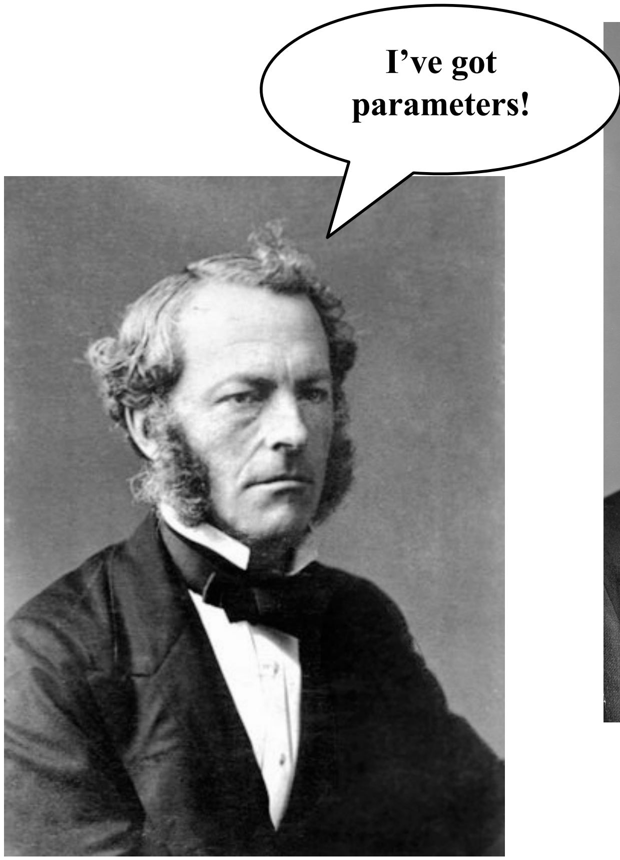
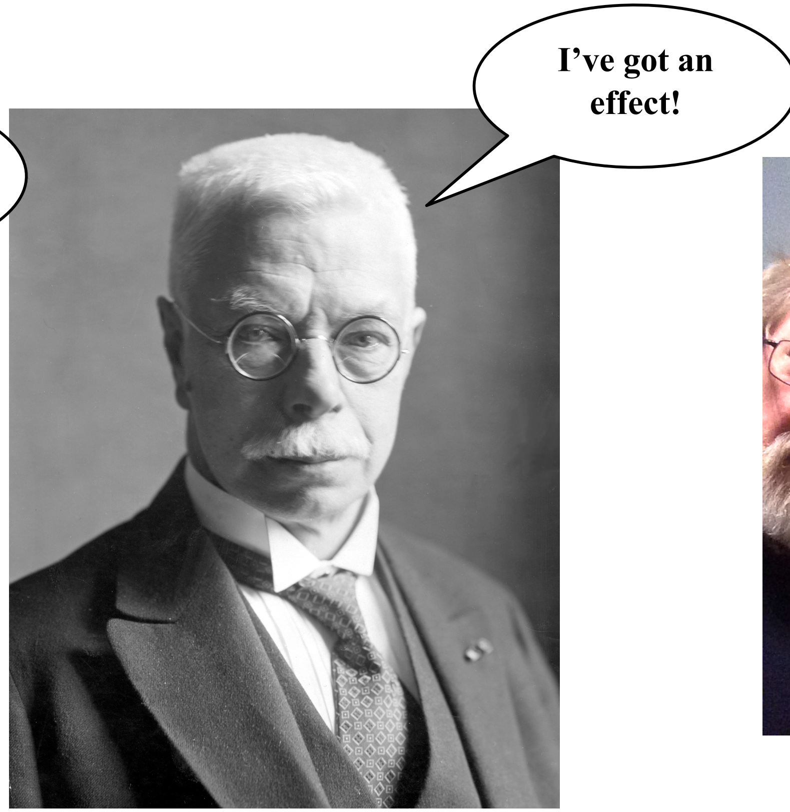
# Magnetic Field Measurements via the Zeeman Effect - Strengths & Limitations




George Stokes




Pieter Zeeman


**Tom Troland**

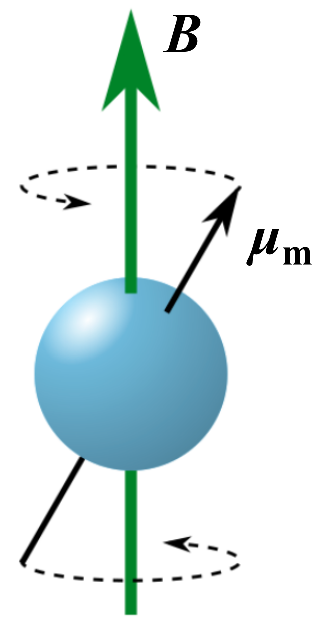
**University of Kentucky**

***Magnetic Fields and the Structure of the Filamentary Interstellar Medium***

**SOFIA Workshop, June 25, 2021**

# 1. Nature of the Zeeman Effect

- **Zeeman Effect results from an interaction between the magnetic dipole moment $\mu_m$ of an atom or molecule and the external magnetic field $B$.**




Wikimedia Commons

- **Gyromagnetic ratio $\gamma = \mu_m / J$**
- **For a particle with charge $q$ and mass $m$:**
  **$\gamma = q / 2m$**
- **$\gamma_{electron} \approx 2000\ \gamma_{proton}$ , so *electronic* angular momentum produces higher $\mu_m$ than proton angular momentum.**

# 1. Nature of the Zeeman Effect

- **Atoms or molecules with *unpaired electrons* have *electronic angular momentum*.**

  – So they have much higher magnetic dipole moments, hence, much higher sensitivity to the Zeeman Effect.

  – Typical Zeeman splitting is 1-2 Hz/$\mu$G*

  – Most other species (e.g. CO) are nearly insensitive to the Zeeman Effect.

*See splitting values in Table 1 of review by **Crutcher & Kemball 2019**

**Note - Table excludes $H_2O$ & $CH_3OH$, only detected in maser emission.**

# 1. Nature of the Zeeman Effect

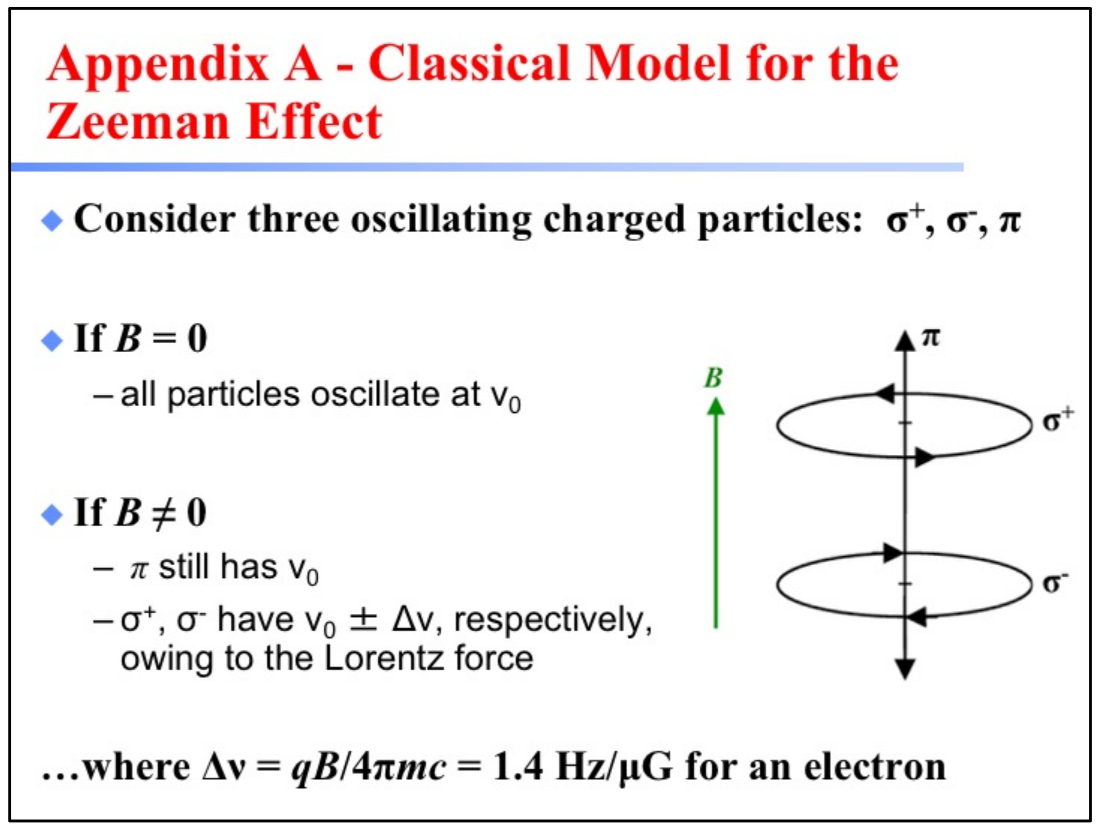
- **Zeeman sensitive species (non-zero electron *J*)**

