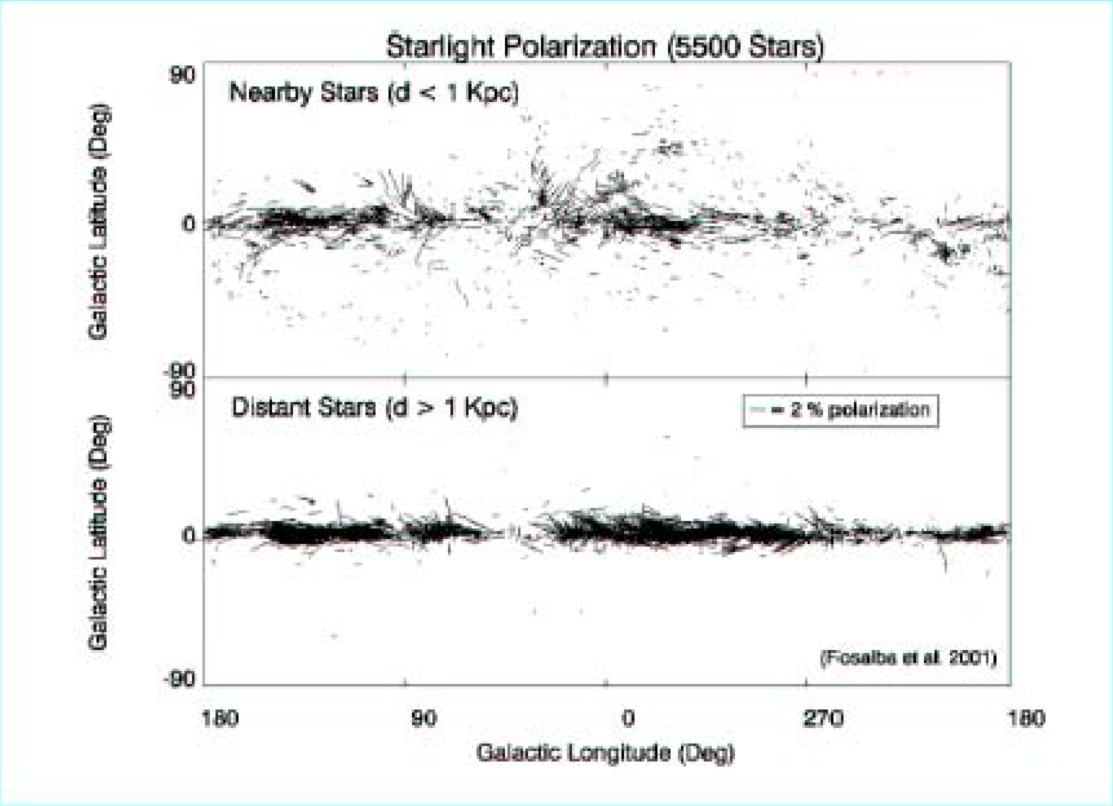
- Two directions of investigations:

A. "in breadth"

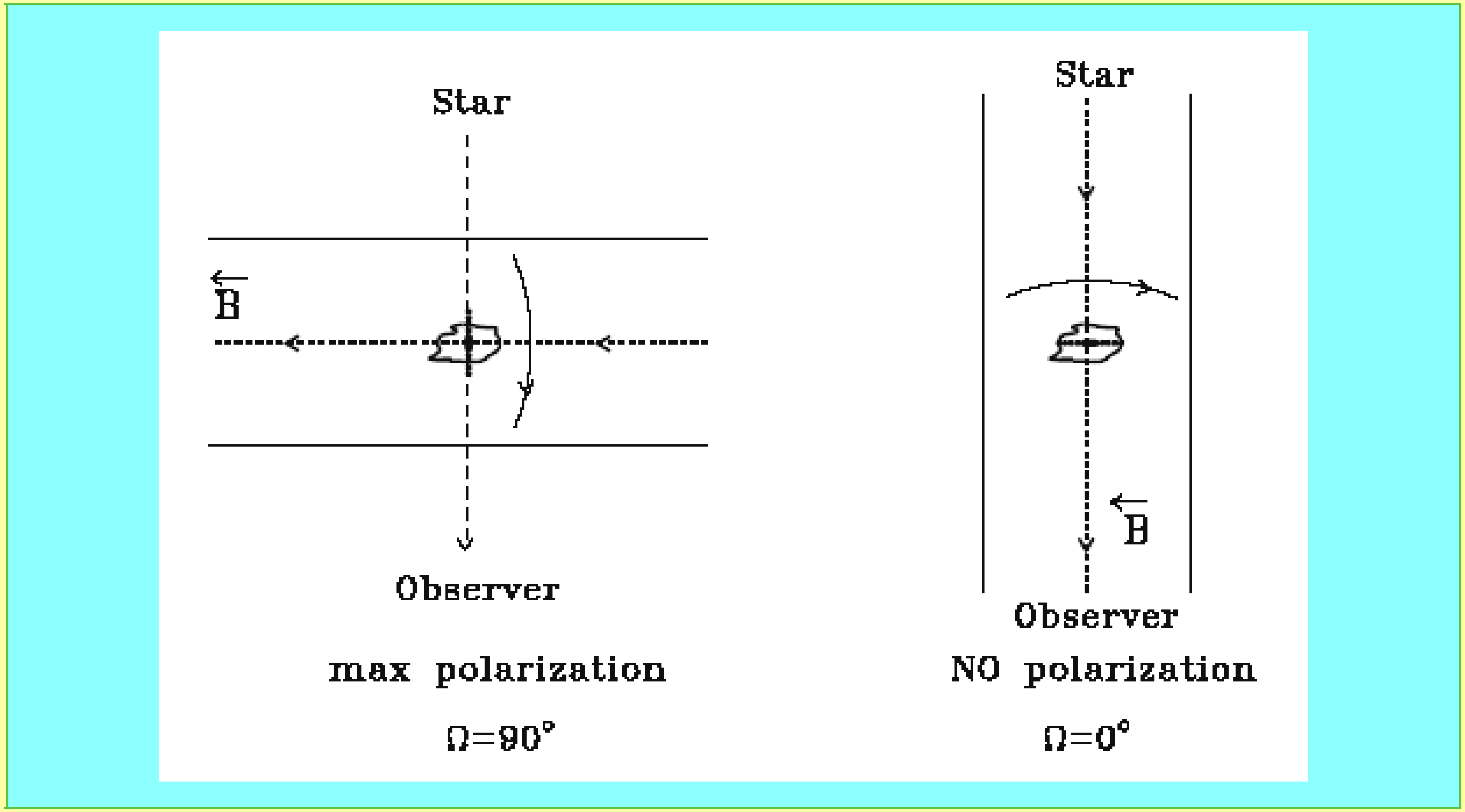
Large-scale polarization in the Galaxy

(direction of alignment, $B_{\perp}$)

Related to the spiral arms and large scale structure of the interstellar magnetic field.



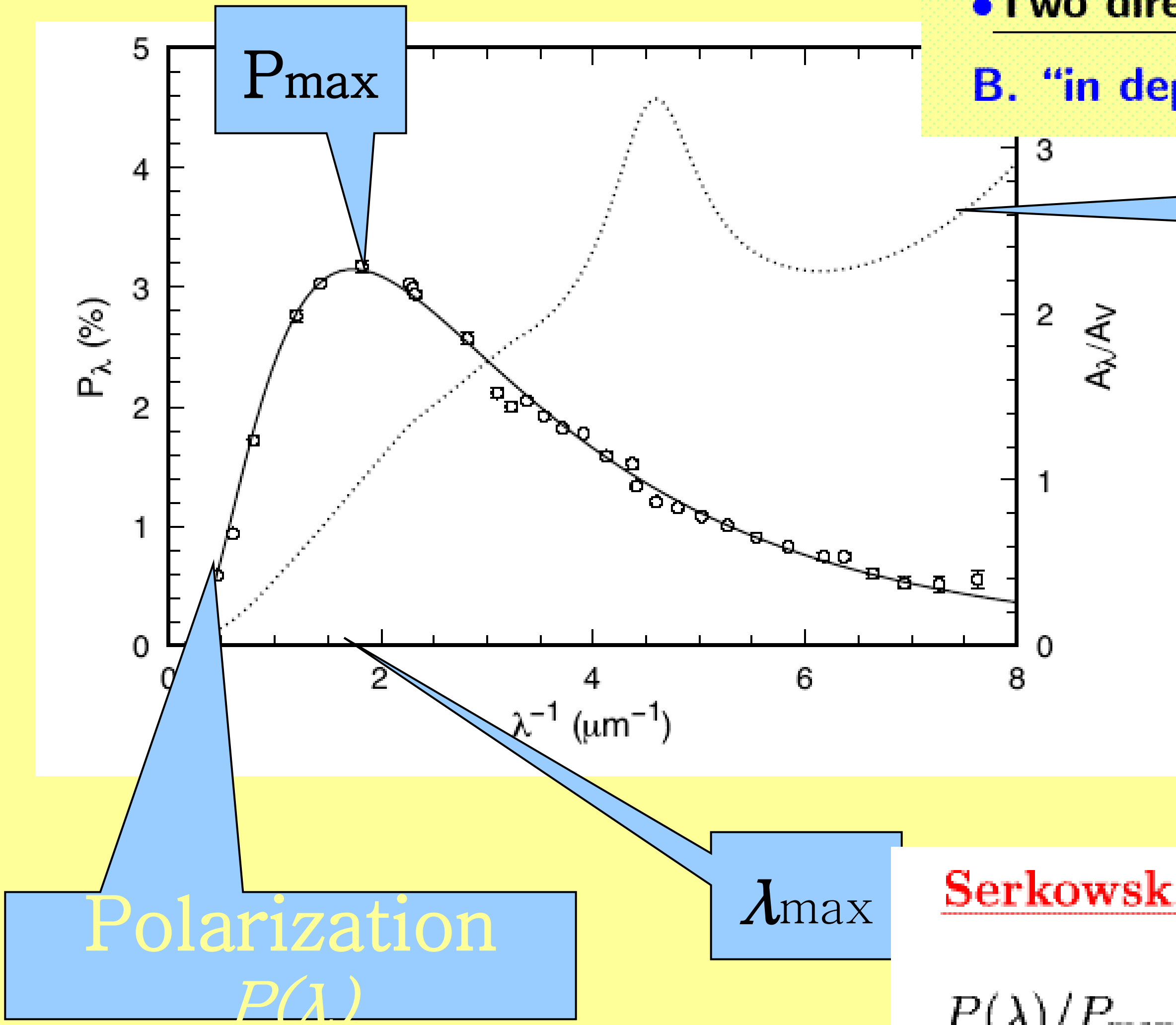
Starlight polarization vectors for nearby stars (upper panel) and distant stars (lower panel). After Fosalba *et al.* (2002).



Scheme of the production of the interstellar polarization in the Galaxy. The magnetic field $\vec{B}$ is directed along the spiral arms. Rotating non-spherical dust grains are aligned with a minor axes along $\vec{B}$.

- **Two directions of investigations:**

B. "in depth"



Serkowski's curve

$$P(\lambda)/P_{\max} = \exp[-K\ln^2(\lambda_{\max}/\lambda)]$$

$P_{\max} \lesssim 10\,\%$
$\lambda_{\max} \approx 0.4 - 0.8\,\mu\mathrm{m}$
$K \propto 1/W$ (W width of Serkowski's curve)

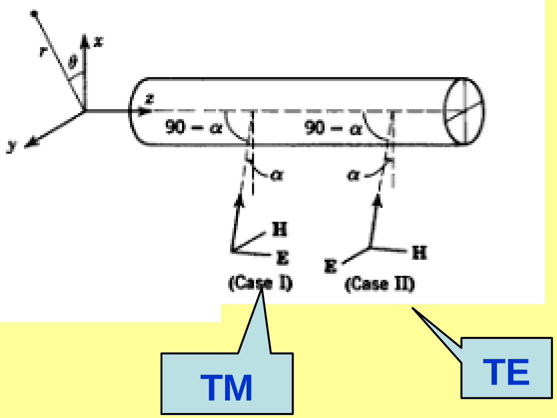
Polarization: unique phenomenon!

1. Dust grains must be non-spherical
2. Dust grains must have sizes close to the wavelength of incident radiation
3. Dust grains must have specific magnetic properties in order to interact with interstellar magnetic field
4. Dust grains must be aligned
5. The direction of alignment must not coincide with the line of sight
6. The distribution of aligned grains along the line of sight must be rather regular in order to exclude the cancellation of polarization

Interpretation

$$P(\lambda) = \int_{r_{V,-}}^{r_{V,+}} \int_{\varphi,\omega,\beta} \frac{1}{2} \left[C_{\rm ext}^{\rm TM}(m, r_V, \lambda, a/b, \alpha) - C_{\rm ext}^{\rm TE}(m, r_V, \lambda, a/b, \alpha)\right]$$
$$\times f(\xi,\beta) \cos 2\psi \, n_{\rm d}(r_{\rm V}) \, {\rm d}[\varphi,\omega,\beta]{\rm d}r_{\rm V} \cdot N_{\rm d} \cdot 100\%$$

$C_{\rm ext}^{\rm TM,\,TE}$ – extinction cross-sections
$N_{\rm d}$ — column density of dust grains
$f(\xi,\beta)$ — alignment function
ξ — alignment parameter



Problems: light scattering by non-spherical particles
alignment mechanism
averaging over rotation

