Astrophysical light scattering problems (PAP316)

Lecture 11a

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Interstellar polarization, Contents

- Introduction
- Extinction by non-spherical particles
- Polarization in emission
- Wavelength dependence
- Grain alignment
- Turbulence in the ISM
- Conclusions and future work

Introduction (1/2)

- Physical characterization of astronomical objects (e.g., surfaces of airless planetary objects)
- Direct problem of light scattering by particles with varying particle size, shape, refractive index, and spatial distribution
- Inverse problem based on astronomical observations and/or experimental measurements
- Plane of scattering, scattering angle, solar phase angle, degree of linear polarization

Introduction (2/2)

- Consistent non-random pattern of polarization discovered across the sky in the Milky Way
- Interstellar origin confirmed
  - positive correlation between polarization and extinction
- Dichroism resulting from asymmetric grains that are aligned with the galactic magnetic field
- Changing alignment along the line of sight causes birefringence and circular polarization
- Grain properties

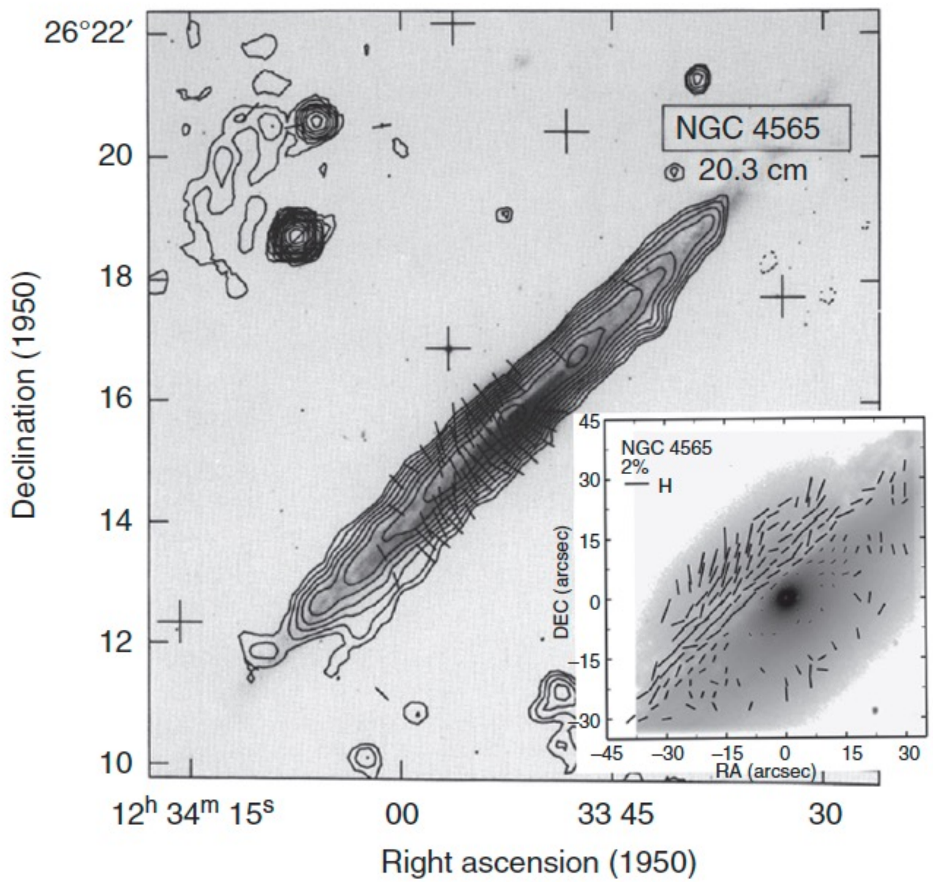

FIGURE 9.1 Comparison of synchrotron polarimetry (Sukumar and Allen 1991) and near-IR interstellar polarization (insert) for the galaxy NGC 4565 (Jones 1989b). Note the difference in angular scale between the two images.

- How do we know that the magnetic field determines the alignment direction?
- In the (very) diffuse interstellar medium (ISM), position angles of polarization agree with synchrotron radiation in the radio
- Both synchrotron observations and near-infrared imaging polarimetry of the external galaxy NGC 4565 show magnetic fields parallel to the dust lane
- Grain alignment mechanism studied intensively for decades
- Radiative torque identified as the key mechanism (cf. studies by Lazarian, Hoang, and Herranen et al.)