| Species | $\nu$ (GHz) | Region sampled | Notes |
|---|---|---|---|
| **$H^0$** | **1.42** | **Diffuse $H^0$** | **Extensive detections** |
| CH | 0.70 - 0.77 | Low density $H_2$ | Zeeman effect not detected |
| **OH** | **1.66** | **Low density $H_2$** | **Extensive detections (OH main lines)** |
| CCS | 11, 22, 33, **45** | Low density $H_2$ | 1 likely detection (Nakamura+ 2019) |
| SO | Various, 30-158 | High Density $H_2$ | Zeeman effect not detected |
| CCH | 87 | Low density $H_2$ | Zeeman effect not detected |
| **CN** | **113, 226** | **High density $H_2$** | **Multiple detections** |
| $H^+$ RRL | various | H+ regions | Zeeman effect not detected |
| $C^+$ RRL | various | $H^0$ in PDRs | Zeeman effect not detected |

# 1. Nature of the Zeeman Effect

- **The normal Zeeman effect can be understood and derived from classical physics by imagining three oscillating charges immersed in a magnetic field.**

- **See Appendix A to this slide set. (To be posted)**



# 2. Application of the Zeeman Effect

- **If the Zeeman splitting >> spectral line width, then the splitting is a measure of *total field strength* $B_{tot}$.**

- **If the Zeeman splitting << spectral line width, then the splitting is a measure of *line-of-sight field strength* $B_{los}$. (Usual case, see Appendix A.)**

  – Zeeman splitting is detected in Stokes V profile (RHC - LHC) as a residual signal having the shape of the *derivative* of the Stokes I profile (RHC + LHC).

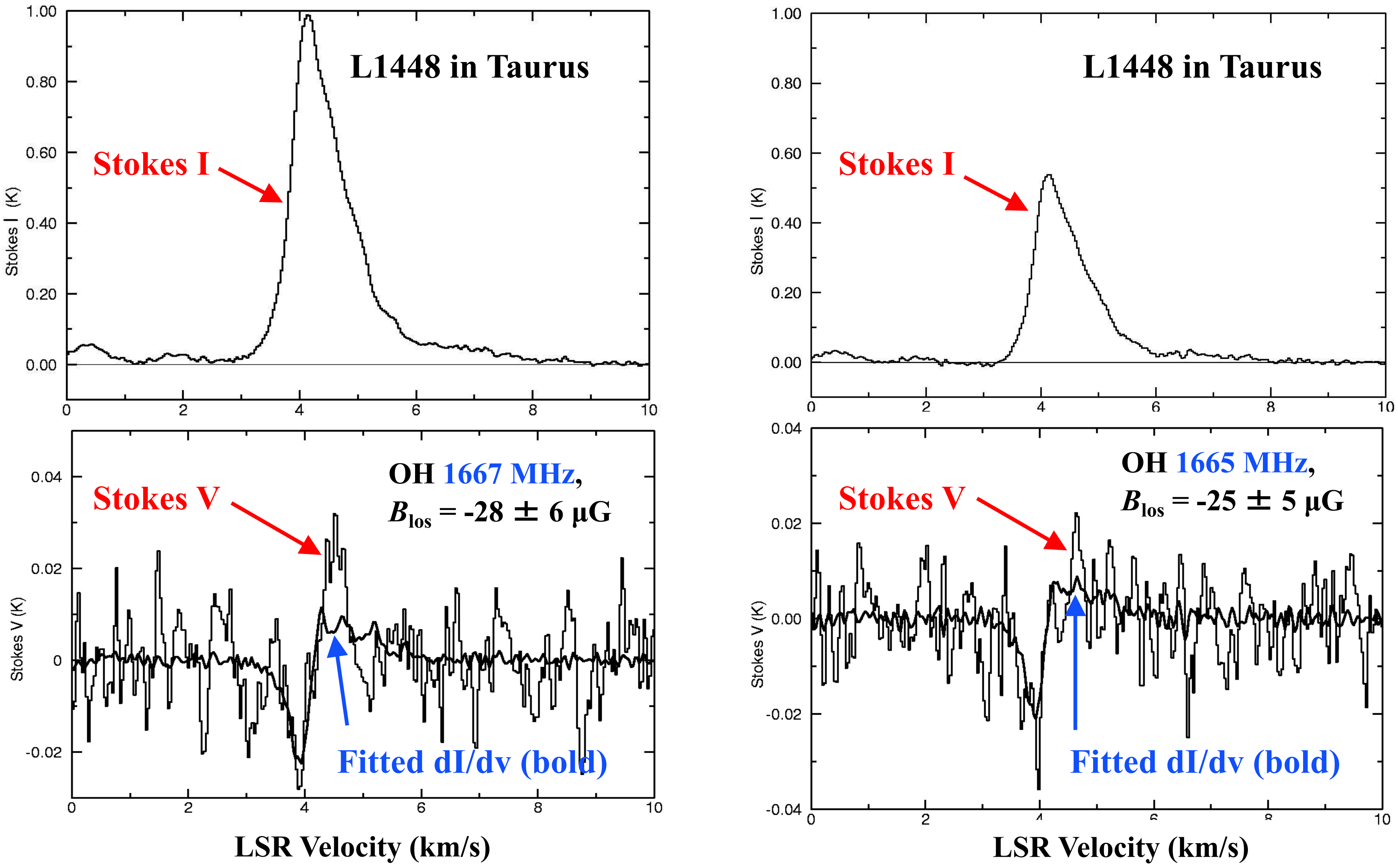
# 2. Application of the Zeeman Effect

**Fitting of the Stokes $V_\nu$ profile to the derivative of the Stokes $I_\nu$ profile:**

- **$V_\nu = \frac{1}{2}\, z\, B_{\mathrm{los}}\, dI_\nu/d\nu$**
  - Where $z$ is Zeeman splitting factor, typically 1-2 Hz/μG
  - For the 21cm HI line, $z$ = 2.8 Hz/μG
- **Result of the fit is values for $B_{\mathrm{los}} \pm \sigma(B_{\mathrm{los}})$**

# 2. Application of the Zeeman Effect

Troland & Crutcher, 2008



# 2. Application of the Zeeman Effect

- The Zeeman effect can independently sample $B_{los}$ in multiple velocity components along the line of sight.