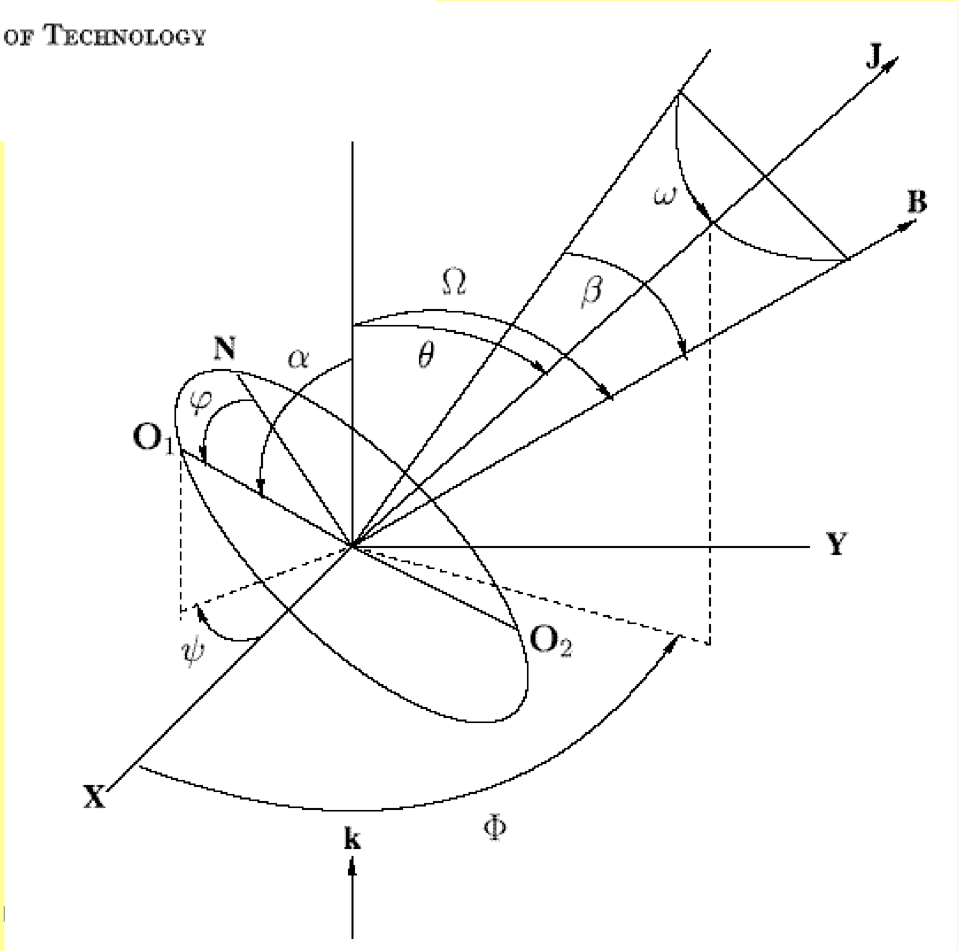
PF — “picket fence” alignment (non-rotating particles)
PDG — perfect Davis–Greenstein orientation [perfect rotational or 2D]
IDG — imperfect Davis–Greenstein orientation
[RAT — orientation due to radiative torques (very special case)]

THE POLARIZATION OF STARLIGHT BY ALIGNED DUST GRAINS

LEVERETT DAVIS, JR.
PHYSICS DEPARTMENT, CALIFORNIA INSTITUTE OF TECHNOLOGY
and
JESSE L. GREENSTEIN

1951ApJ...114..206D

Paramagnetic relaxation in magnetic field (Fe inclusions)



PF — "picket fence" alignment (non-rotating particles)
PDG — perfect Davis–Greenstein orientation [perfect rotational or 2D]
IDG — imperfect Davis–Greenstein orientation
[RAT — orientation due to radiative torques (very special case)]

Infinite cylinders

PF & PDG — Greenberg and Shah (1966), Greenberg (1968), Mathis (1979)
*Mathis (1986) — PDG + only silicate grains above a certain size are aligned [$\Omega = 90°$]
IDG — Hong and Greenberg (1980), Voshchinnikov *et al.* (1986)
IDG — Li and Greenberg (1997) [finite cylinders]

!

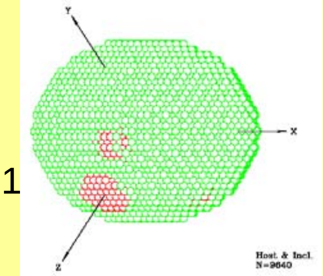
Homogeneous spheroids

PF — Martin (1978), Rogers and Martin (1979)
PDG — Wolff et al. (1993) [$\Omega = 90°$]
PF & PDG — Kim and Martin (1995), Gupta et al. (2005) [$\Omega = 90°$]
Draine and Fraisse (2009) [as Mathis (1986)]
IDG — Voshchinnikov and Das (2008), Das et al. (2010)

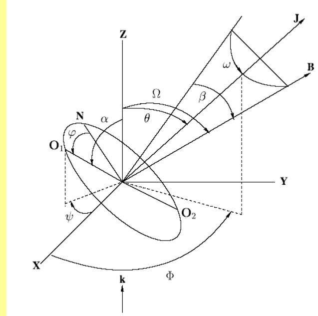
Ω=90deg?

Coated/composite spheroids/ellipsoids

PF — Onaka (1980), Matsumura and Seki (1996), Vaidya, Gupta, Snow (2007)



Alignment



- ***Davis-Greenstein type***

alignment function:

$$f(\xi,\beta) = \frac{\xi \sin\beta}{(\xi^2 \cos^2\beta + \sin^2\beta)^{3/2}}.$$

alignment parameter

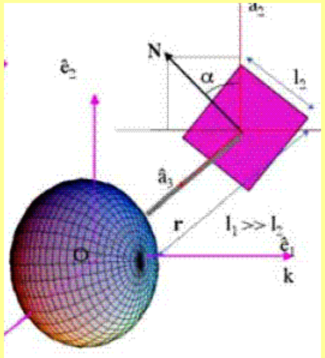
$$\xi^2 = \frac{r_V + \delta_0(T_d/T_g)}{r_V + \delta_0}$$

$$\delta_0 = 8.23 \times 10^{23} \frac{\varkappa B^2}{n_H T_g^{1/2} T_d},\ \mu\mathrm{m}$$

- ***Radiative torques***

alignment function: ?

Particles: helical, dielectric



Calculations, comparison with observations: ?

[Whittet et al., 2008]

$$p_\lambda = \int ds \int_{a_{\mathrm{crit}}}^{a_{\max}} \frac{1}{2} R C a^{-3.5} \pi a^2 Q_{\mathrm{pol}}(a,\lambda)\, da$$

R–Rayleigh reduction factor (Greenberg'68)

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. 404, 265–274 (2010) doi:10.1111/j.1365-2966.2010.16281.x

Model

Interstellar extinction and polarization – a spheroidal dust grain approach perspective

H. K. Das,[1★] N. V. Voshchinnikov[2★] and V. B. Il'in[2,3★]

Parameters:

Refractive index (chemical composition)

Size (size distribution): $r_{V,\min}$, $r_{V,\max}$, q

Shape (*a/b* – aspect ratio)

Degree of alignment: δ_0

Direction of alignment (angle between the line of sight and direction of magnetic field): Ω (0deg.≤ Ω ≤90deg.)

$$A(\lambda) = 1.086 N_{\rm d} \langle C_{\rm ext}\rangle_\lambda\,, \qquad P(\lambda) = N_{\rm d}\langle C_{\rm pol}\rangle_\lambda 100\%\,,$$

$$\langle C_{\rm ext}\rangle_\lambda = \left(\frac{2}{\pi}\right)^2 \int_0^{\pi/2}\int_0^{\pi/2}\int_0^{\pi/2} \pi r_V^2\, Q_{\rm ext}\, f(\xi,\beta)\, d\varphi\, d\omega\, d\beta\,,$$

$$\langle C_{\rm pol}\rangle_\lambda = \frac{2}{\pi^2}\int_0^{\pi/2}\int_0^{\pi}\int_0^{\pi/2} \pi r_V^2\, Q_{\rm pol}\, f(\xi,\beta)\cos 2\psi\, d\varphi\, d\omega\, d\beta\,.$$

$$f(\xi,\beta) = \frac{\xi \sin\beta}{(\xi^2\cos^2\beta + \sin^2\beta)^{3/2}},$$

$$n(r_{\rm s}) \propto r_{\rm s}^{-q}$$

$$\xi^2 = \frac{r_V + \delta_0 (T_{\rm d}/T_{\rm g})}{r_V + \delta_0}$$

$$\delta_0 = 8.23\times 10^{23}\frac{\varkappa B^2}{n_{\rm H} T_{\rm g}^{1/2} T_{\rm d}},\ \mu{\rm m}$$

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

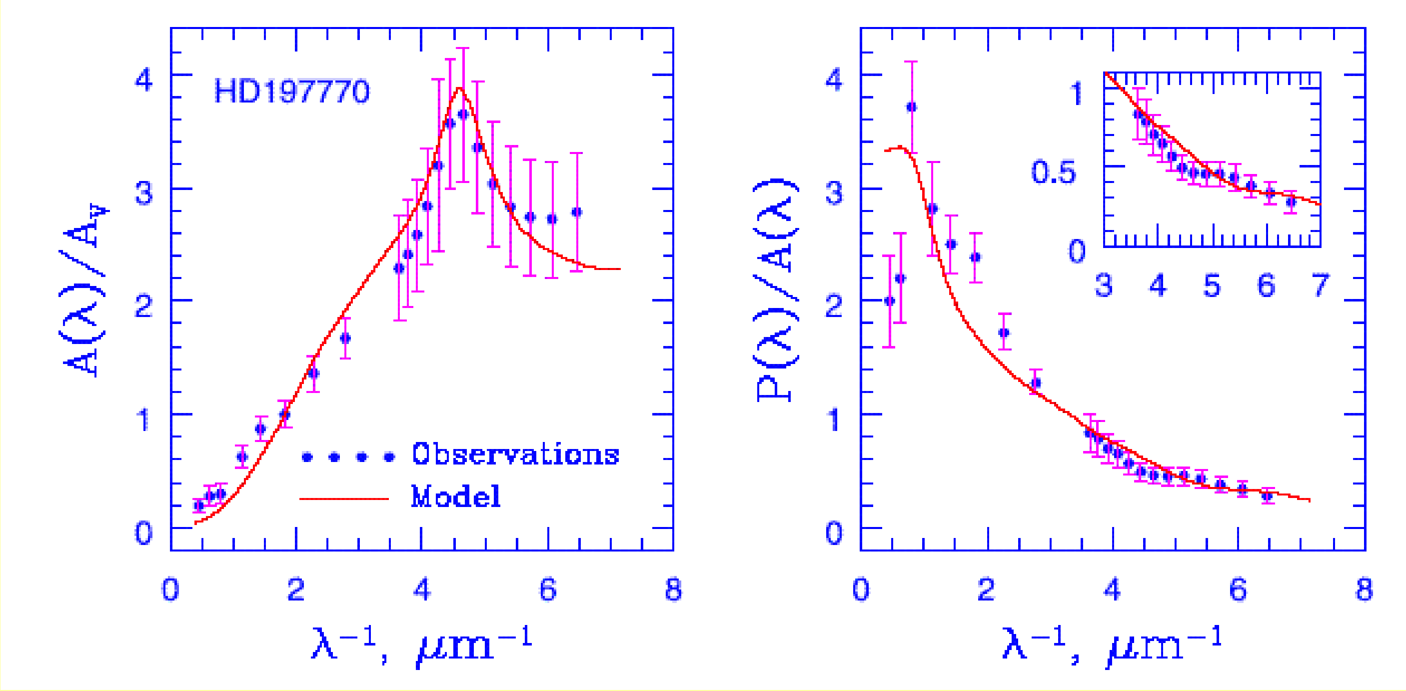
Mon. Not. R. Astron. Soc. 404, 265–274 (2010) doi:10.1111/j.1365-2966.2010.16281.x

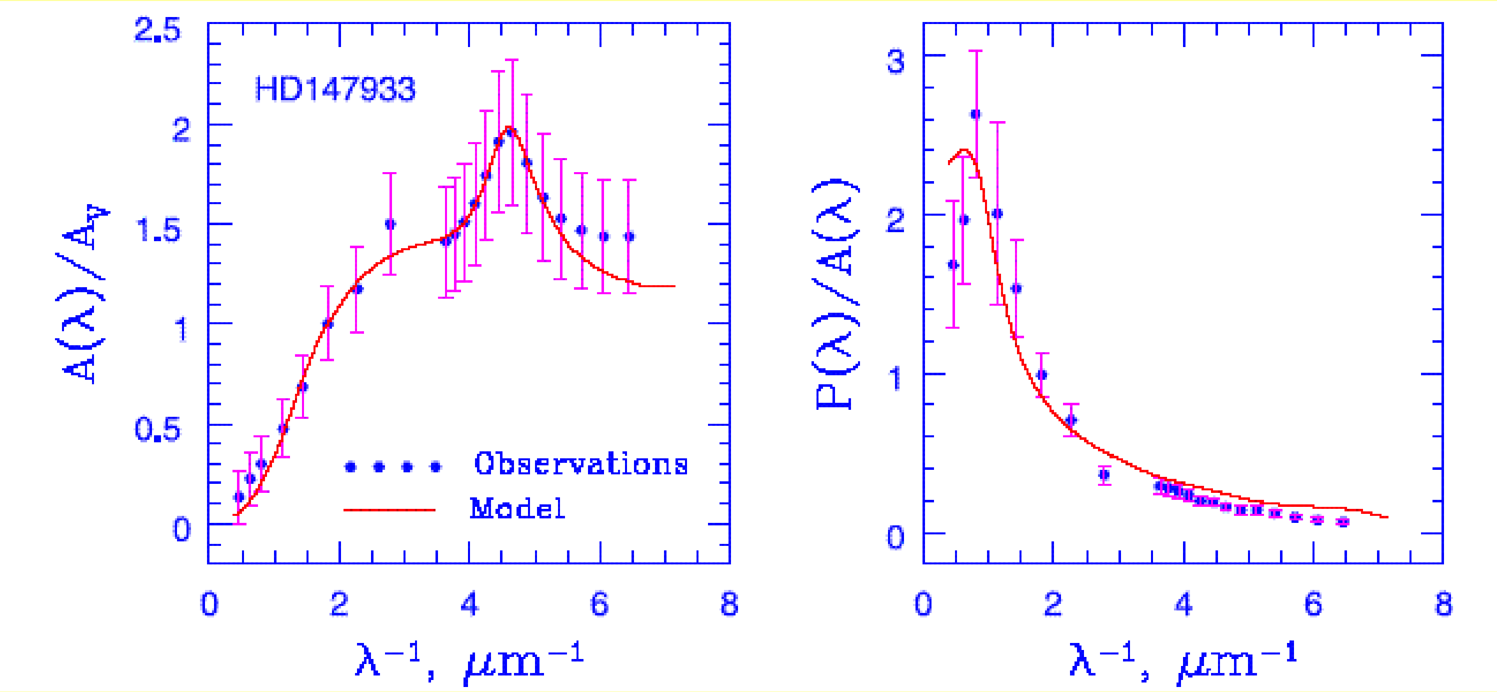
Interstellar extinction and polarization – a spheroidal dust grain approach perspective

H. K. Das,[1★] N. V. Voshchinnikov[2★] and V. B. Il'in[2,3★]

7 stars with known UV polarization

Spheroids: prolate/oblate, *a/b*=1.1–10
Materials: astronomical silicate, amorphous carbon
Alignment: Davis–Greenstein imperfect (IDG)





!