- Extinction

$$A_\lambda = -2.5\log\left(\frac{I_\lambda}{I_{0,\lambda}}\right) = -2.5\log\left(e^{-\tau_\lambda}\right) = 1.086\,\tau_\lambda$$

- Color (positive number for ISM, reddening)

$$E(B-V) = A_B - A_V \propto \tau_B - \tau_V$$

Extinction by non-spherical particles

- Beam of light transmitted through a medium becomes linearly polarized if
  - dust particles are optically anisotropic
  - there is net alignment of the axes of anisotropy
- Particle shape mostly likely source of anisotropy, grain material the less likely option

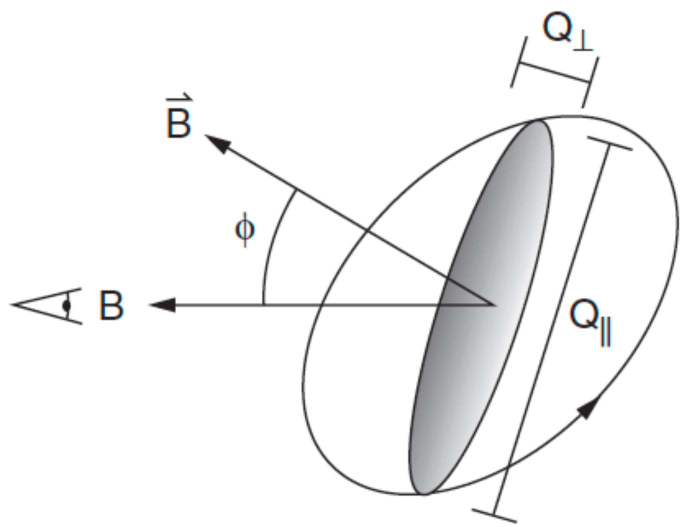

FIGURE 9.2 Geometry of a spinning grain and the external magnetic field. The extinction efficiency coefficients, $Q_\parallel$ and $Q_\perp$, refer to the *time-averaged* values in projection when $\varphi = 90°$, assuming the angular momentum, $\vec{\mathbf{J}}$, is perpendicular to the long axis of the grain and that $\vec{\mathbf{J}}$ and $\vec{\mathbf{B}}$ are aligned.

- Radiative transfer through a homogeneous medium of aligned particles:

$$\frac{dI}{dz} + \kappa I + \kappa_Q Q + \kappa_U U = 0$$

$$\frac{dQ}{dz} + \kappa_Q I + \kappa Q = 0$$

$$\frac{dU}{dz} + \kappa_U U + \kappa U = 0$$

- For unpolarized incident light

$$P_L(\%) = 100\frac{\sqrt{Q^2 + U^2}}{I} = 100 \tanh \tau_P$$

$$\tau_P = \int_0^Z \kappa_P(z)\,dz$$

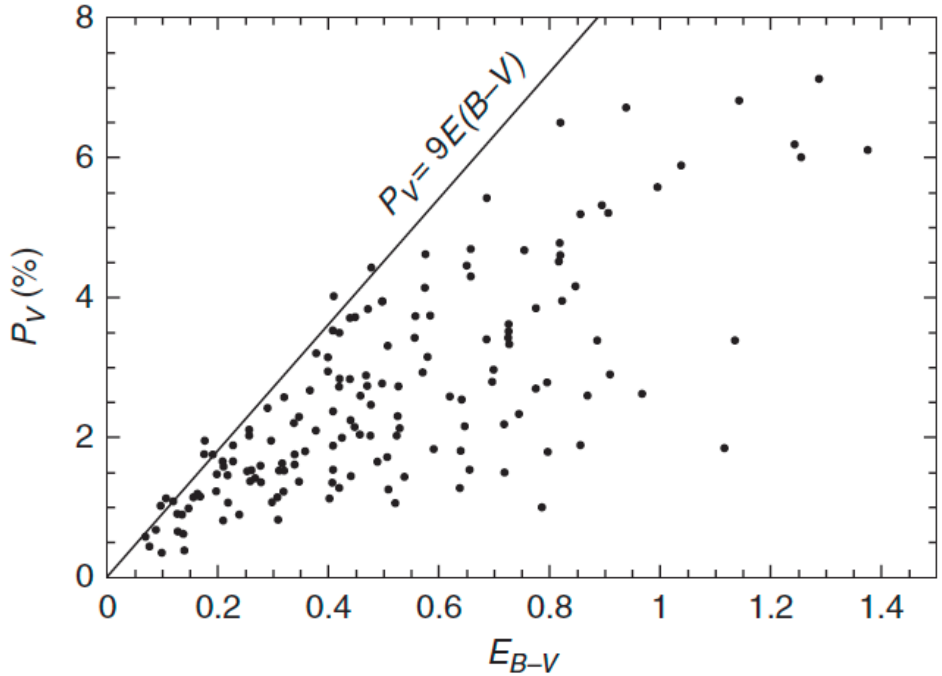

FIGURE 9.3 Fractional polarization plotted against extinction at visible wavelengths. Note the clear upper limit to the trend with a slope of $P_V = 9.0E(B-V)$.