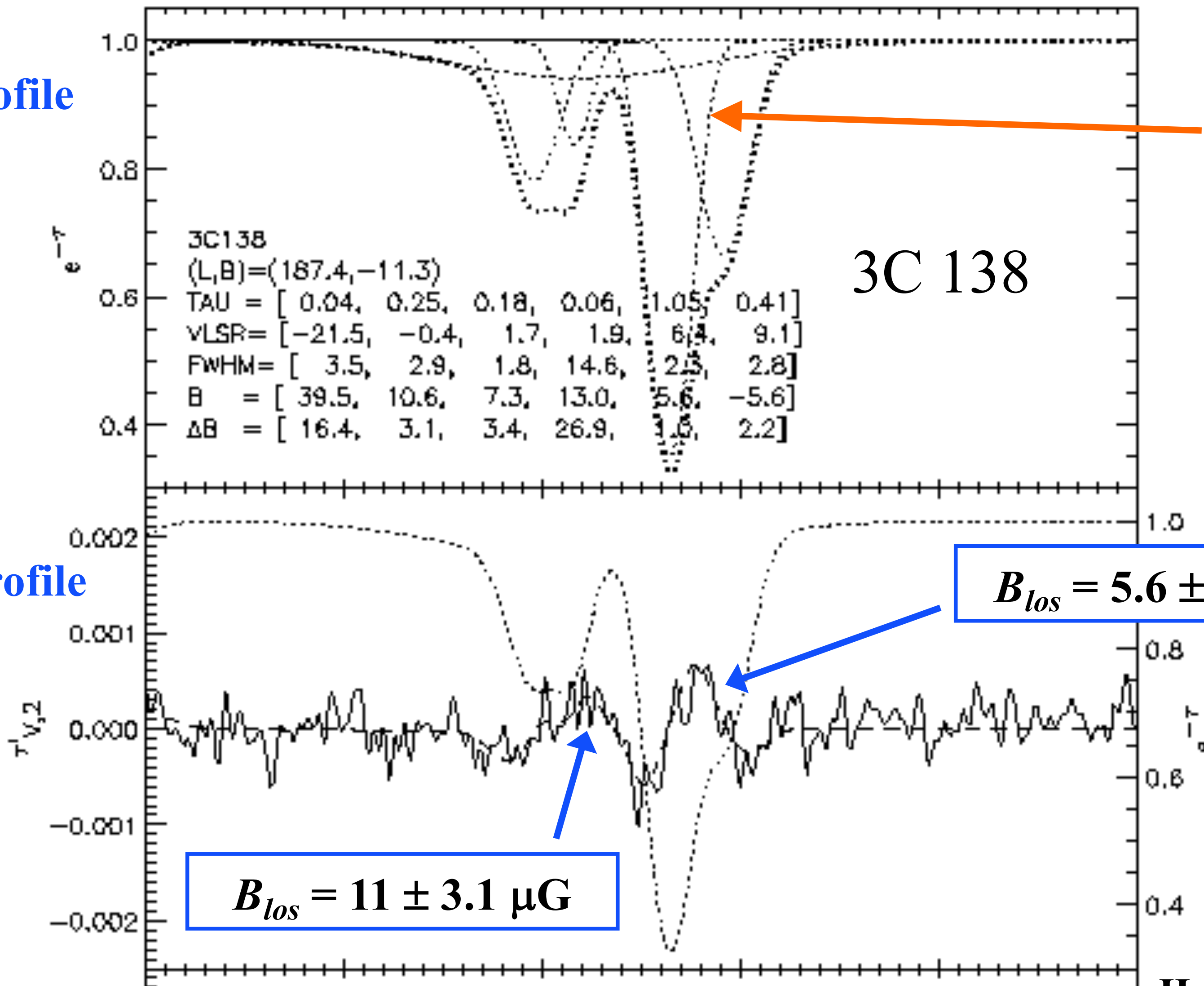
- Zeeman effect can be detected in *emission* and *absorption* lines (i.e. localized regions along los).

- Example (next slide) from Heiles & Troland 2005, *Arecibo Millennium Survey* of Zeeman effect in HI absorption lines (seen against extra-galactic continuum sources).

# 2. Application of the Zeeman Effect – HI Absorption from CNM

*I* opacity profile

*V* opacity profile
∝ dI/dv

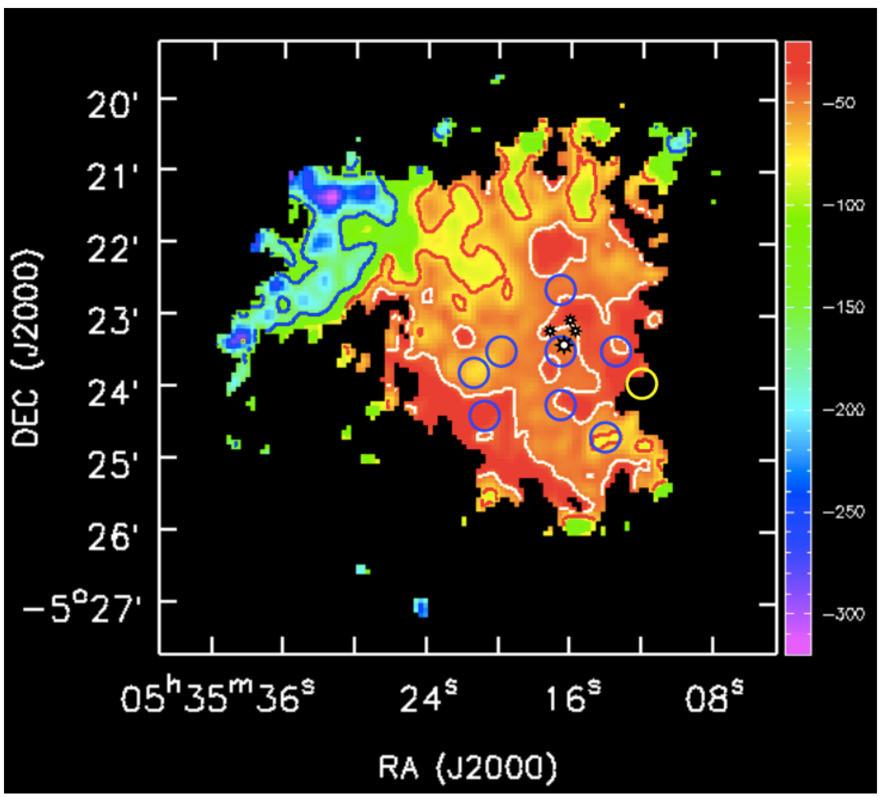



Cold Neutral Material components

Heiles & Troland 2005

# 2. Application of the Zeeman Effect

- **The technique can be used with *aperture synthesis arrays* as well as single dishes. Creates maps of $B_{los}$.**
  - VLA used for Zeeman effect in HI & OH *absorption* lines towards galactic $H^+$ regions.




**$B_{los}$ in $H^0$ gas of Orion Veil (Troland+ 2016)**

# 2. Application of the Zeeman Effect

- **The technique is applicable to $\lambda_{mm}$ arrays (ALMA) with CN emission lines. (Recall Peter Barnes talk.)**

# 3. Limitations of the Zeeman Effect

A. **Only $B_{\mathrm{los}}$ (and its sign) is measured, so individual results only provide lower limits to $B_{\mathrm{tot}}$.**

– However, multiple measurements of $B_{los}$ can be used to derive $B_{\mathrm{tot}}$ *statistically* (Crutcher+ 2010).

B. **Since Zeeman splitting $\Delta\nu$ << spectral line width (typically 1%), circular polarization in the line is very weak, requiring long integrations times.**

# 3. Limitations of the Zeeman Effect

C. **Zeeman-sensitive species are few (since unpaired electrons are required).**

D. **Zeeman-sensitive molecules (with unpaired electrons) are *reactive*, so regions sampled may be difficult to specify on basis of astrochemical models.**

# 3. Limitations of the Zeeman Effect

E. **Measurements are sensitive to instrumental polarization effects.**

– Instrumental circular polarization arises when telescope beam pattern is different in orthogonal circular polarizations.