Table 3. Modelling results for HD 147933.

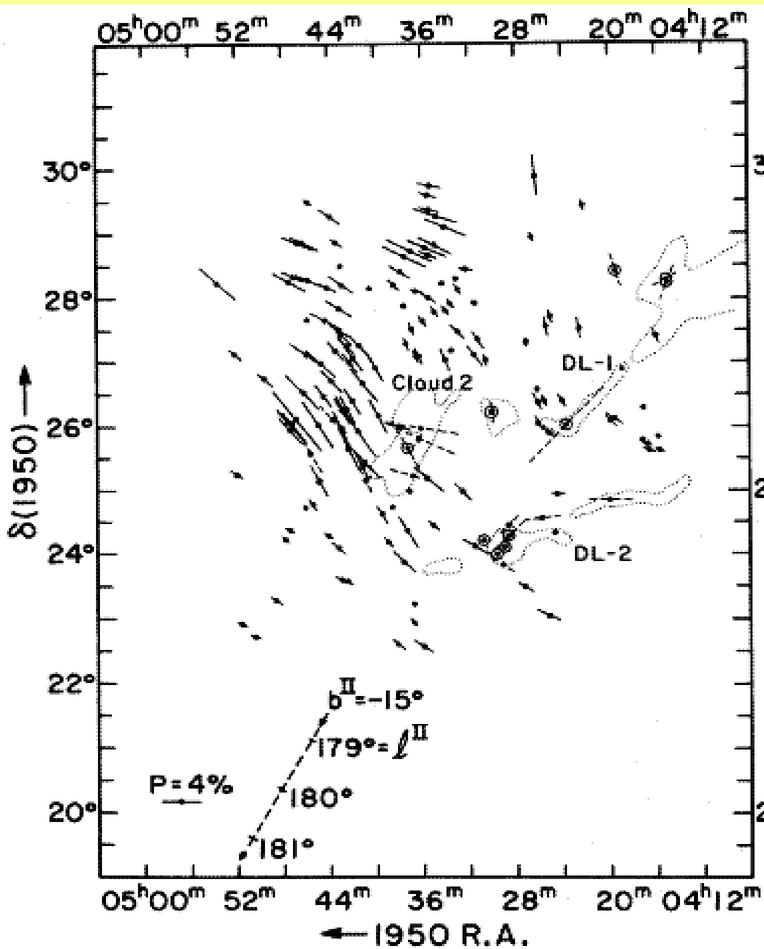
Amorphous carbon				Astrosil				Graphite	shape;			χ^2	
$\mathcal{K}_C$	$r_{V,\min}$[a]	$r_{V,\max}$	q	$\mathcal{K}_{Si}$	$r_{V,\min}$	$r_{V,\max}$	q	$\mathcal{K}_{gra}$	a/b	δ_0(μm)	Ω (°)	A/A_V	P/A
0.24	0.03	0.15	1.5	0.73	0.08	0.25	1.5	0.03	pro; 5	0.5	35	1.04	24.6
0.54	0.10	0.20	2.0	0.40	0.01	0.25	1.3	0.06	pro; 3	0.3	42	0.19	8.2
0.50	0.10	0.25	2.0	0.47	0.07	0.20	2.0	0.03	obl; 3	0.3	33	0.19	2.2

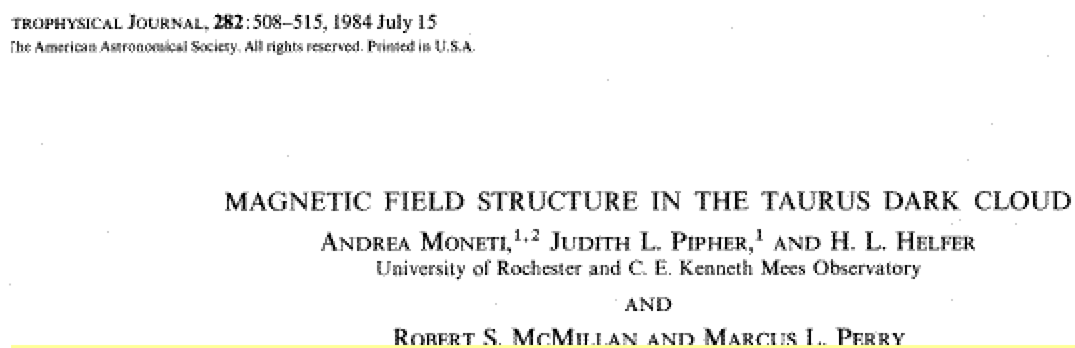
[a] $r_{V,\min}$ and $r_{V,\max}$ are in μm.

Parameters: 4 (C) + 4 (Si) + 1 (shape) + 2 (alignment)

But UV polarization was measured in a few directions. We can search for relations between parameters of $P(\lambda)$ curves (P_{max}, λ_{max}, K) + $R(V)$(?) and properties of dust grains (size, shape) + degree and direction of alignment.

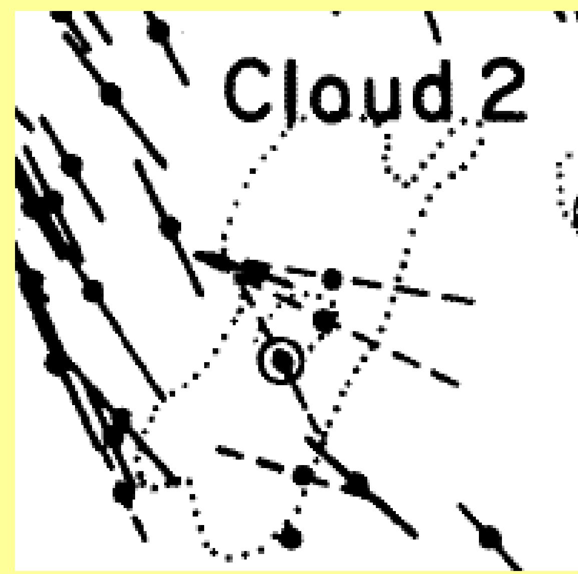
Stars in Taurus molecular cloud (TMC1/Heiles cloud2)



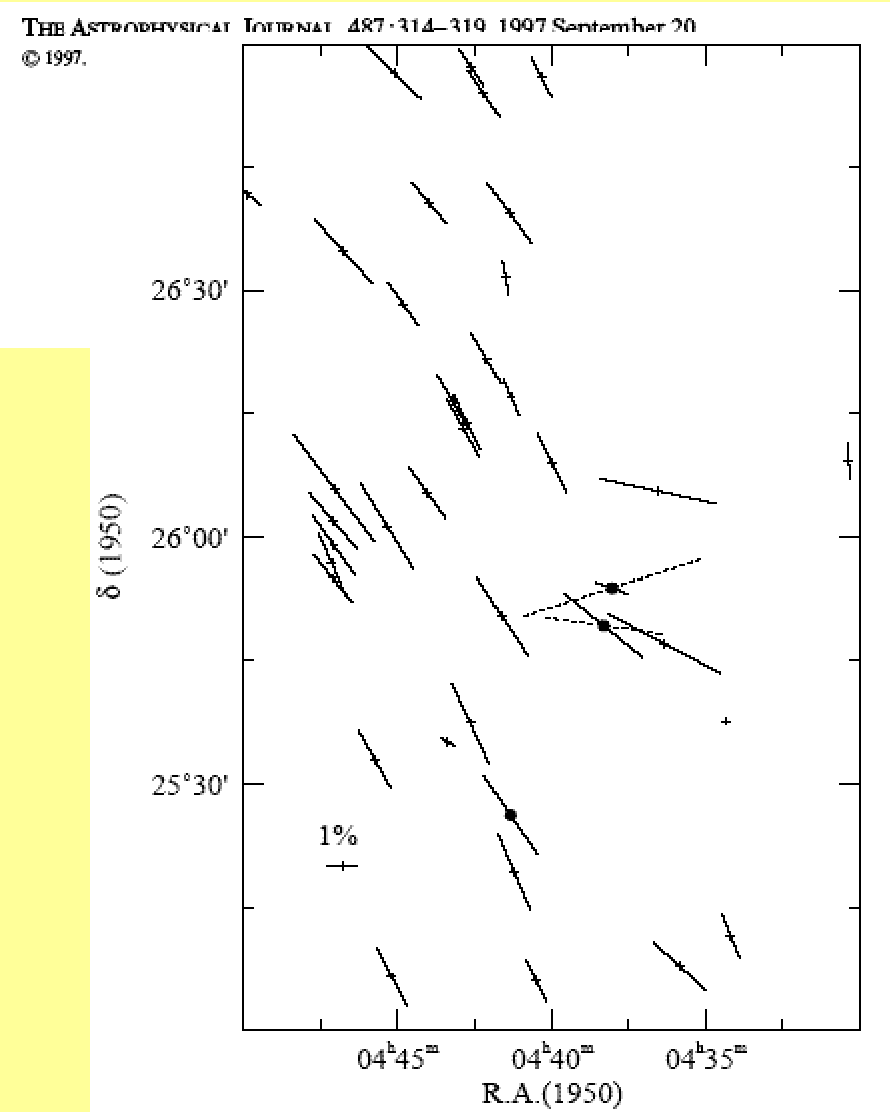

TROPHYSICAL JOURNAL, 282:508–515, 1984 July 15

MAGNETIC FIELD STRUCTURE IN THE TAURUS DARK CLOUD

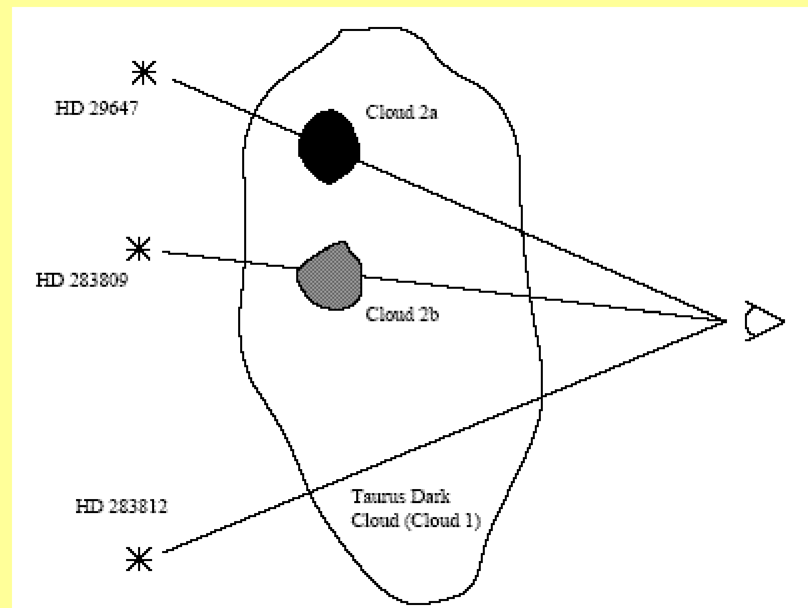
ANDREA MONETI,[1,2] JUDITH L. PIPHER,[1] AND H. L. HELFER
University of Rochester and C. E. Kenneth Mees Observatory
AND
ROBERT S. MCMILLAN AND MARCUS L. PERRY

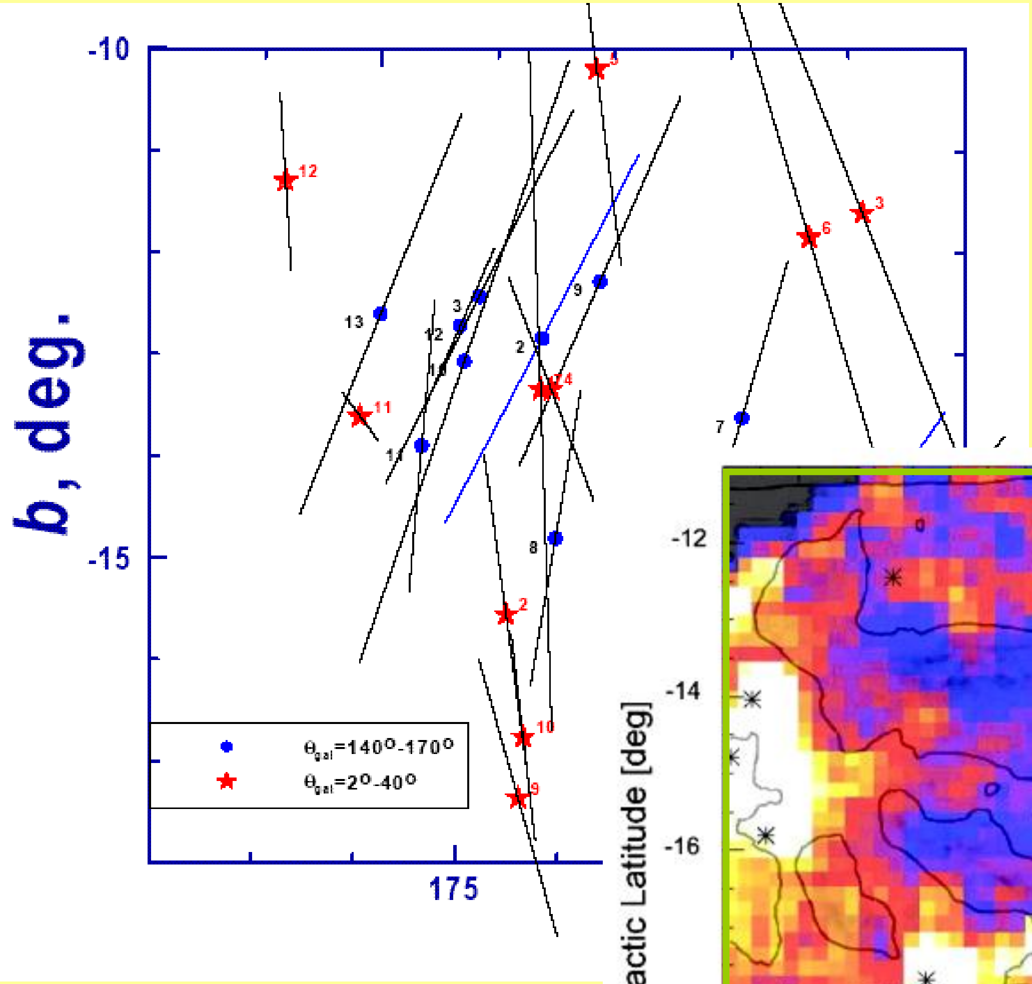


Stars in Taurus molecular cloud (TMC1/Heiles cloud2)