Polarization in emission

- Polarized emission typically assumed to take place in optically thin conditions
- Polarization of emitted light stronger in optically thin conditions (opposite to the characteristics in extinction)
- Interesting possibility for multiwavelength studies of the ISM

Wavelength dependence

- Empirical Serkowski law:

$$P_\lambda = P_{max} \exp\left\{-K \ln^2\left(\frac{\lambda_{max}}{\lambda}\right)\right\}$$

- K = 1.15 in the visible, empirically

$$K = c_1 \lambda_{max} + c_2$$

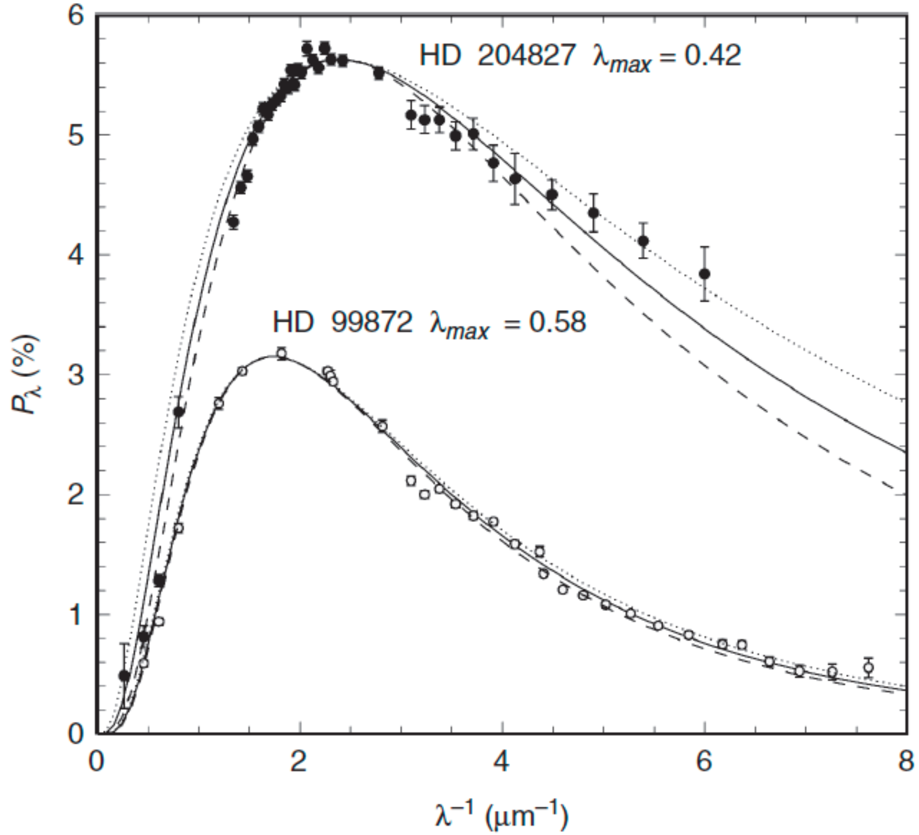

FIGURE 9.4 Interstellar linear polarization curves for two stars with different values of the wavelength of maximum polarization. Observational data are from Martin *et al.* (1999) and references therein. Also shown are empirical fits based on the Serkowski law: visual-IR optimized fit (dashed curve); visual-UV optimized fit (dotted curve); compromise fit (continuous curve). Note the abscissa is in inverse wavelength units.

- Not all dust grains contributing to the extinction contribute to the polarization
- Extinction increasing for shorter wavelengths but polarization decreasing (overall, exceptions exist)
- Smaller grains causing extinction not participating in polarization
- Small carbon grains responsible for the extinction bump
- Thermal disalignment of small grains?