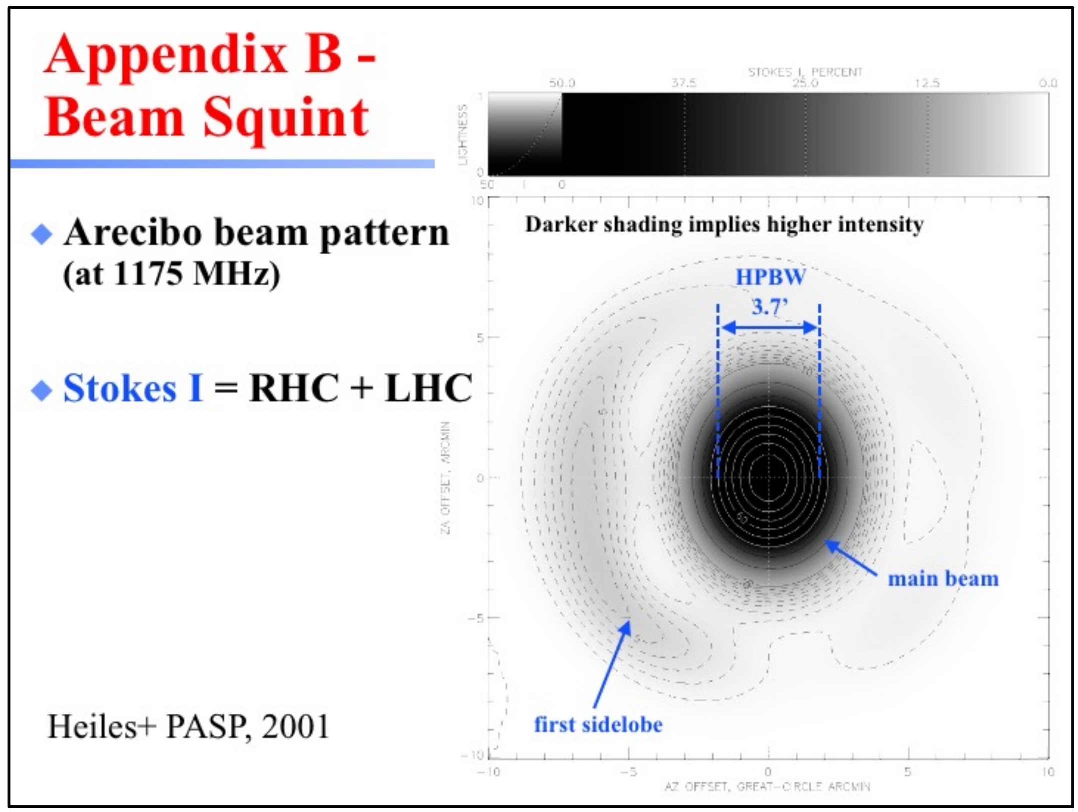
– That is, *polarized* (Stokes V) beam pattern is non-zero.

# 3. Limitations of the Zeeman Effect

- One common type of instrumental polarization (*beam squint*) can lead to false Zeeman effects.

- See Appendix B in this slide set. (To be posted)

- See, also, Troland & Heiles 1982

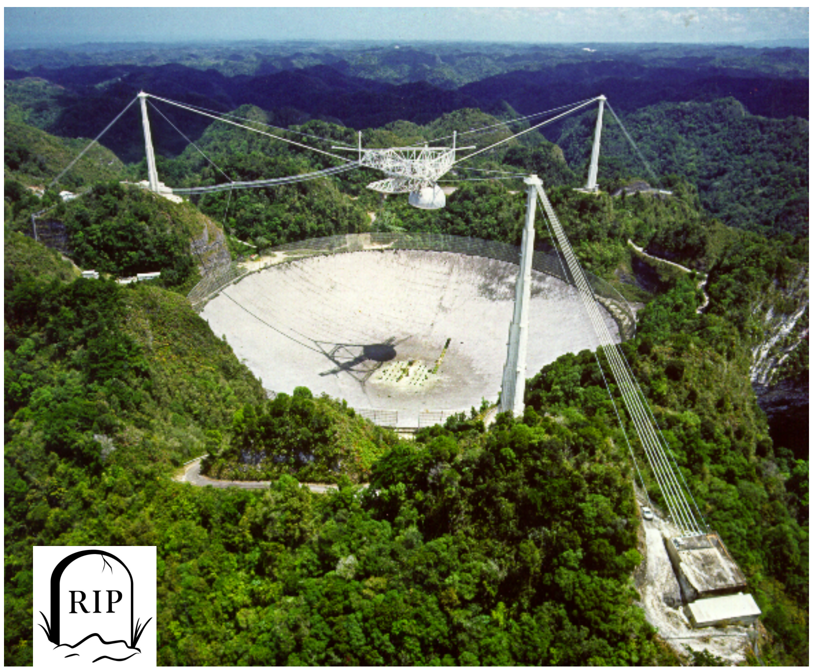


# 3. Limitations of the Zeeman Effect

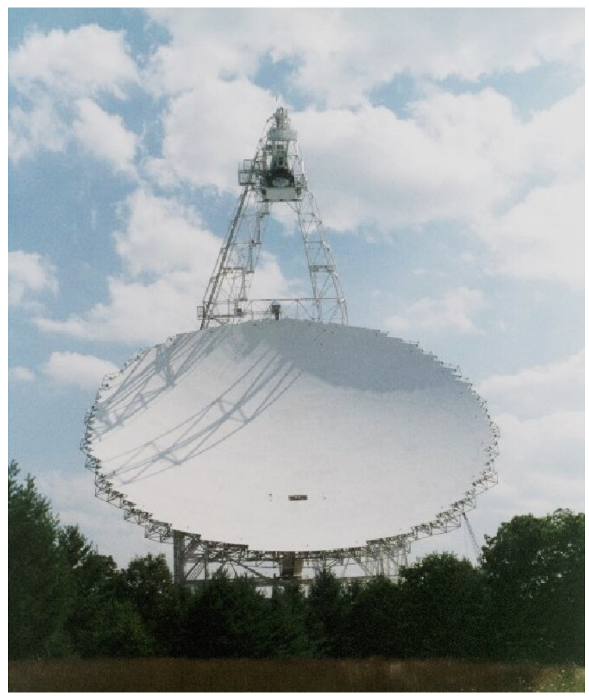
- **However, if a molecule (*e.g.* CN, CCH) has *multiple hyperfine transitions*, each with a *different Zeeman splitting*, then beam squint effects can be separated from true Zeeman effects.**
  - See Crutcher+ 1996; Crutcher+ 1999; Falgarone+ 2008

# 4. Existing Zeeman Effect Data

- A relatively large body of Zeeman effect observations now exists covering a *large range in n(H) and N(H)*.




Arecibo
(HI, OH)



Green Bank Telescope
(OH)

IRAM 30m Telescope
(CN)

# 4. Existing Zeeman Effect Data

- Three Zeeman species sample *different densities*

| Species (Beam size) | Wavelength | *n*(H) sampled |
|---|---|---|
| **HI** (pencil beam to extra-galactic sources) | 21 cm | $10^1 - 10^2$ cm$^{-3}$ (diffuse gas) |
| **OH** (3' at Arecibo) | 18 cm | $10^3 - 10^4$ cm$^{-3}$ (low density $H_2$) |
| **CN** (23" at IRAM 30m) | 3 mm | $10^5 - 10^6$ cm$^{-3}$ (high density $H_2$) |

# 4. Existing Zeeman Effect Data

- Published Zeeman data comprise ≈ 200 measurements of $B_{los}$

| Data set | Reference | No. of $B_{los}$ |
|---|---|---|
| **Compilation** (HI, OH, CN as of 1999) | Crutcher 1999 | 27 |
| **OH absorption toward galactic $H^+$ regions** | Bourke, Myers, Robinson & Hyland 2001 | 22 |
| **Arecibo HI absorption Millennium Survey** | Heiles & Troland 2004, 2005 | 67 |
| **Arecibo OH emission (dark clouds)** | Troland & Crutcher 2008 | 34 |
| **IRAM 30m CN emission** | Falgarone, Troland, Crutcher & Paubert 2008 | 11 |