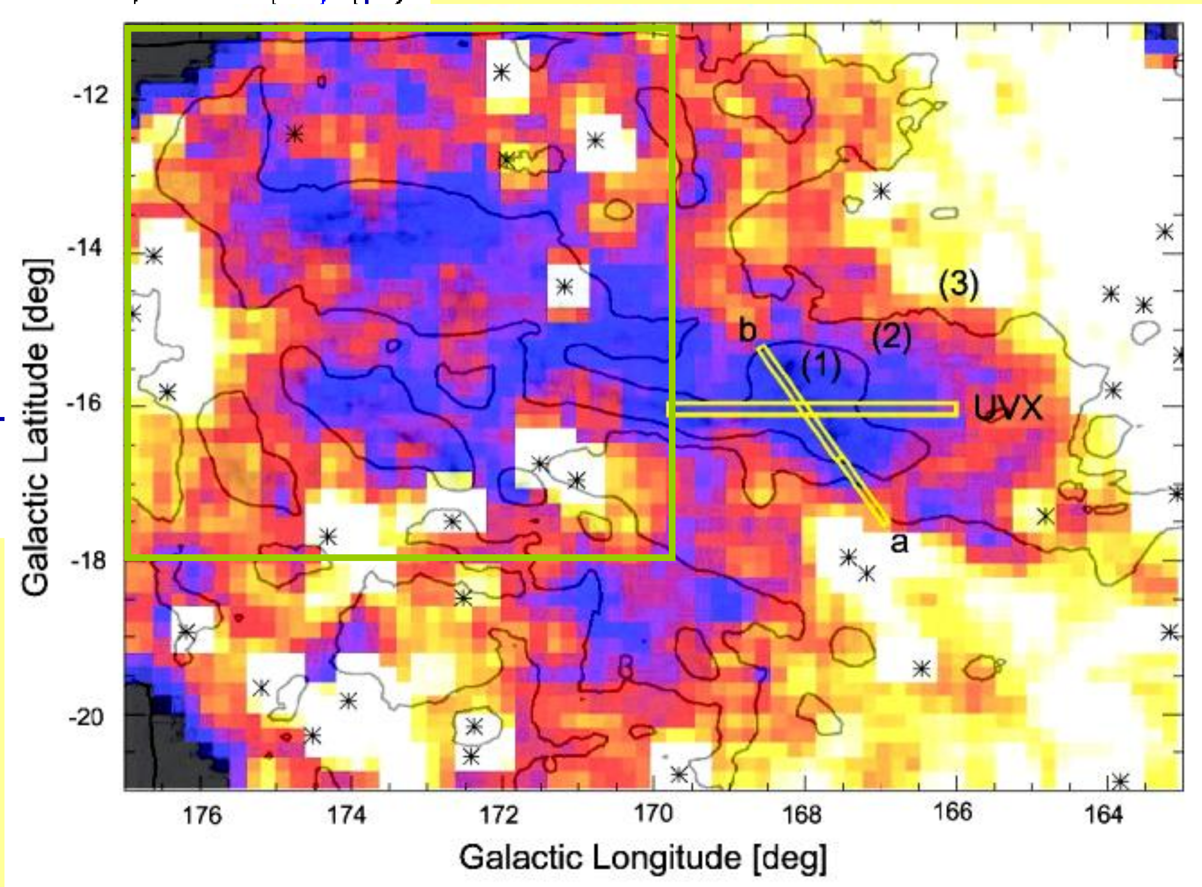


THE TAURUS DARK CLOUDS:
’OSITION ANGLES AND
NEAR TMC-1
TET, AND W. G. ROBERGE

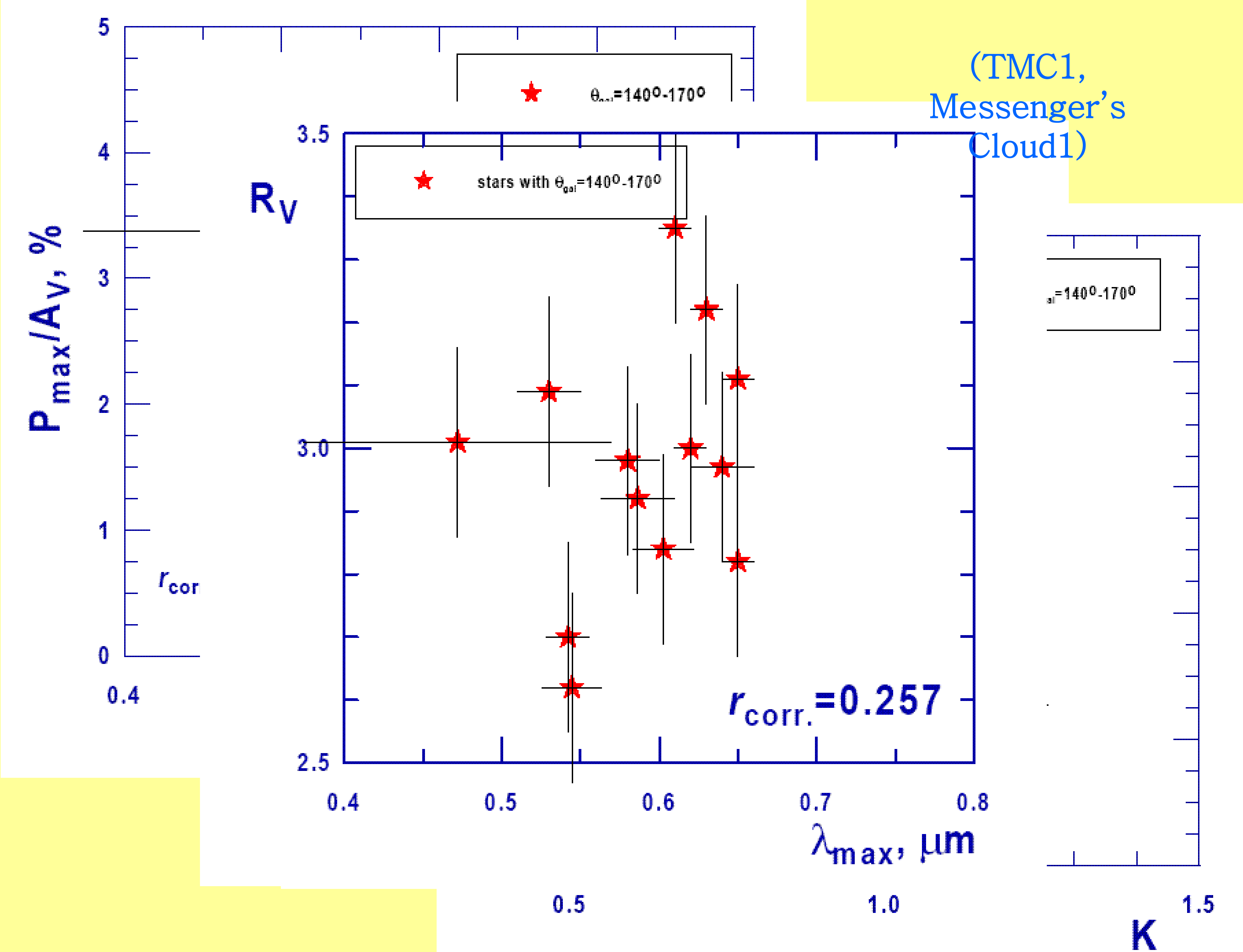




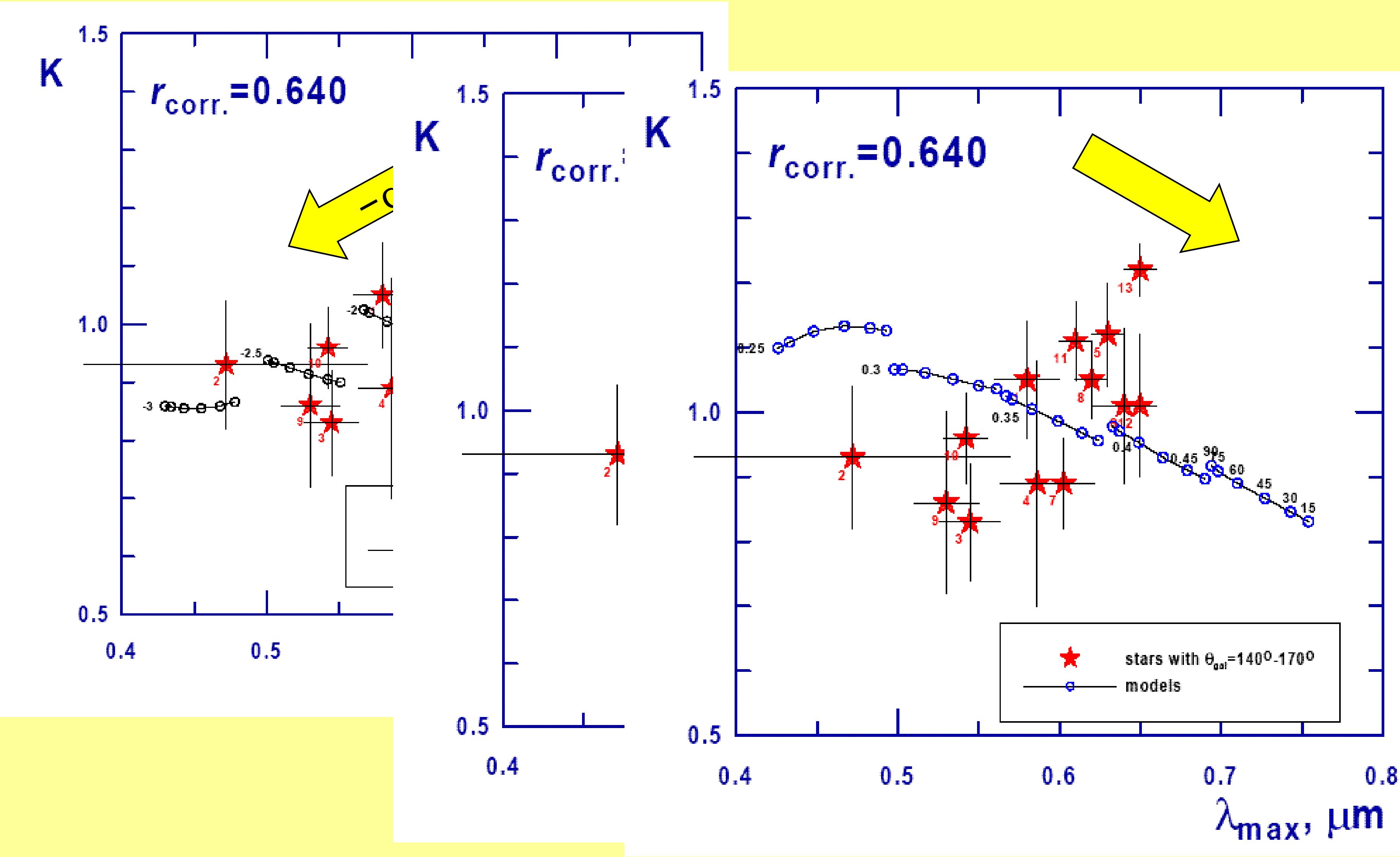
Data from Whittet et al. (2001)



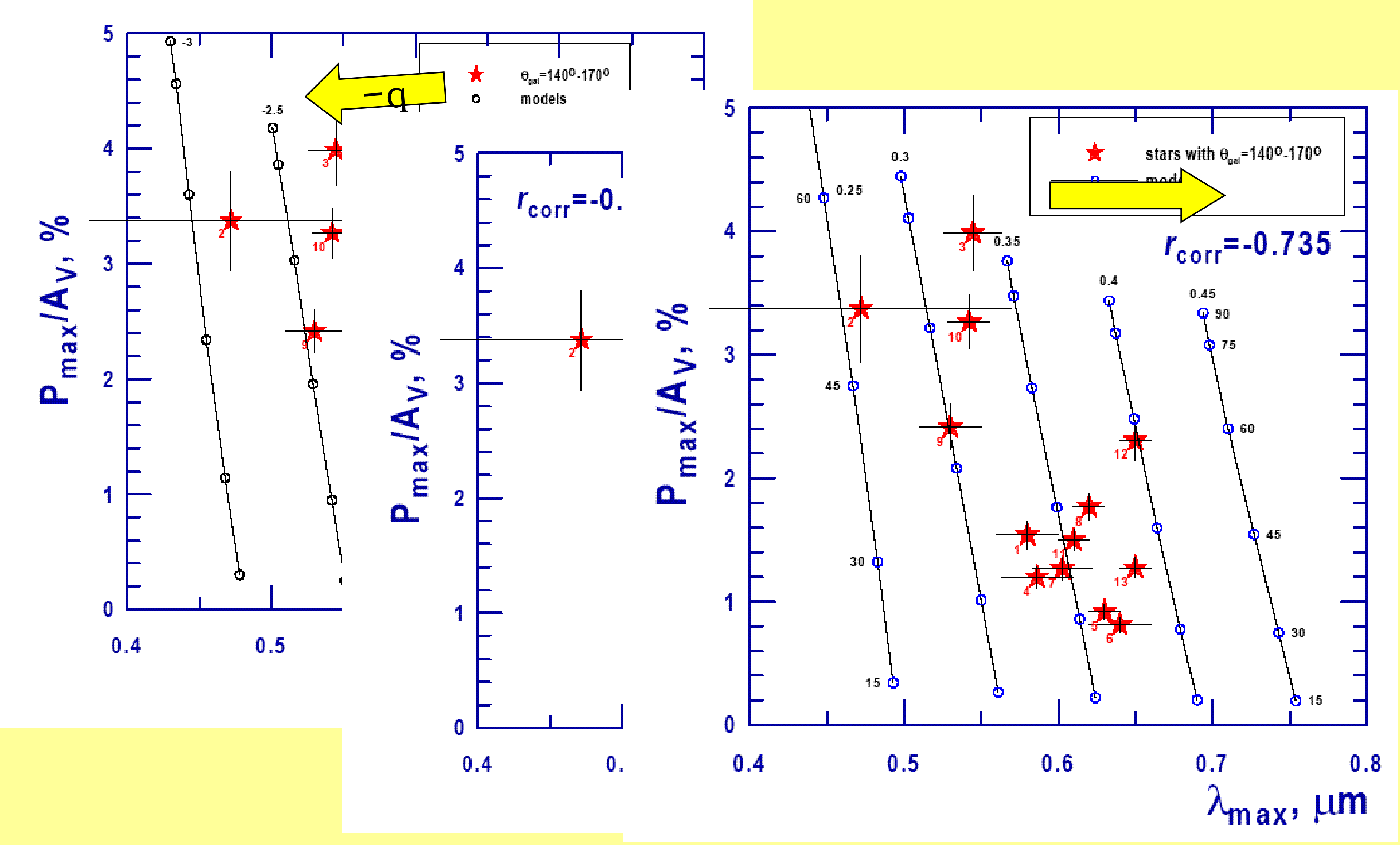
(TMC1, Messenger’s Cloud1)