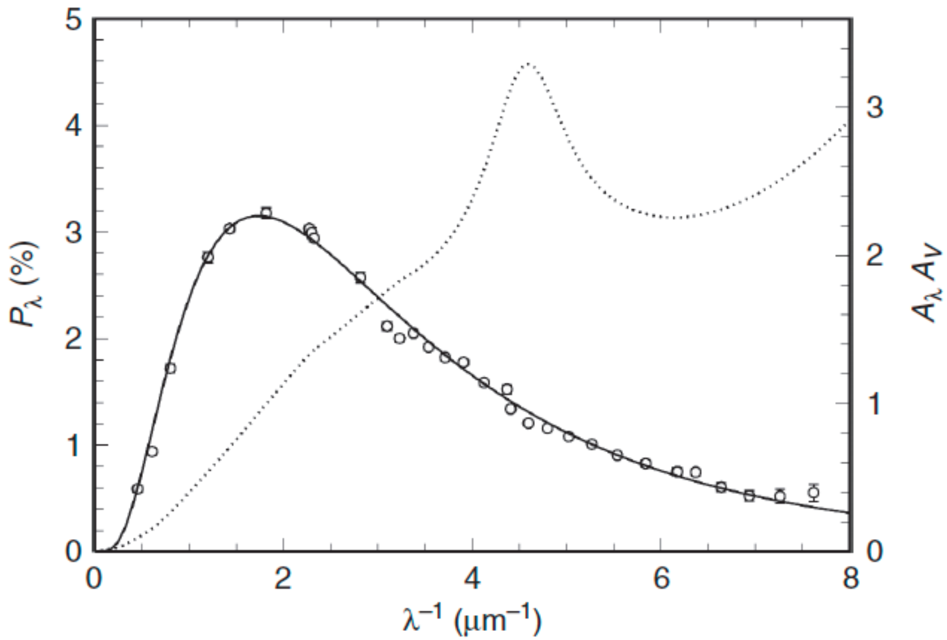

FIGURE 9.5 Illustration of the wavelength dependence of interstellar extinction and polarization. Polarization is the solid line, extinction is the dotted line.

From Whittet (2004), copyright Astronomical Society of the Pacific; reproduced with permission.

- Evidence that large (>0.1 microns) silicate grains produce most of the polarization
- Ice and silicate features seen in a heavily extinguished young star (Becklin-Neugebauer object, BN)

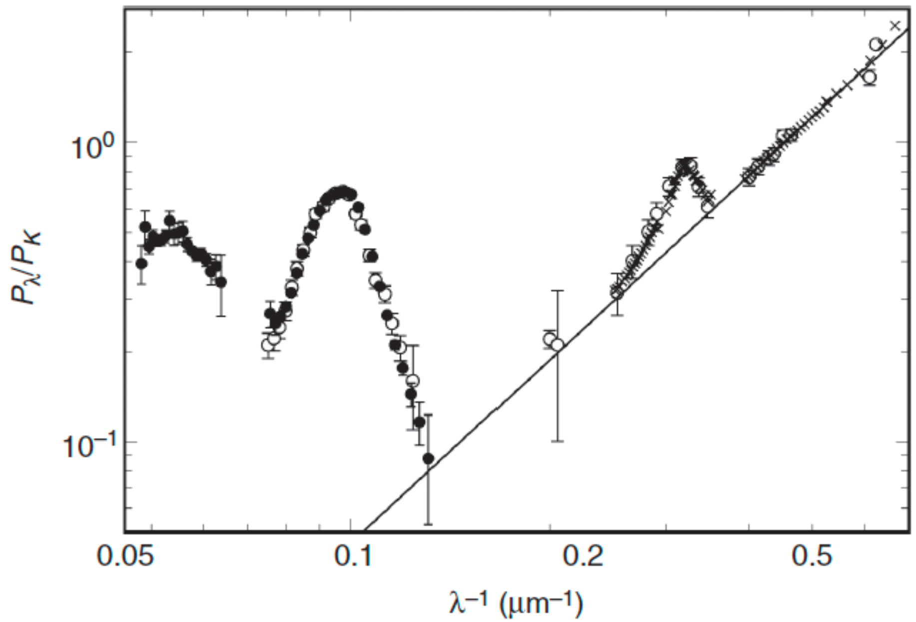

FIGURE 9.6 The wavelength dependence of interstellar polarization for BN.

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- At far-IR, sub-mm, and mm wavelengths, large grains producing polarization in extinction are emitting polarized thermal radiation
- Decreasing polarization from 60 to 350 microns and increasing polarization from 350 to 1300 microns
- Polarization at a given wavelength depends on the temperature of the dominant component in the line of sight
- Polarization perhaps surprisingly similar for other galaxies