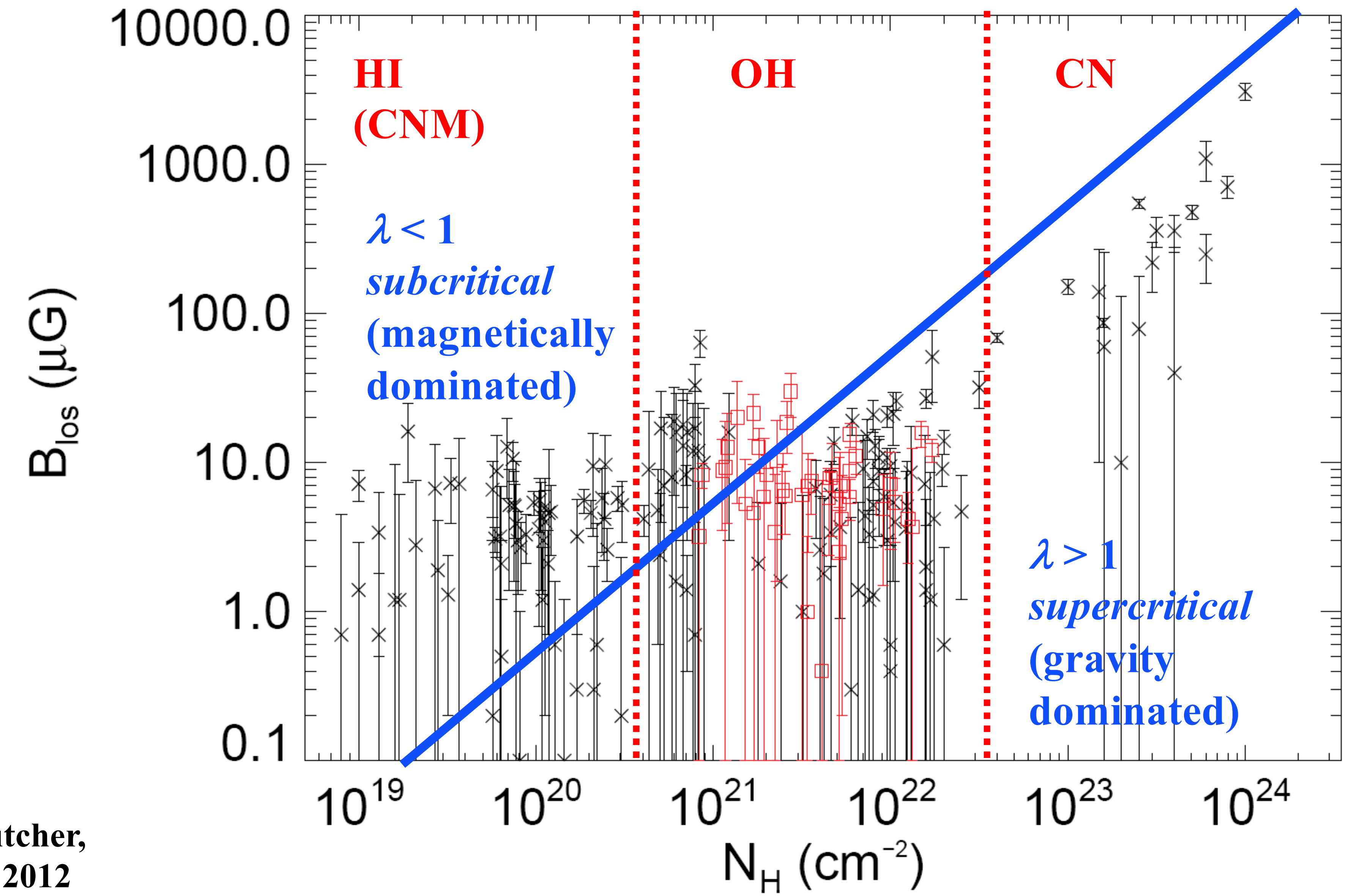
# 4. Existing Zeeman Effect Data

- Published Zeeman data comprise ≈ 200 measurements of $B_{los}$

| Data set | Reference | No. of $B_{los}$ |
|---|---|---|
| Galactic OH absorption towards extragalactic continuum sources | Thompson, Troland & Heiles, 2019 | 38 |

**λ is mass-to-flux ratio. $\lambda^2$ = grav. energy/B energy.**

# 4. Existing Zeeman Effect Data




See Crutcher, ARAA, 2012

# 5. Zeeman Effect Studies - The Future

## Diffuse $H^0$ and low-density molecular gas:

- HI and OH absorption line Zeeman observations via FAST and SKA instruments (creating a much denser matrix of extra-galactic lines-of-sight).

- Survey of the Zeeman effect in HI emission at DRAO led by Tim Robishaw.

# 5. Zeeman Effect Studies - The Future

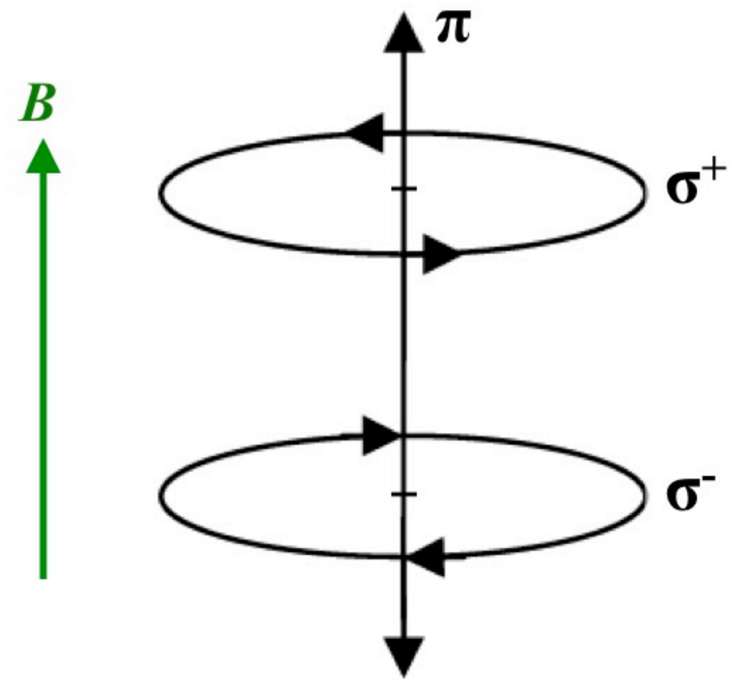
## High-density molecular gas:

- **ALMA observations of the CN Zeeman effect will offer the best opportunity to measure magnetic field strengths at high spatial resolution in star forming regions.**
  - **Data will provide more definitive indications roles of turbulence vs. magnetic fields in shaping the star formation process.**
  - **Good luck to Peter Barnes and collaborators!**

# END of regular presentation

# Appendix A - Classical Model for the Zeeman Effect

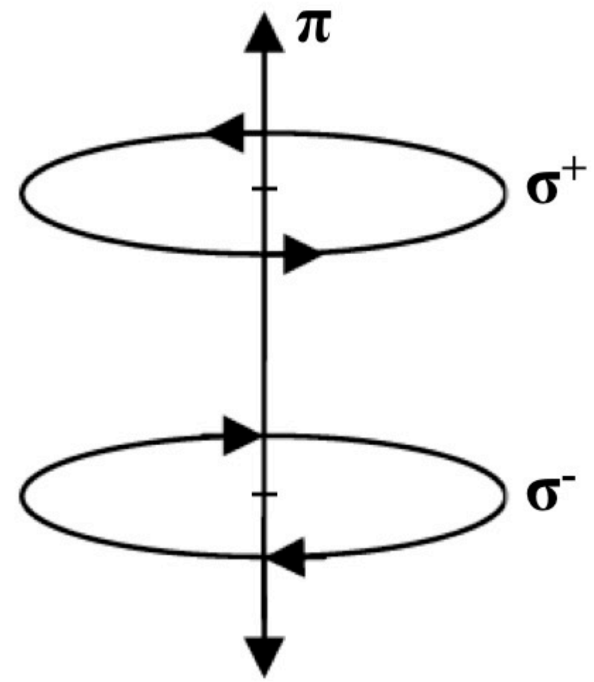
- **Consider radiation from three oscillating charges: σ+, σ-, π**
  - **π** is a *linear* oscillator
  - σ+ and σ- are *circular* oscillators in opposite senses