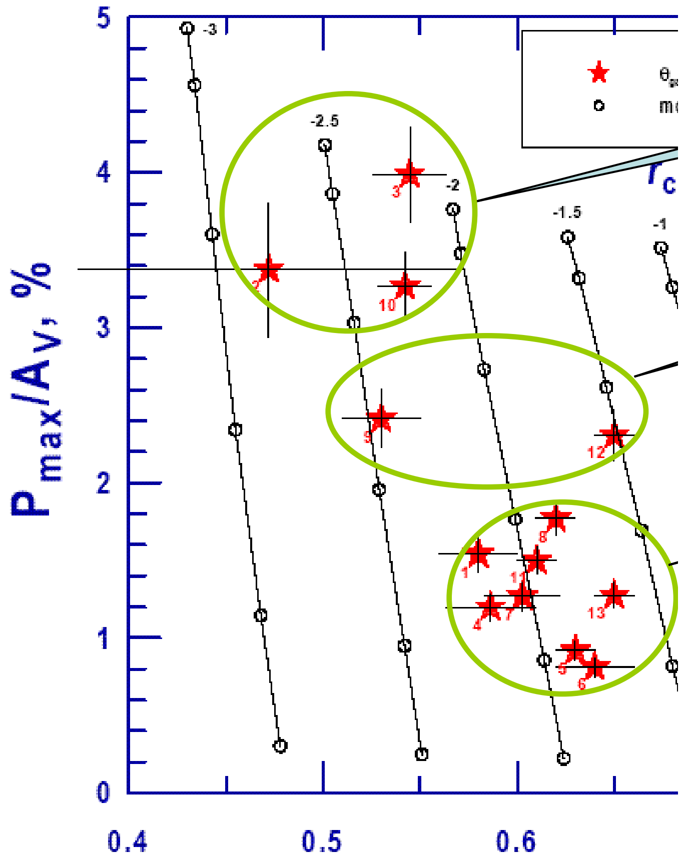
TMC1, cloud1: prolate (Si!) spheroids, a/b=3, r_{Vmin}=0.07μm, r_{Vmax}=0.35μm, q=-1.7, δ_0=3μm, Ω=15(15)90

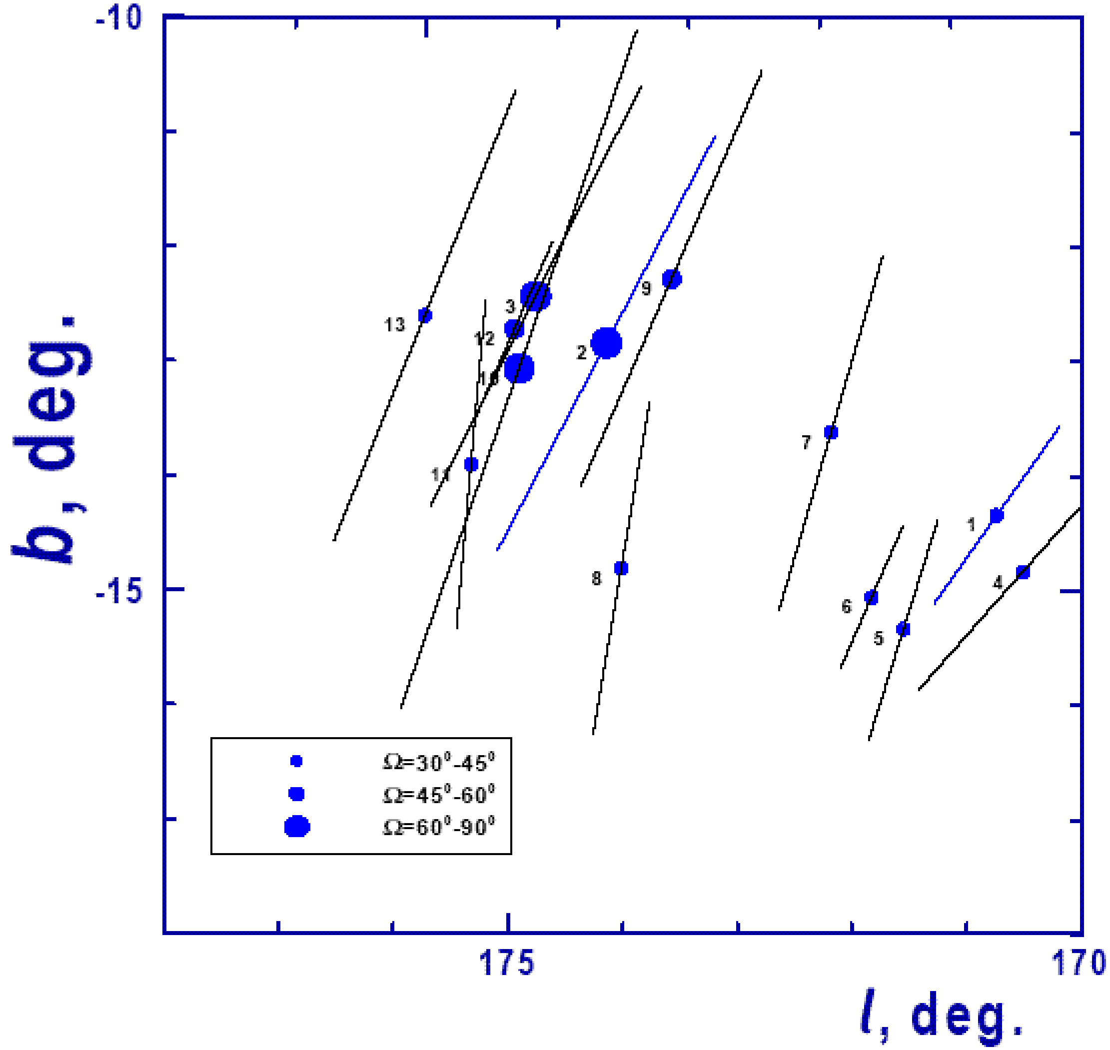


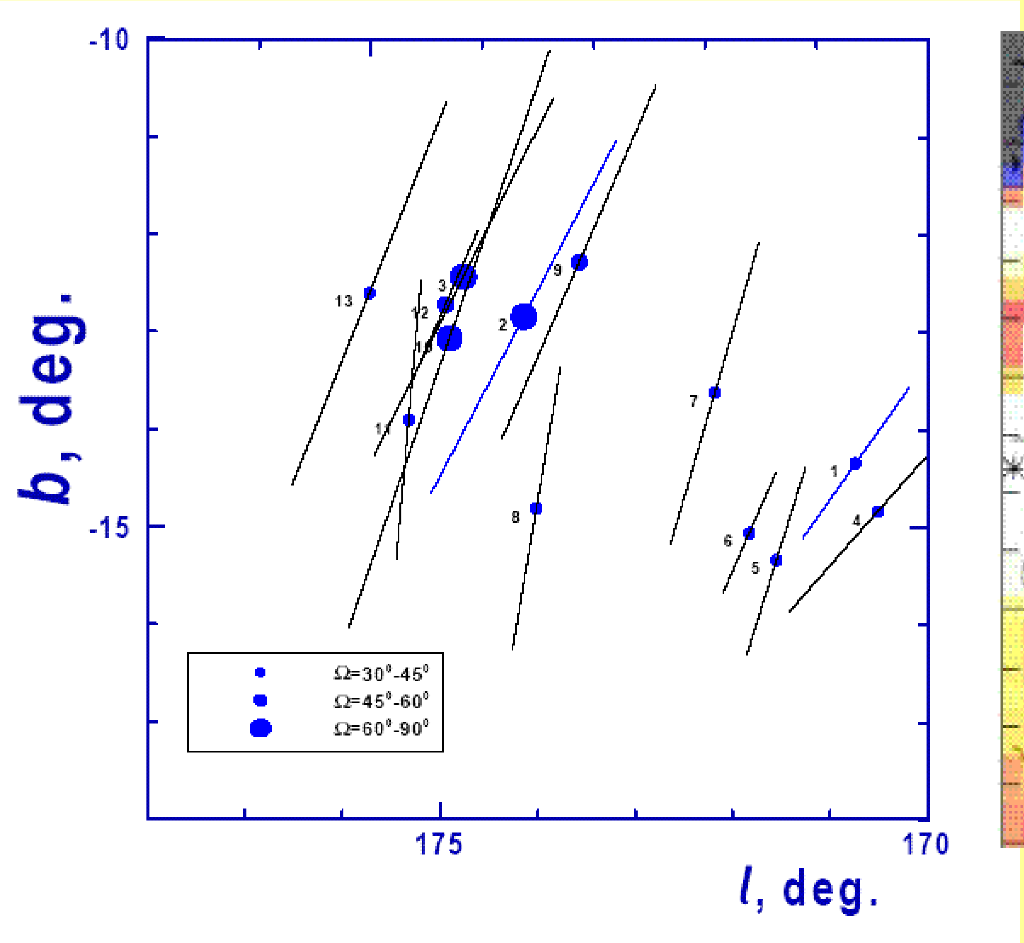
TMC1, cloud1: prolate spheroids, a/b=3, r_{Vmin}=0.07μm, r_{Vmax}=0.35μm, q=-1.7, δ_0=3μm, Ω=15(15)90

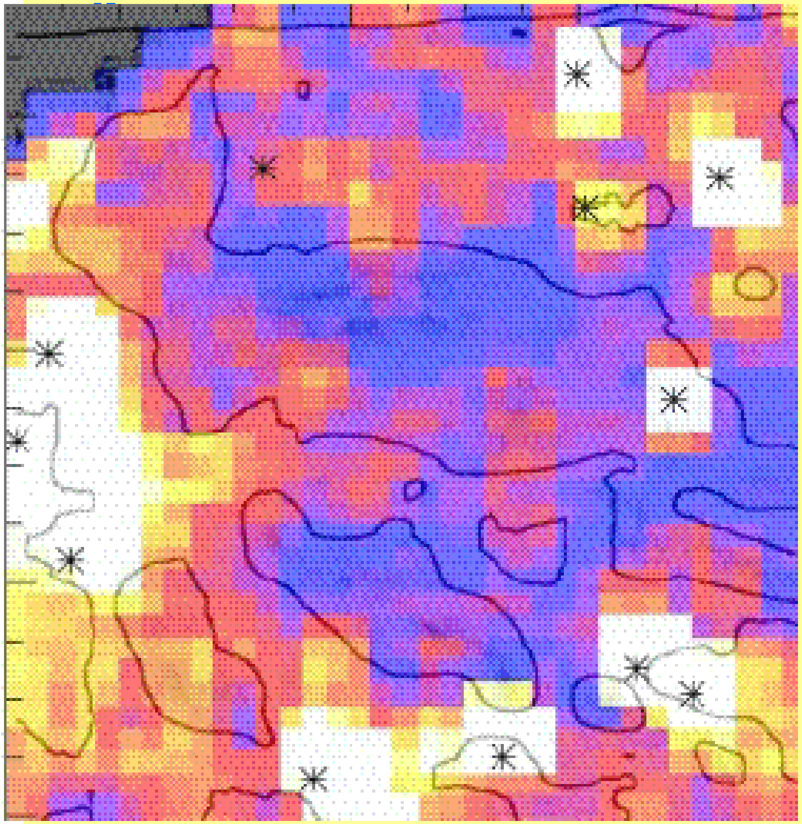


TMC1, cloud1: prolate spheroids, a/b=3, r_{Vmin}=0.07μm, r_{Vmax}=0.35μm, q=-1.7, δ_0=3μm, Ω=15(15)90deg.

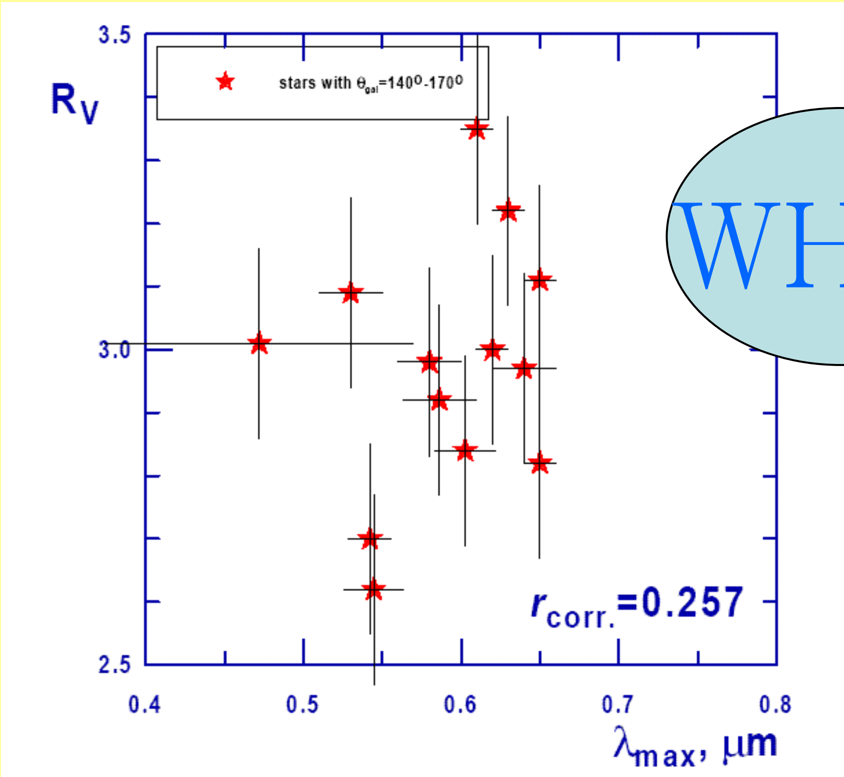





-10
-15
b, deg.
175
170
l, deg.
13
12
11
10
3
2
9
8
7
6
5
1
4
Ω=30°-45°
Ω=45°-60°
Ω=60°-90°



Polarizing grains:?



WHY?

C grains do not produce polarization

May be Fe grains?

(Fe+Mg)/Si>2 !