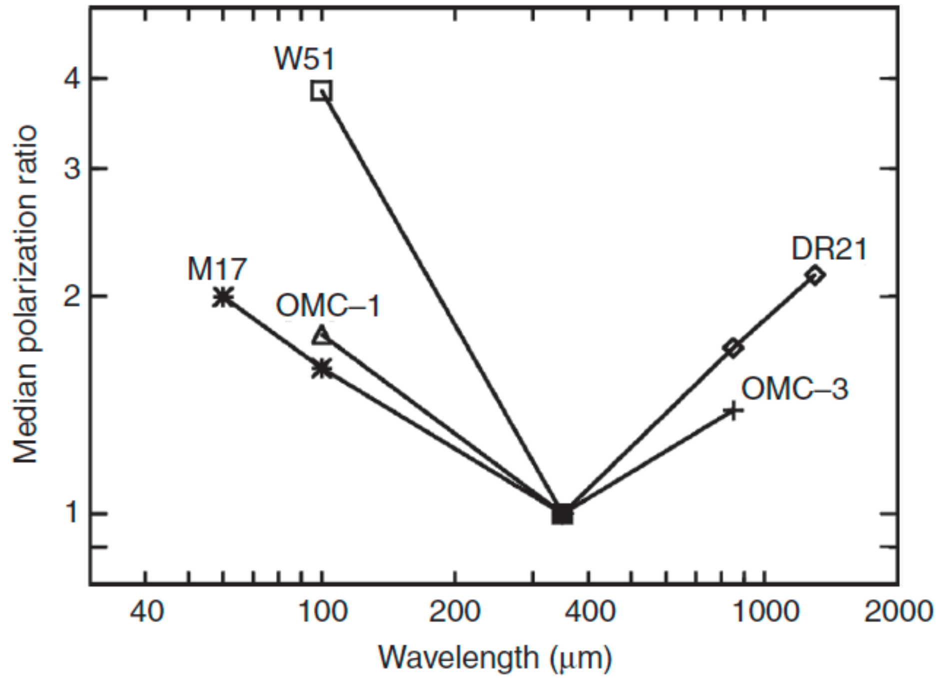

FIGURE 9.7 Wavelength dependence of interstellar polarization from dust grains in emission for selected sources. Median polarization is the median of the distribution in fractional polarization in emission for each of the designated (labeled) molecular cloud regions, divided by the median at 350 μm.

From Vaillancourt (2002); reproduced with permission of the AAS.

Grain alignment

- Efficiency of grain alignment crucial for determining the fractional polarization
- Evidence for nearly perfect grain alignment in the very diffuse ISM
- Two questions to study
  - alignment of the grain body with its angular momentum
  - alignment of angular momentum with the magnetic field
- Assumption of angular momentum alignment with the magnetic field
- Highly intricate physics involved
- Rigorous studies of scattering dynamics by Joonas Herranen (Ph.D. thesis, 2020)