# Appendix A - Classical Model for the Zeeman Effect

- **Consider radiation from three oscillating charges: σ+, σ-, π**

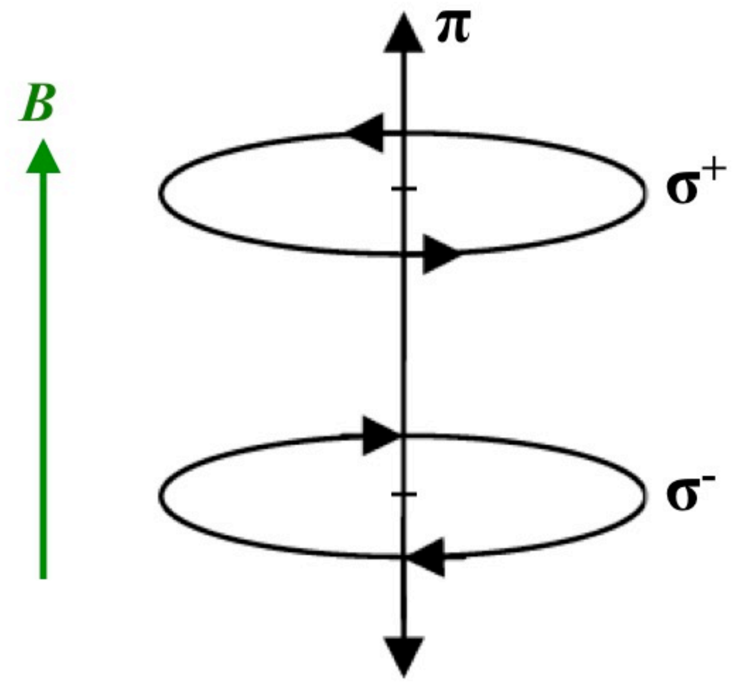
- **If *B* = 0**
  - all particles oscillate at $\nu_0$



# Appendix A - Classical Model for the Zeeman Effect

- **Consider radiation from three oscillating charges: σ+, σ-, π**

- **If $B \neq 0$**
  - $\pi$ still has $\nu_0$
  - σ+, σ- have $\nu_0 \pm \Delta\nu$, respectively, owing to the Lorentz force