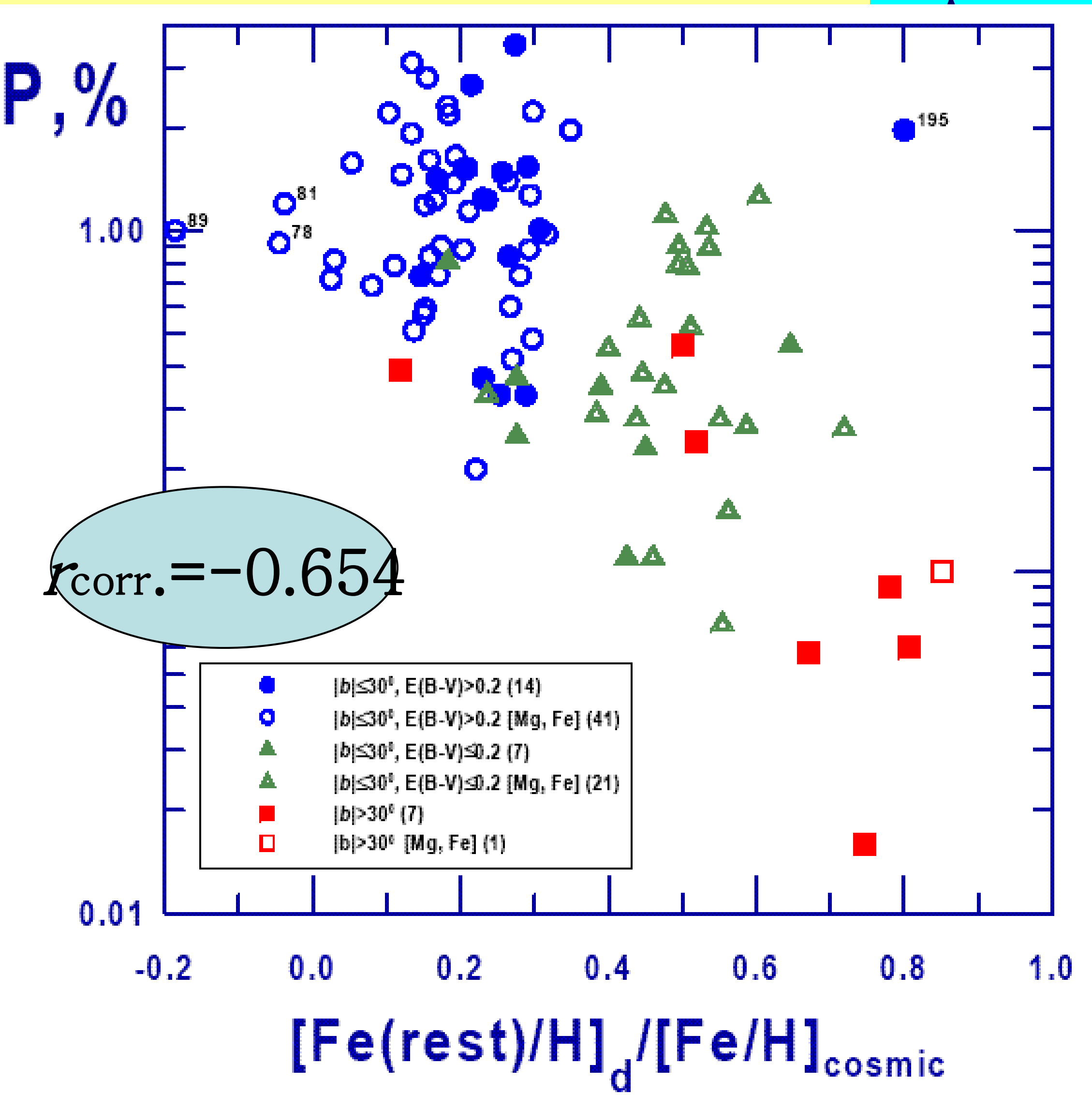
A&A 517, A45 (2010)
DOI: 10.1051/0004-6361/200912817

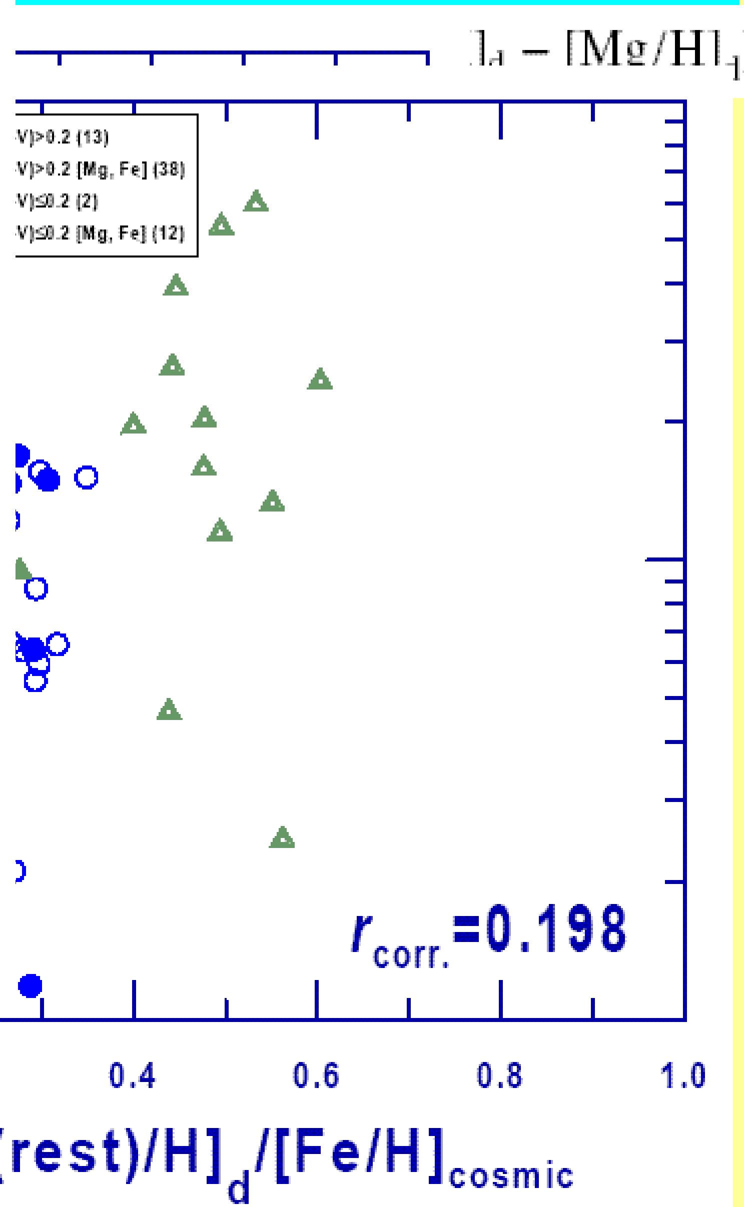
Astronomy & Astrophysics

From interstellar abundances to grain composition: the major dust constituents Mg, Si, and Fe*

N. V. Voshchinnikov[1,2,3] and Th. Henning[1]

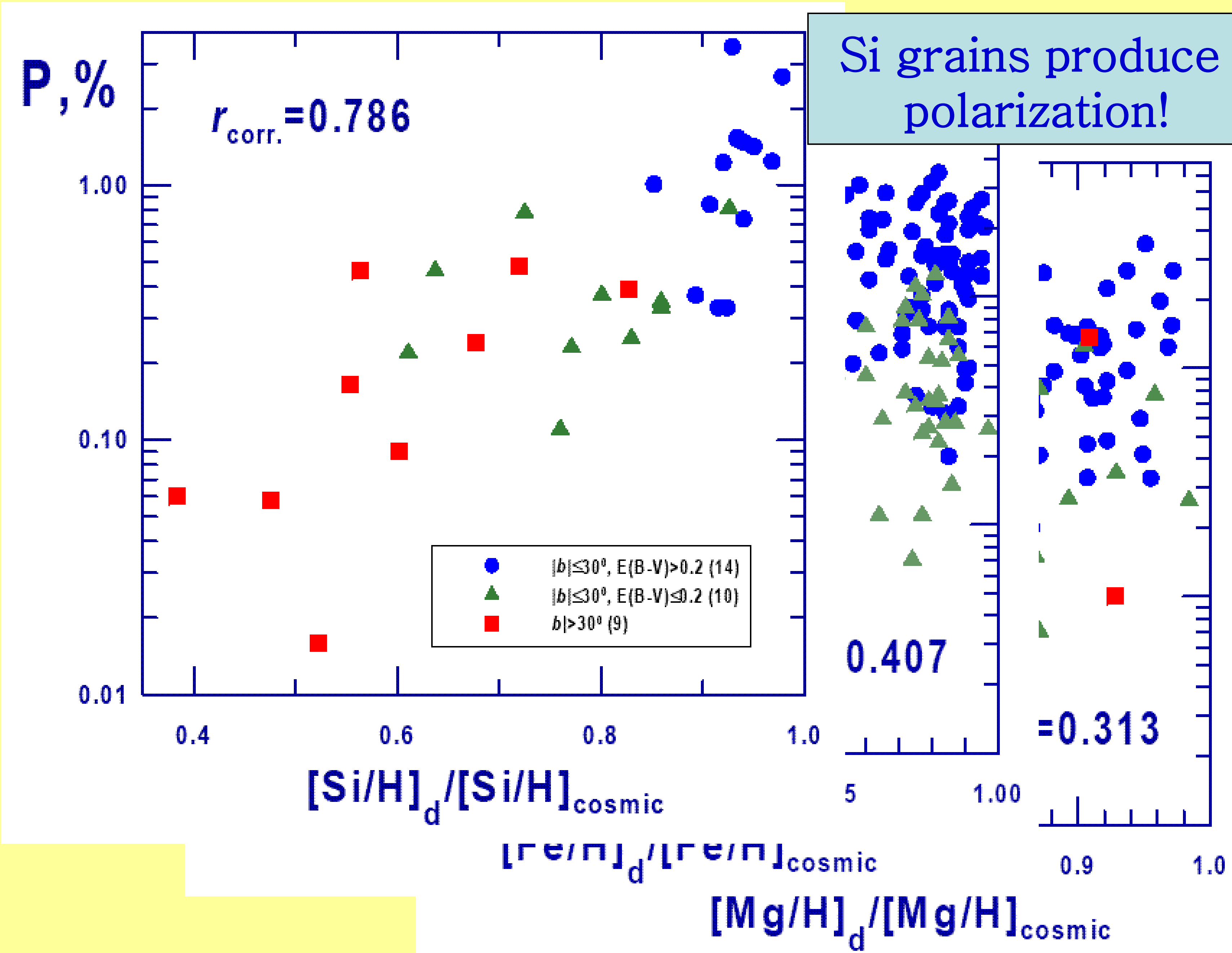
hous silicate (olivine type)
$(Mg,Fe)_2SiO_4$





Fe grains do not produce polarization!

Si grains produce polarization!



Some conclusions and future work

- **Accurate modelling of interstellar linear polarization for individual objects allows one to get information about the spatial structure of magnetic fields.**
- **More likely: polarization is produced by Si grains and is not produced by C and Fe-rich grains.**
- **Development of appropriate models (inhomogeneous particles + imperfect alignment) with a reasonable number of parameters is highly appreciated.**

- **THANKS!**
- **शुक्रिया**
- **ВСЁ!**

C,O,Mg,Si,Fe + vacuum (!)

COSMIC → Sun

$$\left[\frac{X}{H}\right]_d = \left[\frac{X}{H}\right]_{cosmic} - \left[\frac{X}{H}\right]_g$$

A&A 517, A45 (2010)
DOI: 10.1051/0004-6361/200912817

Astronomy & Astrophysics

From interstellar abundances to grain composition: the major dust constituents Mg, Si, and Fe★

N. V. Voshchinnikov[1,2,3] and Th. Henning[1]

ppm – parts per million: N(X)/N(H)*10^6

Average values: ppm / X_d/X_{cosmic}

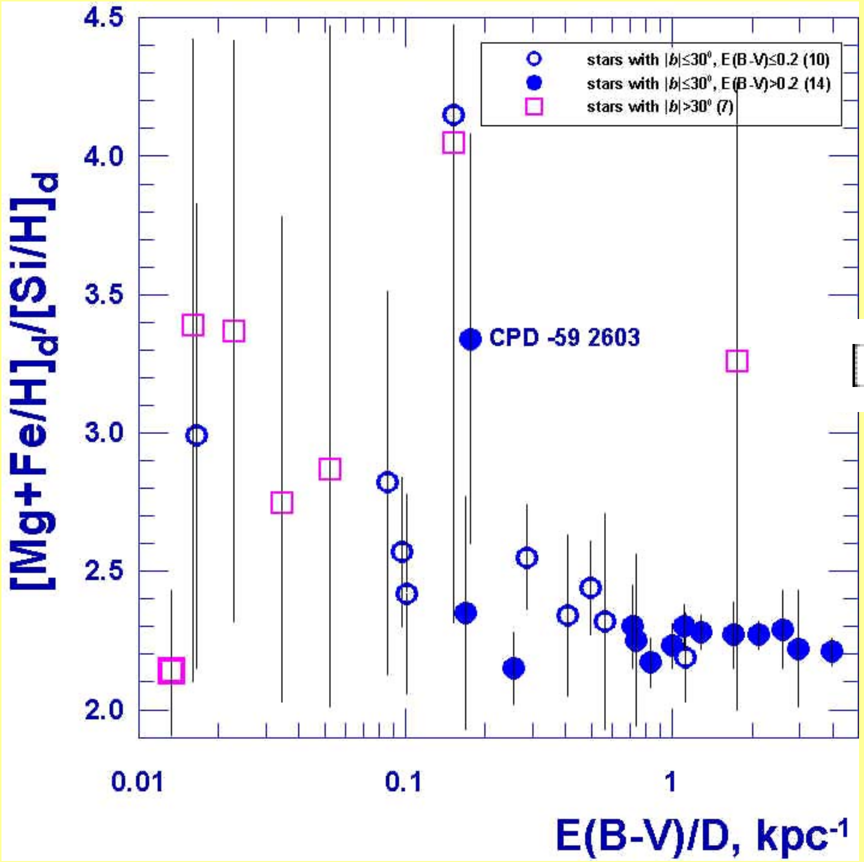
	Fe	Mg	Si
all stars	30.64 /97.0%(134)	33.13/83.2%(147)	25.01/77.2%(39)
|b|<30deg, E(B-V)>0.2	30.86 (78)	34.11 (85)	29.30 (15)
|b|>30deg	28.68 (9)	29.98 (14)	20.03 (10)