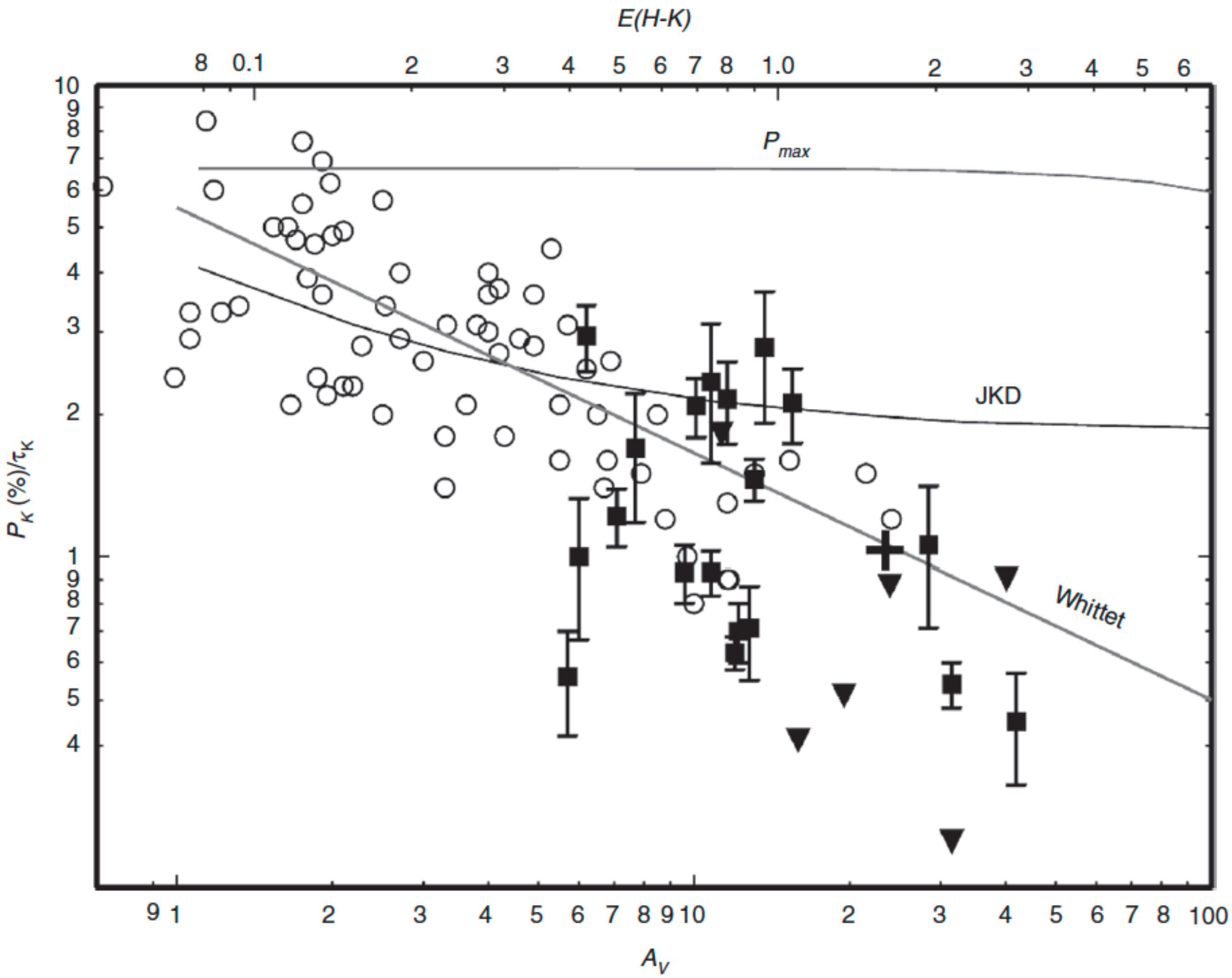

FIGURE 9.8 Polarization efficiency plotted against extinction in visual magnitudes for background stars. The labeling of the lines is explained in the text. The plus symbol is the star Elias 16, which shows H_2O and CO ice absorption features, which are polarized.

Hough *et al.* (1988, 2008).

- Potential for probing great dust column densities using sub mm and mm polarimetry in emission

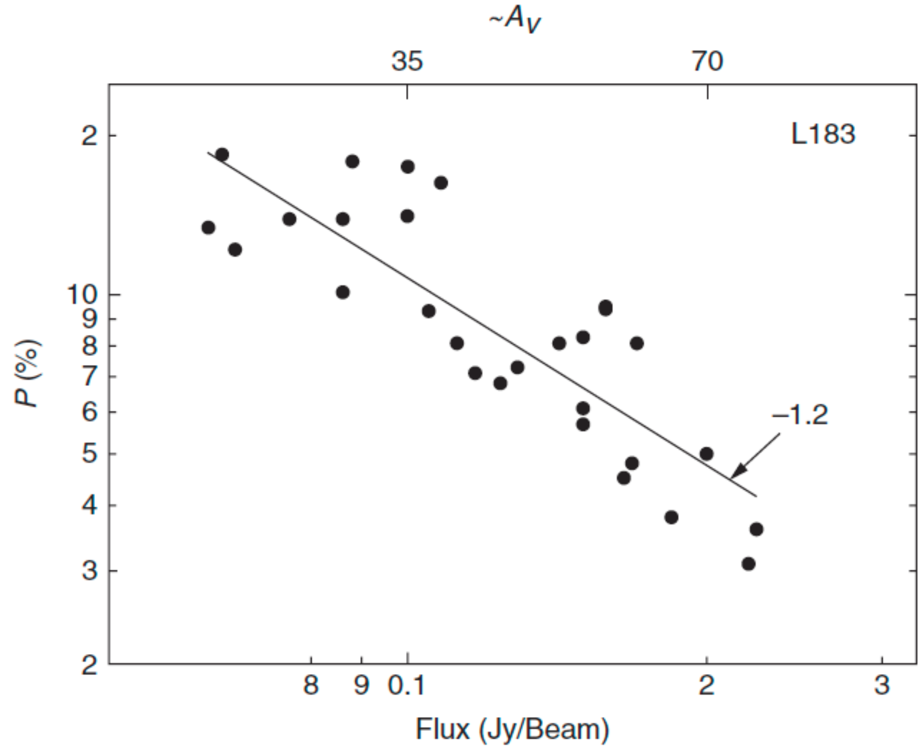

FIGURE 9.9 Fractional polarization in emission at submillimeter wavelengths for the molecular cloud core L183 plotted against surface brightness (bottom axis in Janskys) and extinction (top horizontal axis in A_V). The slope of the solid line is −1.2, indicating no grain alignment at these very high extinctions.

See also Jones *et al.* (2011).

Turbulence in the ISM

- Wiggles in consistent patterns of polarization position angles due to wiggles in magnetic field
- Wiggles tied to movement in the gas
- Model based on random and constant components of the magnetic field
  - in Fig. 9.10, long dashed line corresponds to perfect alignment, short dashed line to pure random field geometry