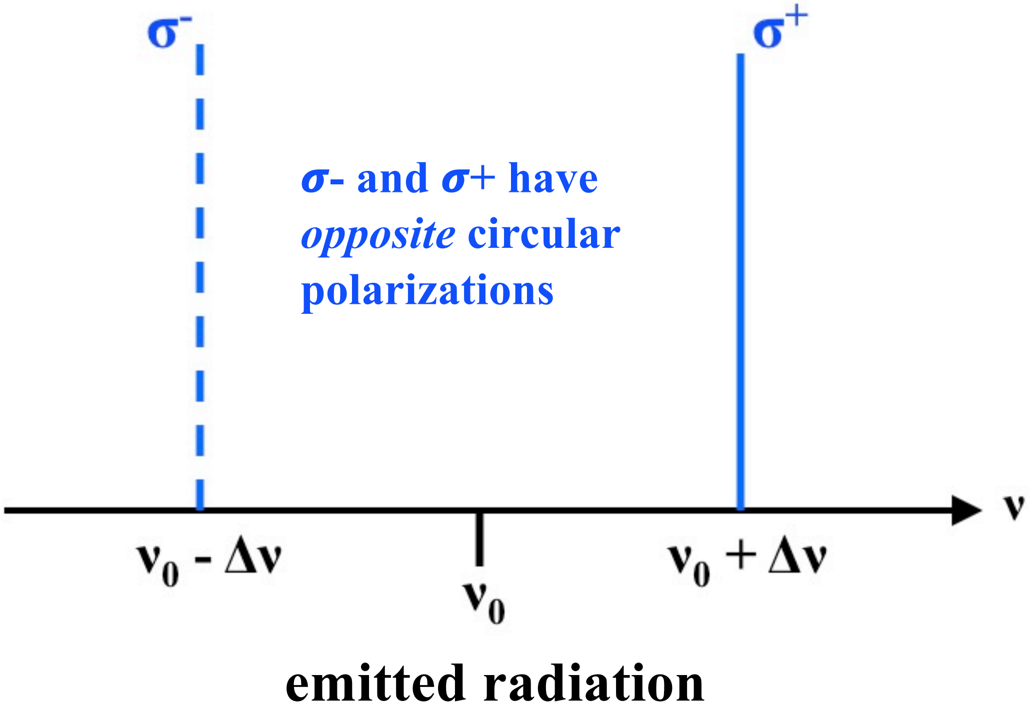


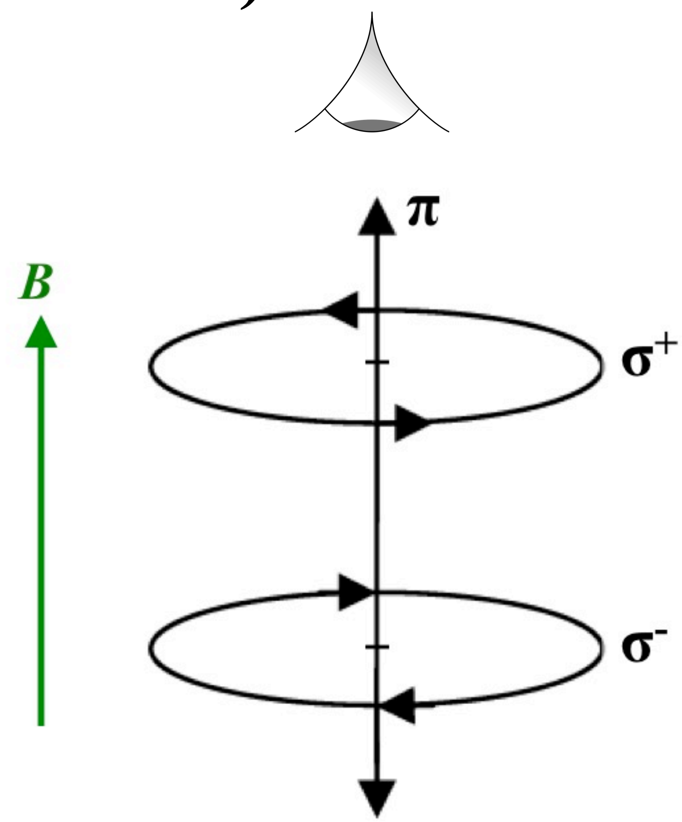

**…where $\Delta\nu = qB/4\pi mc$ = 1.4 Hz/μG for an electron**

# Appendix A - Classical Model for the Zeeman Effect

- **If radiation viewed *parallel* to *B*:**

- **Circular polarization (blue) *only* (π not seen)**

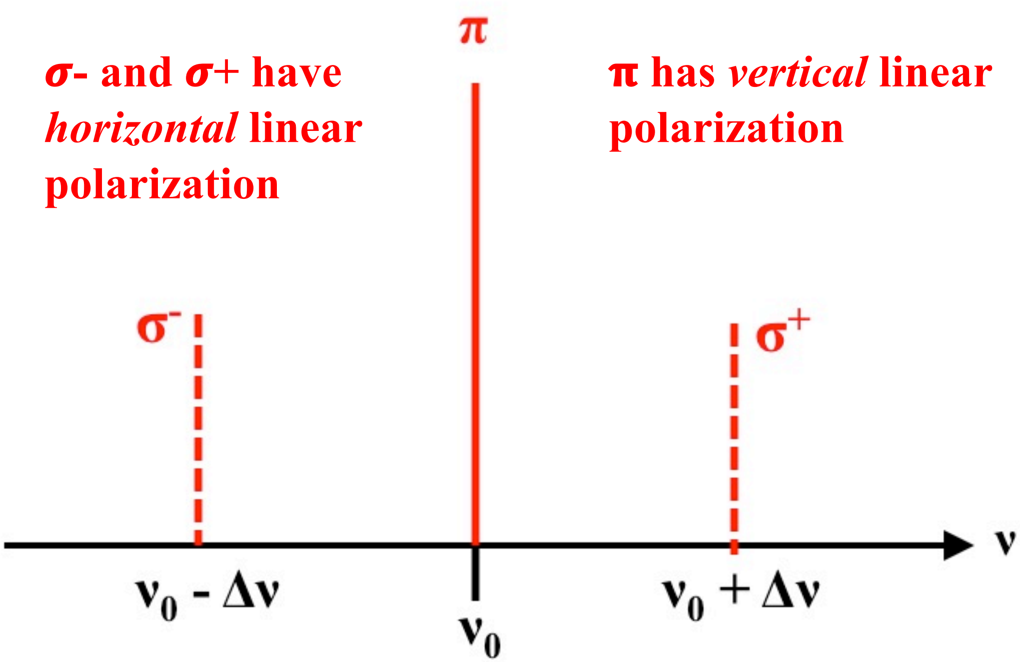


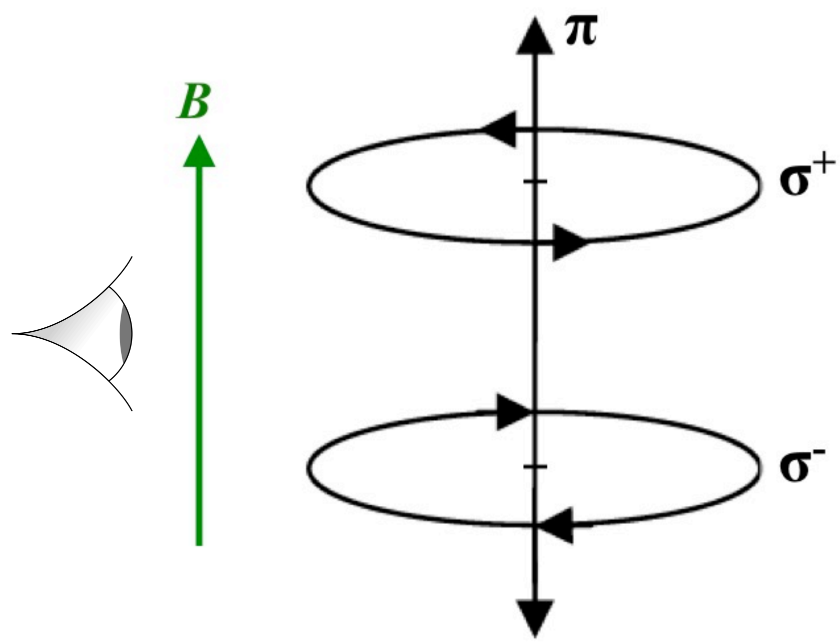
# Appendix A - Classical Model for the Zeeman Effect

- If radiation viewed *perpendicular* to *B*:

- Linear polarization (red) *only*



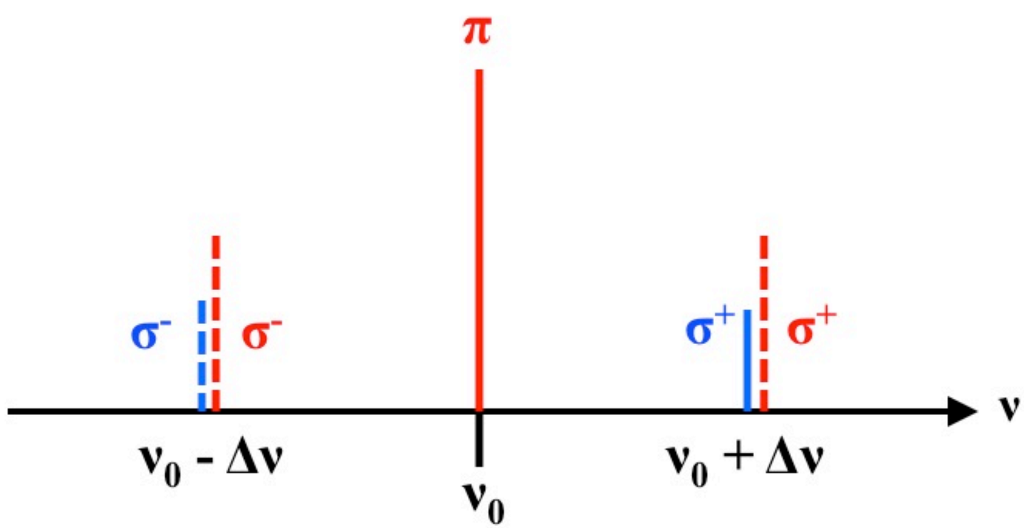

emitted radiation



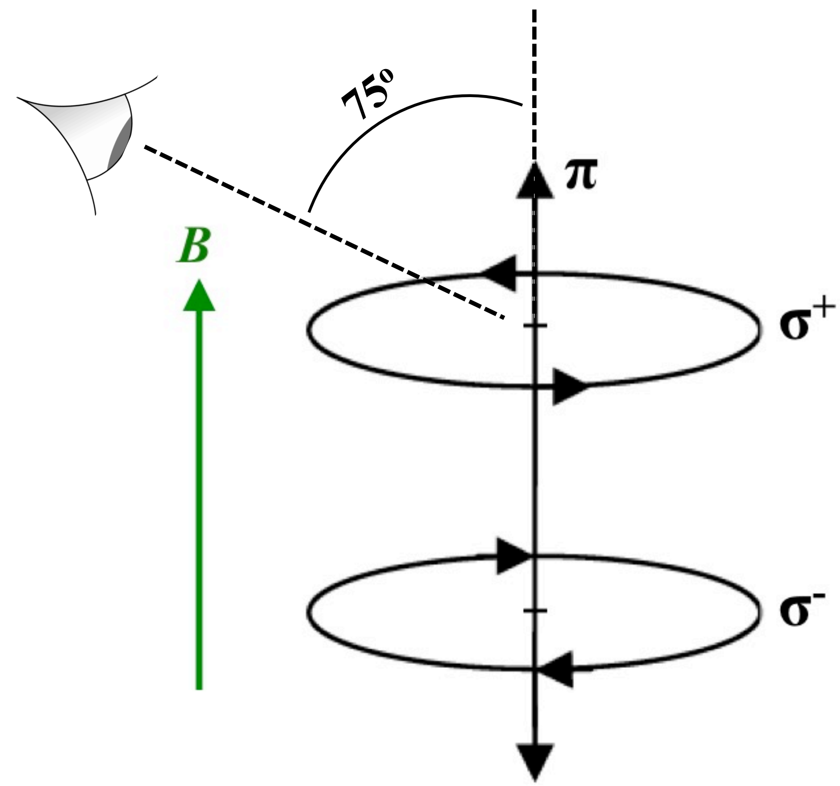
# Appendix A - Classical Model for the Zeeman Effect

- If radiation viewed *at an angle* $\boldsymbol{\theta}$ to *B* (*e.g.* 75$^o$):

- Circular (blue) & linear (red) polarization (*i.e. elliptical* polarization)