E(B−V)<0.8 --- diffuse and translucent IS clouds

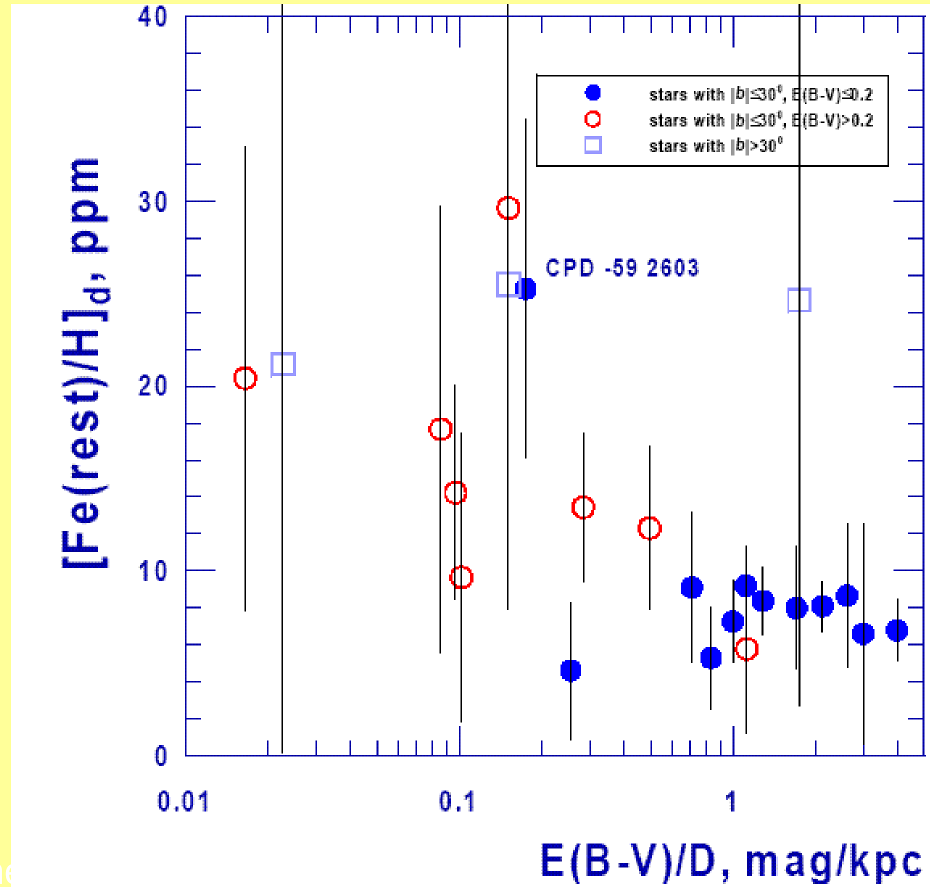
Amorphous silicate (olivine type)

$(Mg,Fe)_2SiO_4$

(31 sightlines with Fe + Mg + Si)



$$[Fe(rest)/H]_d = [Fe/H]_d - (2\ [Si/H]_d - [Mg/H]_d)$$



(Fe+Mg)/Si>2 !

Principal elements

O(~120 stars)

C(~18 (!) stars)

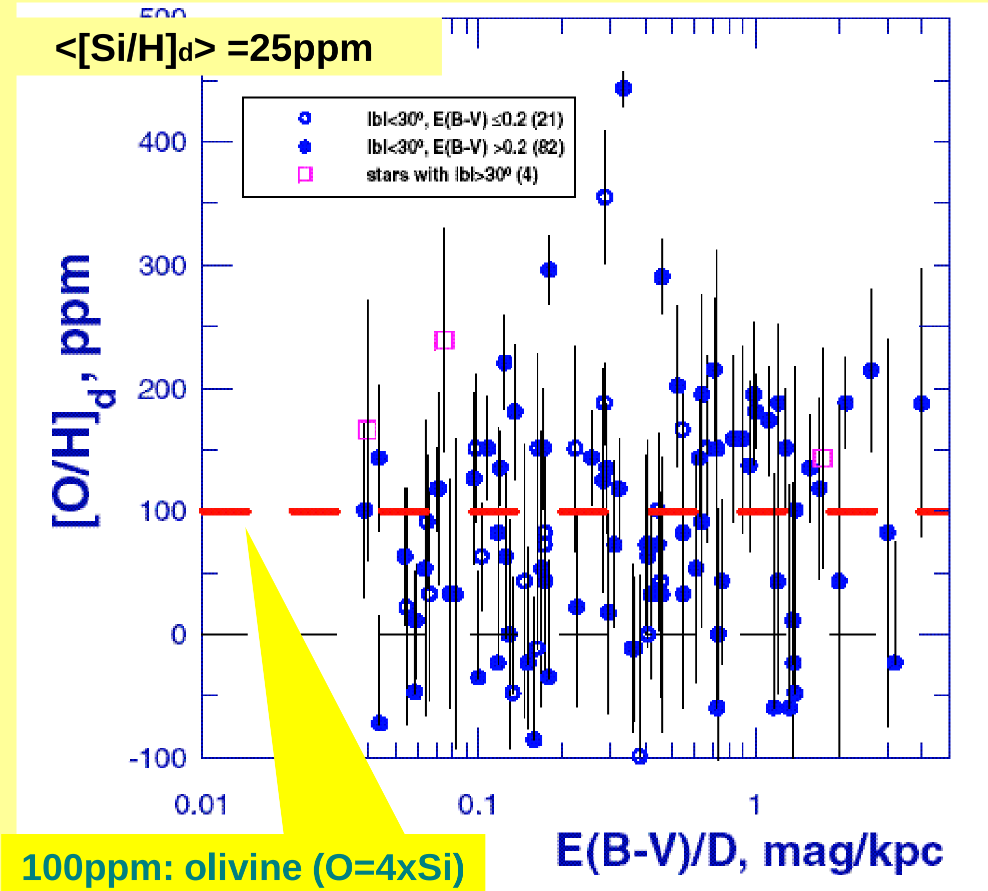


Fig. 11. Dust phase abundances of O in ppm with 1σ error bars reduced in twice in dependence on average reddening $E(B-V)/D$. Open and filled circles show data for disk stars seen through diffuse and translucent interstellar clouds, respectively. Squares correspond to sightlines with $|b| > 30°$.

Jenkins ApJ 700, 1299, 2009;
C_Sun = 269ppm, Asplund,... ARAAA (2009)

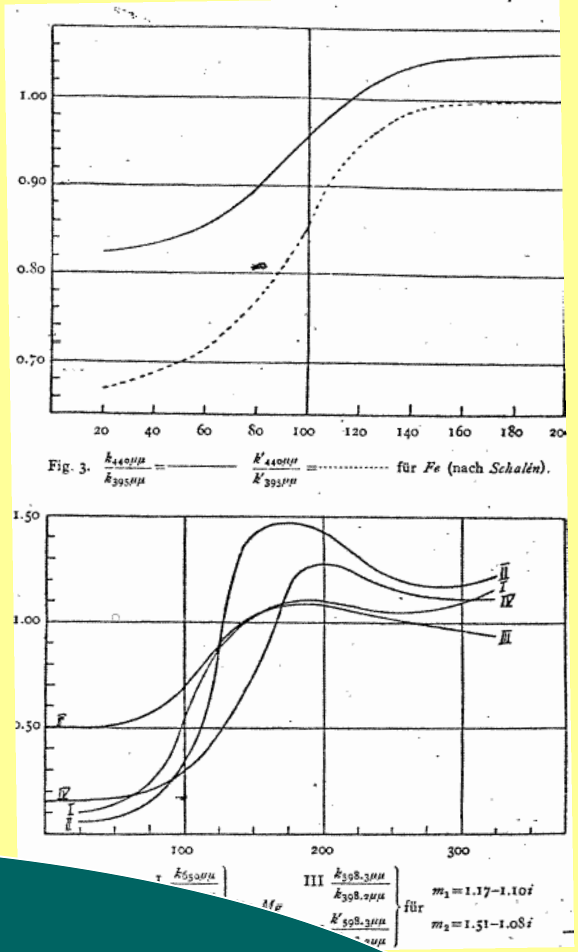
	Star	[CII/H]g		[CII/H]d		
1	HD 24398	141.25	73.74	127.75	73.74	
2	HD 24534	147.91	70.07	121.09	70.07	
3	HD 24912	309.03	192.15	-40.03	192.15	!
4	HD 27778	173.78	108.06	95.22	108.06	
5	HD 34029	363.08	218.22	-94.08	218.22	!
6	HD 35149	223.87	124.31	45.13	124.31	
7	HD 36861	158.49	126.70	110.51	126.70	
8	HD 37021	147.91	112.63	121.09	112.63	
9	HD 37061	251.19	88.49	17.81	88.49	
10	HD 38771	234.42	25.59	34.58	25.59	
11	HD 57061	181.97	94.94	87.03	94.94	
12	HD 143275	177.83	174.68	91.17	174.68	
13	HD 144217	169.82	57.65	99.18	57.65	
14	HD 147888	181.97	114.85	87.03	114.85	
15	HD 149757	162.18	68.38	106.82	68.38	
16	HD 152590	549.54	207.96	-280.54	207.96	!
17	HD 154368	123.03	135.08	145.97	135.08	
18	HD 207198	199.53	98.76	69.47	98.76	

very uncertain!

Interpretation

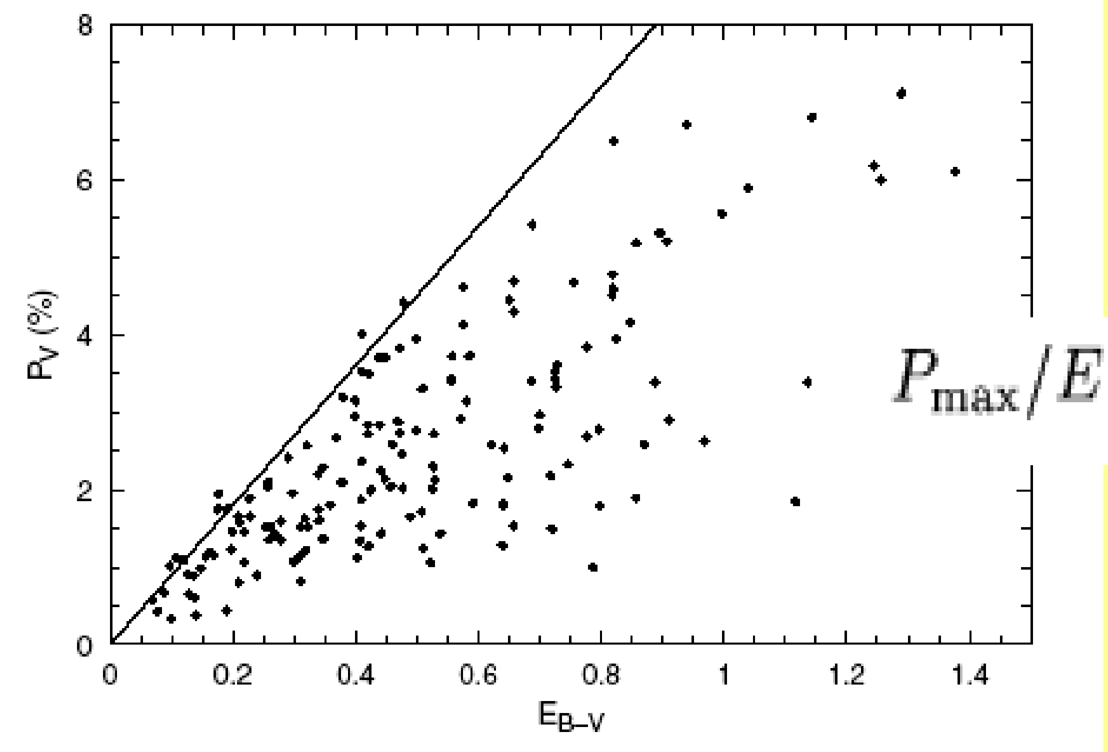
(first application of the Mie theory)

- 1933 Schalen --- **Fe**
- 1934 Schoenberg & Jung --- **Mg**
- **Ambiguity!**

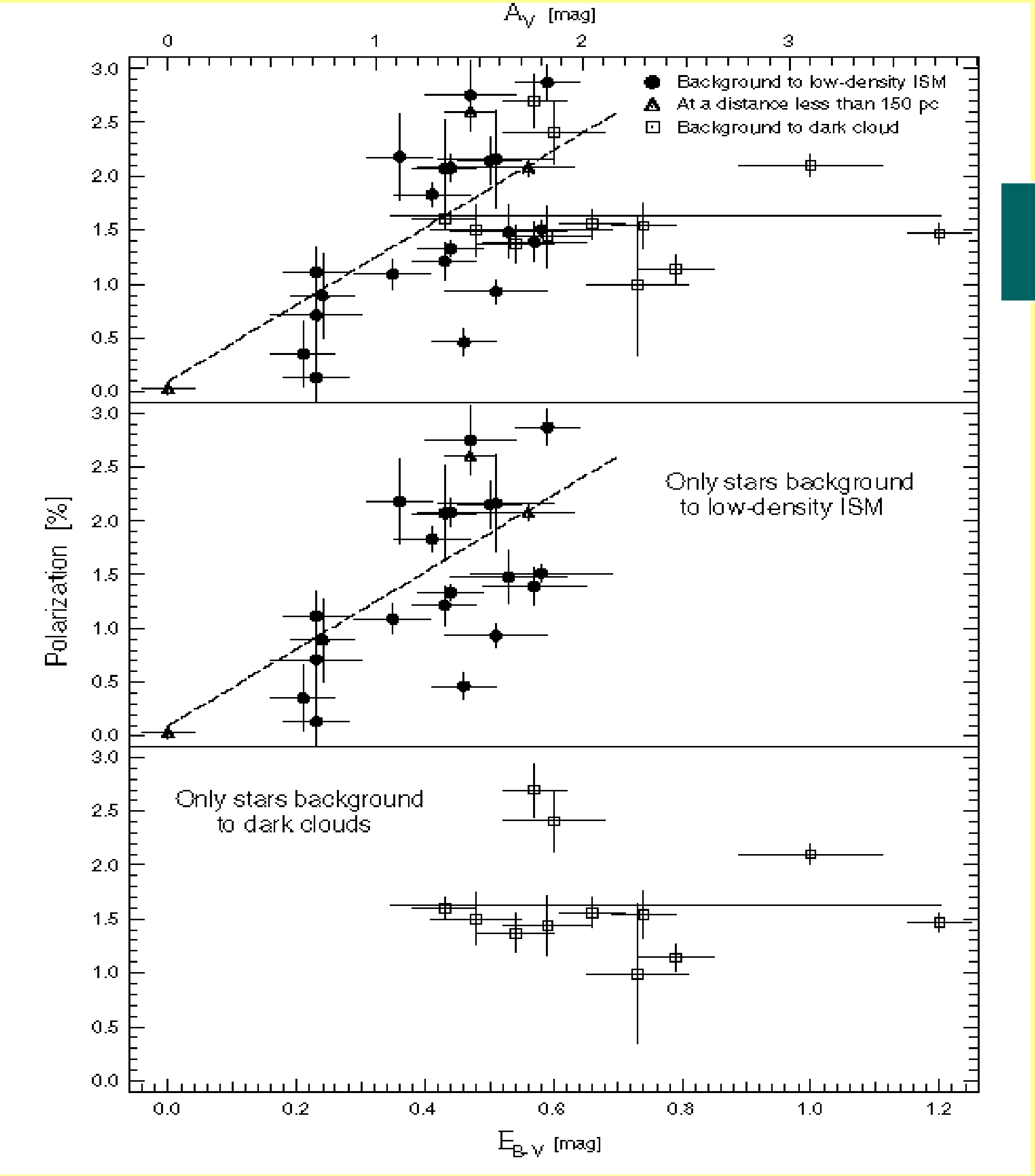


Stokes principle of optical equivalence:

It is *impossible* to distinguish two beams which are the sum of non-coherent simple waves if they have the same Stokes parameters



$$P_{\max}/E(\mathrm{B-V}) \lesssim 9\%/\mathrm{mag}\,.$$



A_V [mag]
0
1
2
3
Background to low-density ISM
At a distance less than 150 pc
Background to dark cloud
Only stars background to low-density ISM
Only stars background to dark clouds
Polarization [%]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
E_{B-V} [mag]

Why?