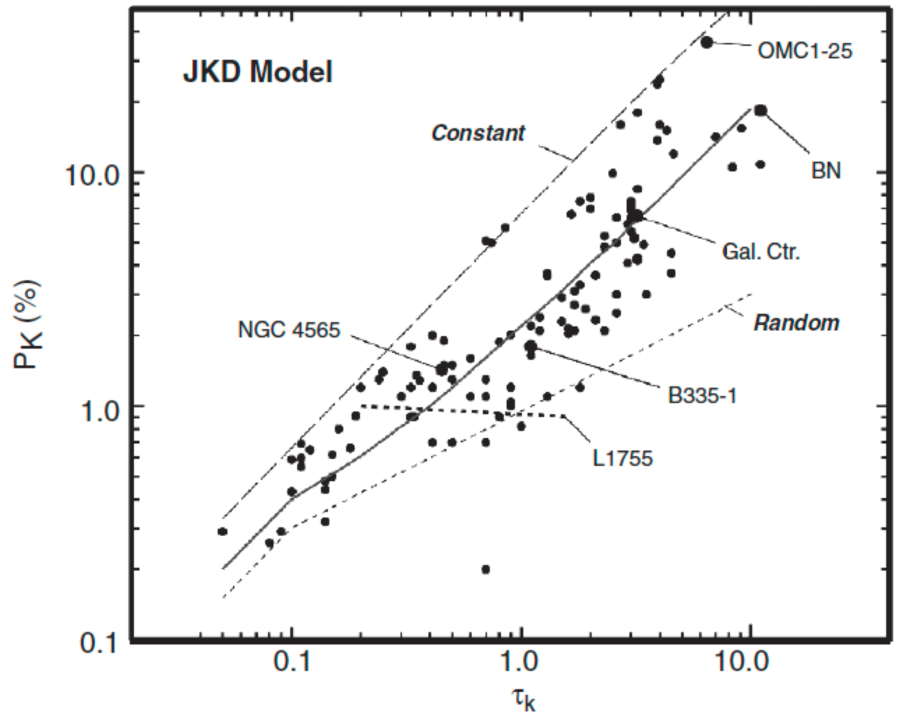

FIGURE 9.10 Observed trend of linear polarization vs. optical depth (extinction) at 2.2 μm (K-band). Several specific astronomical sources are individually labeled. Gal. Ctr. corresponds to the center of the Milky Way galaxy and BN is the Becklin–Neugebauer object.

See also Jones *et al.* (1992).

- Based on GPIPS (Galactic Plane Infrared Polarization Survey), combining polarimetry with ^{13}CO spectral line widths, local regions of higher field strength detected
- Evidence for magnetic field continuing to suppress star formation

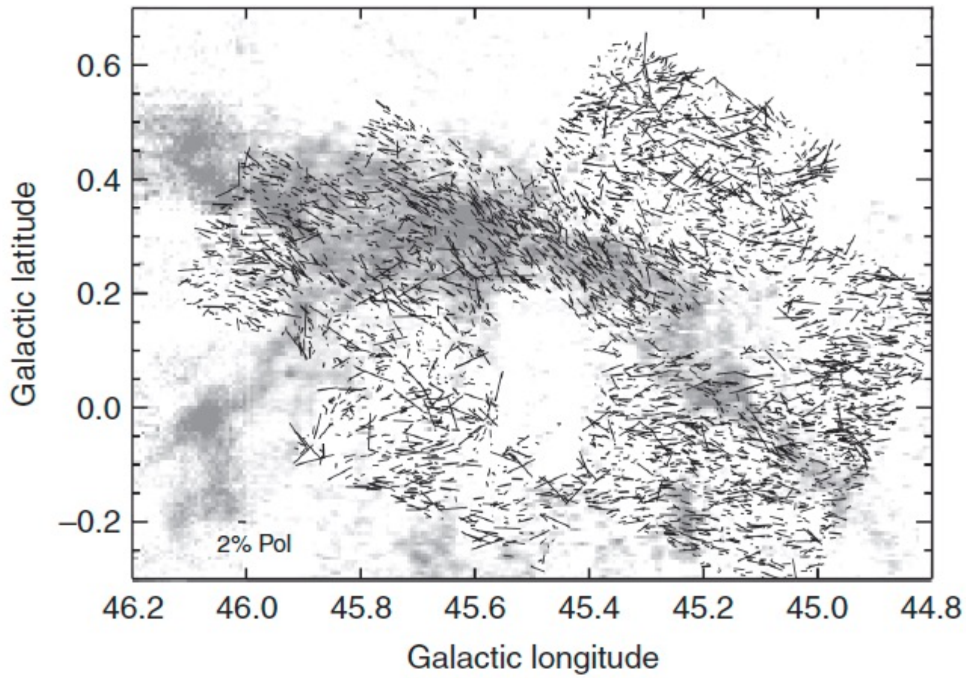

FIGURE 9.11 GPIPS polarization map of stars shining through the ISM in the direction of GRSMC 45.60+0.30. Axes units are in degrees.

From Marchwinski *et al.* (2012); reproduced with permission of the AAS.