Cosmic dust grains

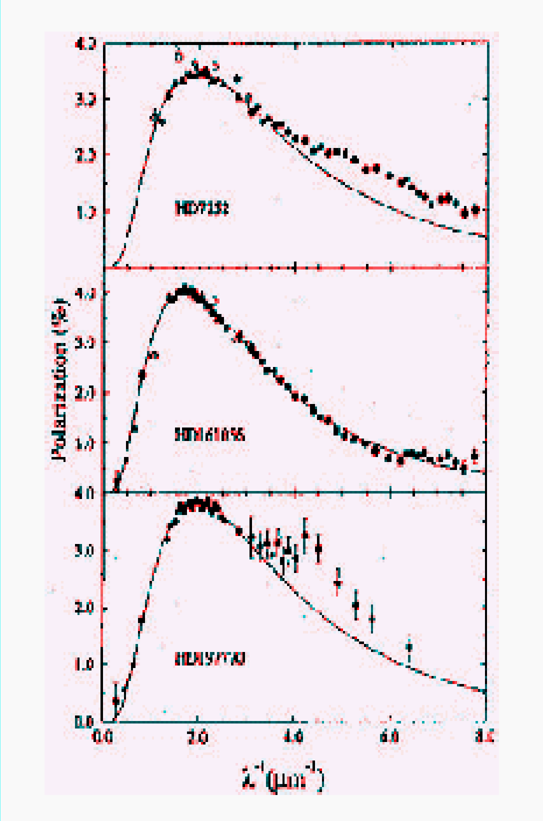
- ***Observations***

- Interstellar extinction
- Interstellar polarization
- Scattered radiation (nebulae, circumstellar shells)
- Infrared radiation (dust emission)
- Dust features
- (Element depletions)

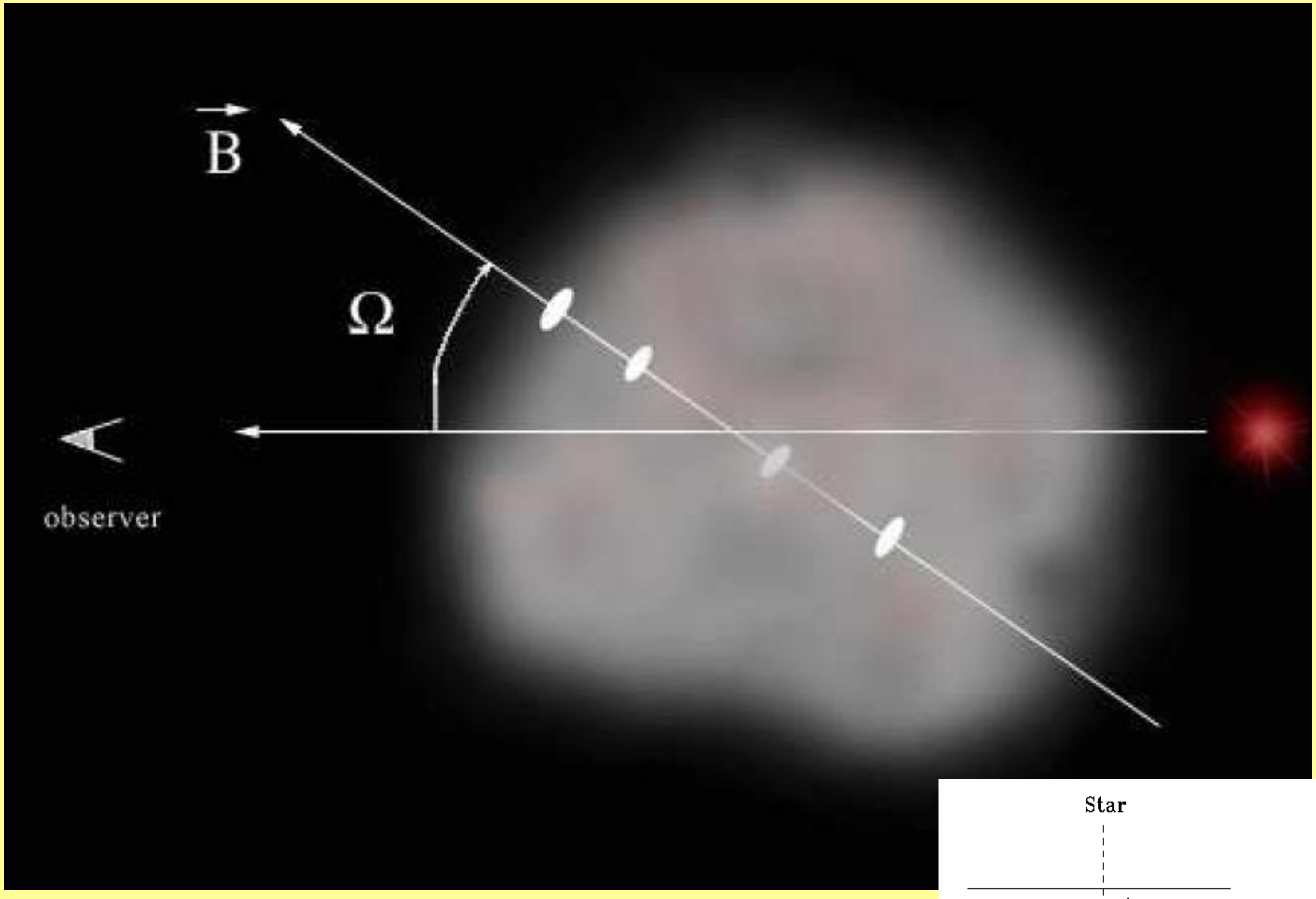
- ***Interpretation***

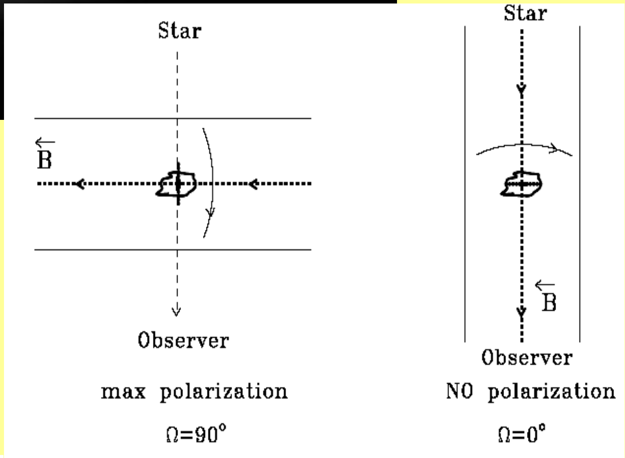
  (grain characteristics)

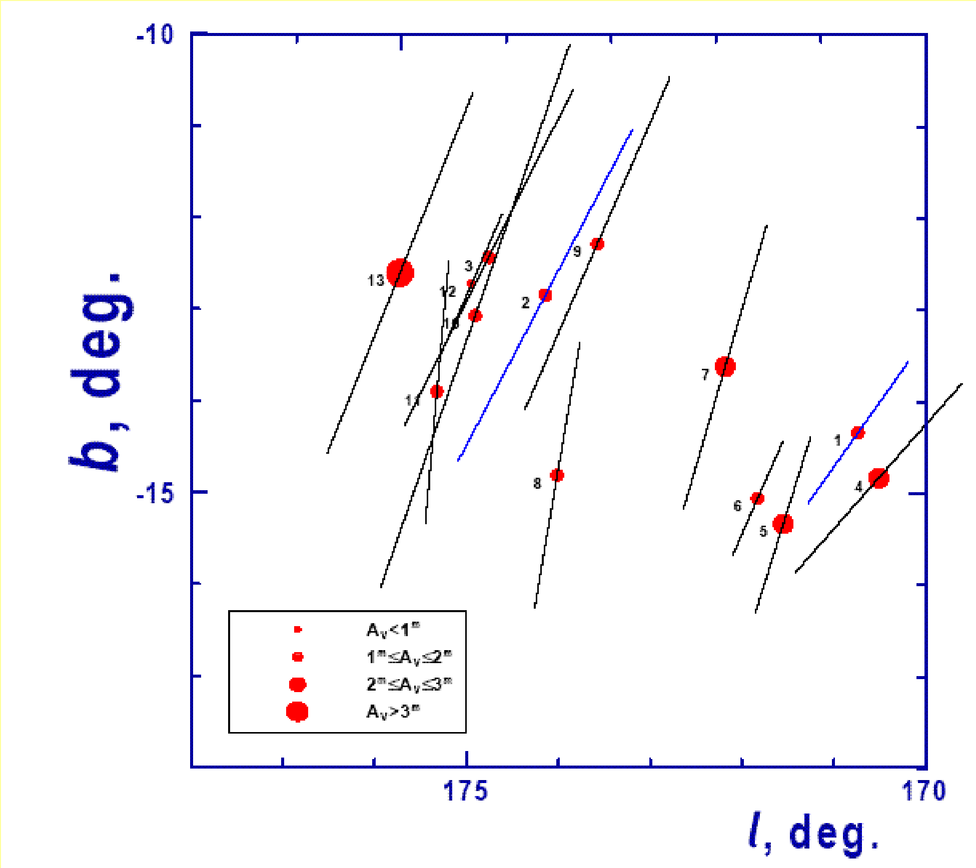
- composition
- size
- shape
- structure
- (surface properties)



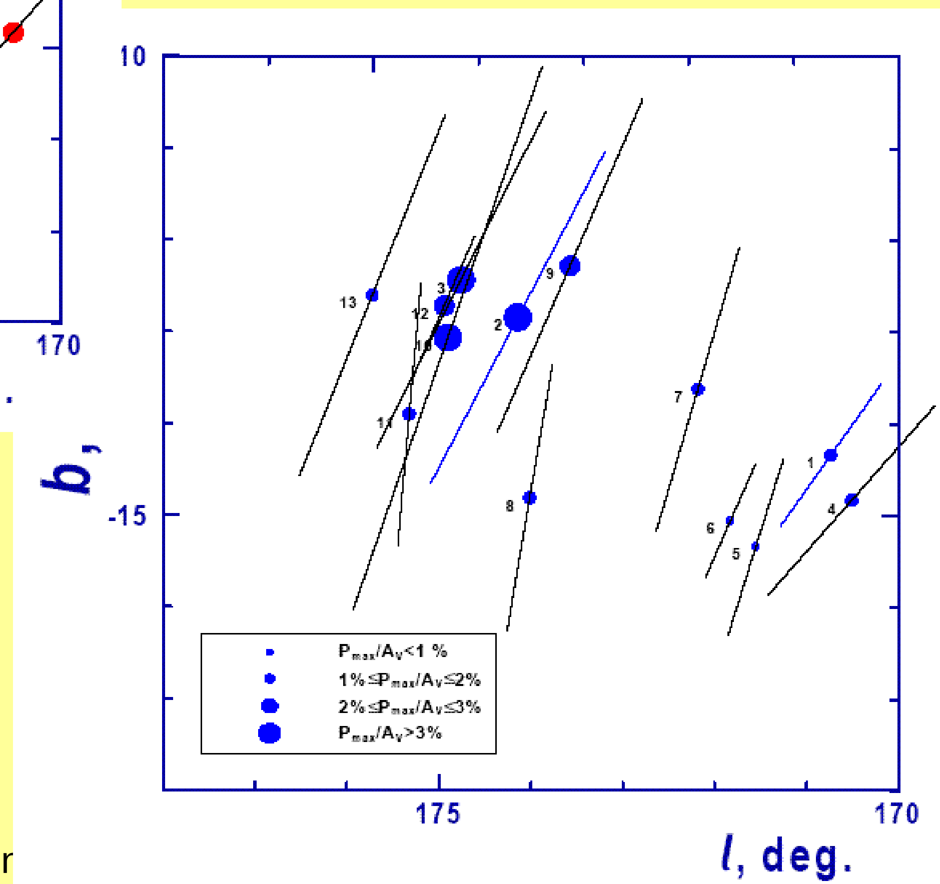
Polarization curves for three stars with different behaviour of the UV polarization. Solid curves — fitting using Serkowski's curve. After Whittet (1996).


B
Ω
observer


Star
B
Observer
max polarization
Ω=90°
Star
B
Observer
NO polarization
Ω=0°


-10
-15
175
170
b, deg.
l, deg.
13
12
3
10
11
2
9
8
7
6
5
1
4
$A_V<1^m$
$1^m \le A_V \le 2^m$
$2^m \le A_V \le 3^m$
$A_V>3^m$

(TMC1, cloud1)


10
-15
175
170
b,
l, deg.
13
12
3
10
11
2
9
8
7
6
5
1
4
$P_{max}/A_V<1$ %
$1\% \le P_{max}/A_V \le 2\%$
$2\% \le P_{max}/A_V \le 3\%$
$P_{max}/A_V>3\%$