- Structure function, difference in position angles $\Delta\theta$ as a function of angular distance l:

$$\Theta_{rms}(\ell) = \left\langle \Delta\theta^2(\ell) \right\rangle^{1/2} = \left[\frac{1}{N} \sum_{1}^{N} \left(\theta(x) - \theta(x-\ell) \right)^2 \right]^{1/2}$$

- Five simplified cases
  - A: noiseless data without turbulence
  - B: data with noise but no turbulence
  - C: data with noide but with turbulence
  - E: showing the scale length for turbulence
  - D: including the effects of beam size

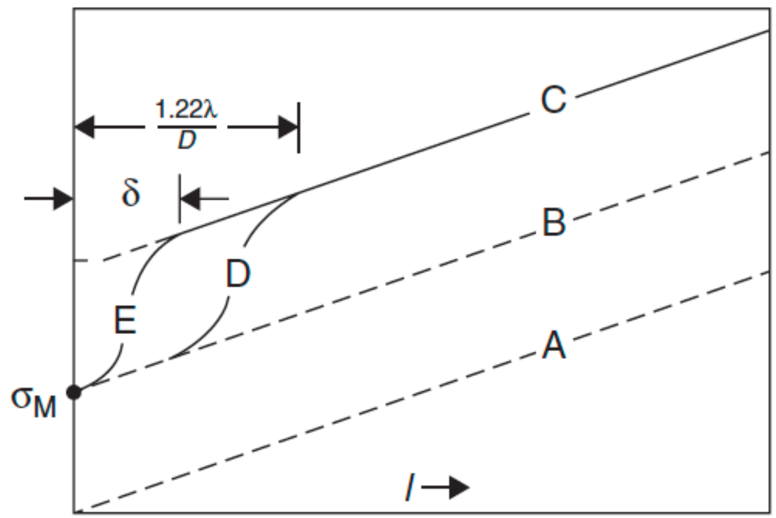

FIGURE 9.12 Idealized trend in the dispersion function with angular separation on the sky.

From Hildebrand (2009); reproduced with permission of the AAS.

- Cygnus OB2 region, scale length about 0.7°
  - leveling off of the structure function
- Drop in the smallest angular bin, but not enough star separations for definitive conclusions

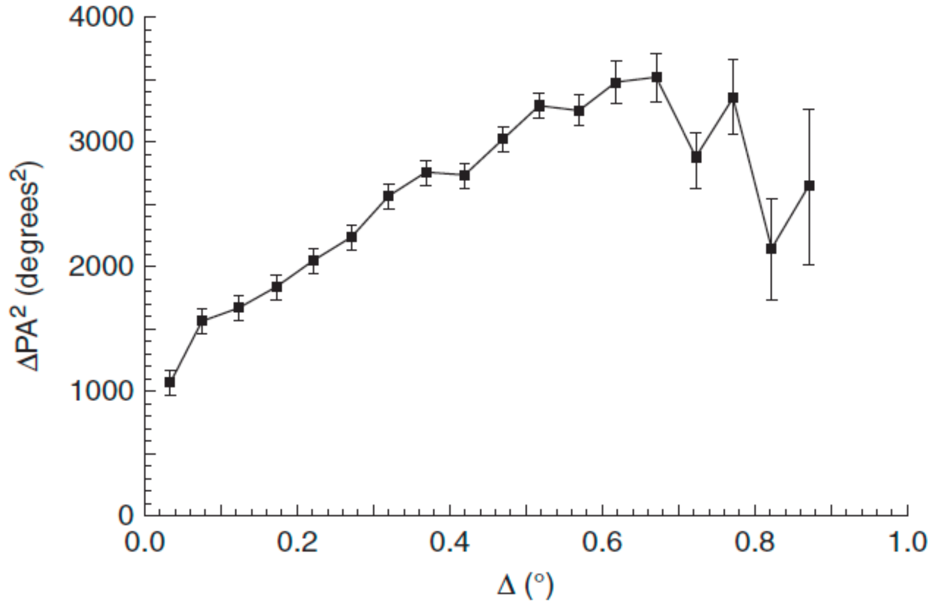

FIGURE 9.13 Plot of the observed structure function for polarimetric position angles against angular separation on the sky for stars in the Cygnus OB2 region.

From Kobulnicky *et al.* (1994); reproduced with permission of the AAS.

Conclusions and future work

- Polarization important in tracing the magnetic field geometry in the diffuse ISM
- Grain alignment efficient in the ionized and atomic regions of the ISM
- Magnetic field important in the most diffues ISM regions for understanding
  - gas motions and turbulence
  - molecular cloud formation
  - the field connection to the molecular clouds embedded in the galactic magnetic field
- Heavy elements in the dust so studies of dust composition, size distribution, and structure important for cycling of the elements
- Polarization provides grain properties and clues to grain crowth and nature of the radiation field

- Spectro-polarimetry powerful there but underused
- Interstellar polarization significant foreground contaminant to the cosmic microwave background
  - how to account for foreground polarized emission and magnetic field (synchrotron radiation)
- Observations, analysis, and theoretical modeling advancing
  - GPIPS producing H-band polarimetry of hundreds of thousands of field stars in the galactic plane
  - tens of thousands of data points of polarization and position angle
- Star formation taking place in dense cores of molecular clouds
  - can grain alignment shed light on the magnetic fields there?
  - further research needed on grain alignment mechanisms