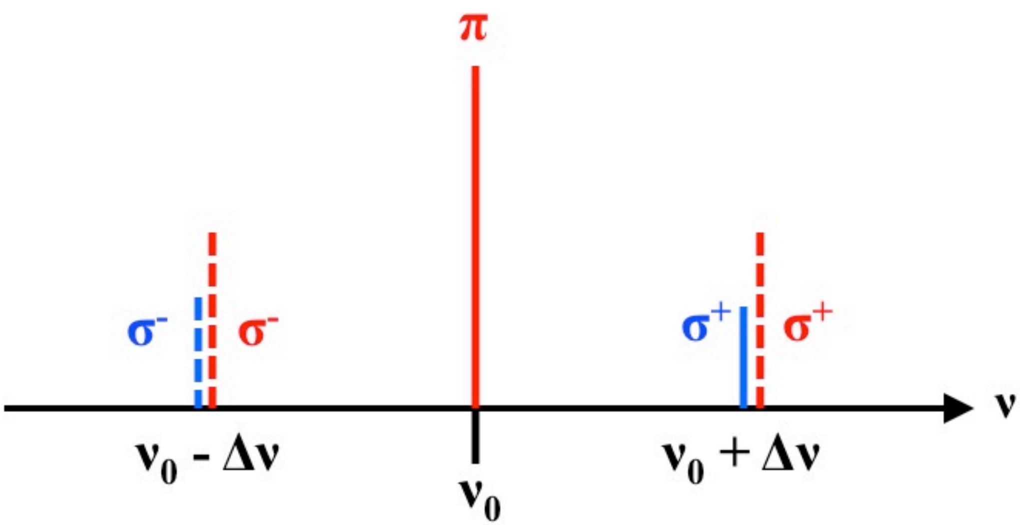



emitted radiation

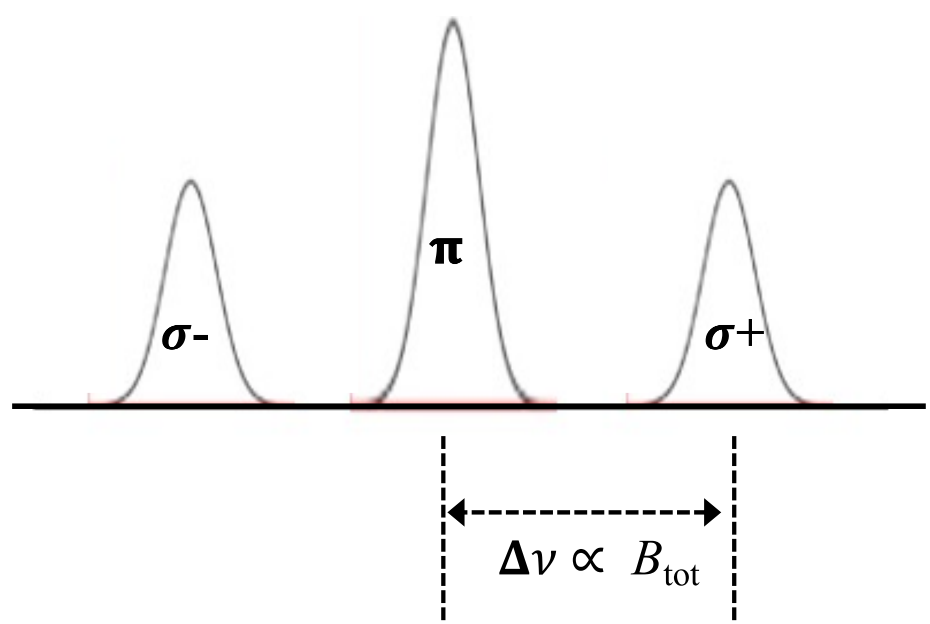


# Appendix A - Classical Model for the Zeeman Effect

- **If *spectral line width* << Δν**
  - Frequency offset Δν of σ+ and σ- is a measure *of total field strength B* (*i.e.* $B_{tot}$).
  - This offset can be observed in *any* polarization sense.



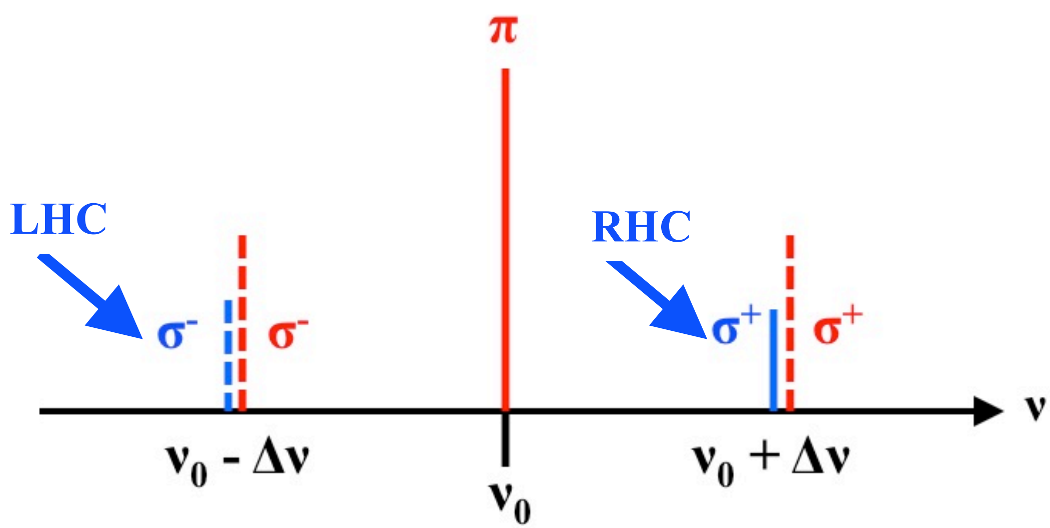

**emitted radiation**



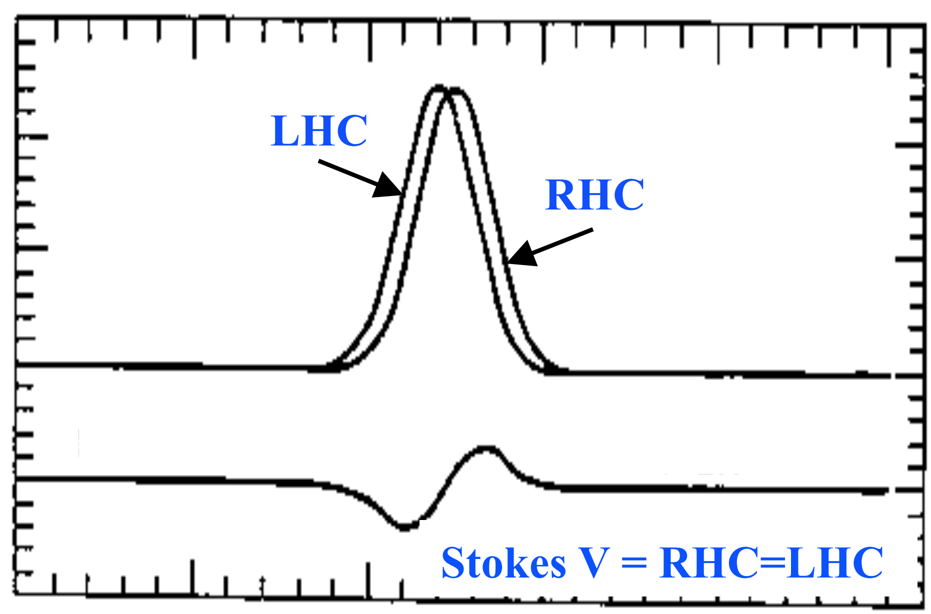
# Appendix A - Classical Model for the Zeeman Effect

- **If *spectral line width* >> Δν (the usual case)**

  – There is a frequency offset between orthogonal *circular polarizations* of σ- and σ+, leading to a non-zero Stokes V profile, proportional to the *derivative* of the line profile.



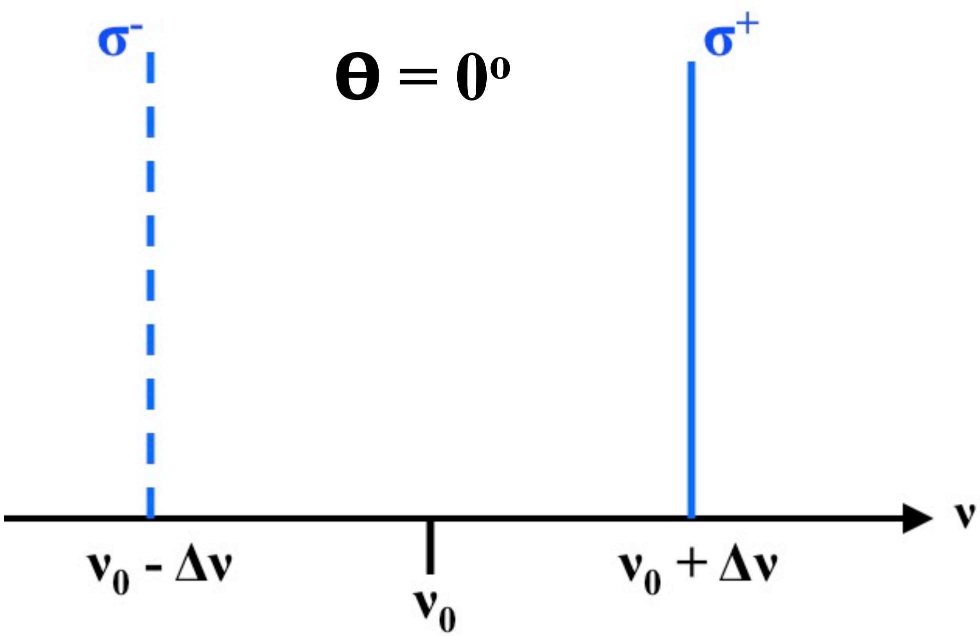
emitted radiation

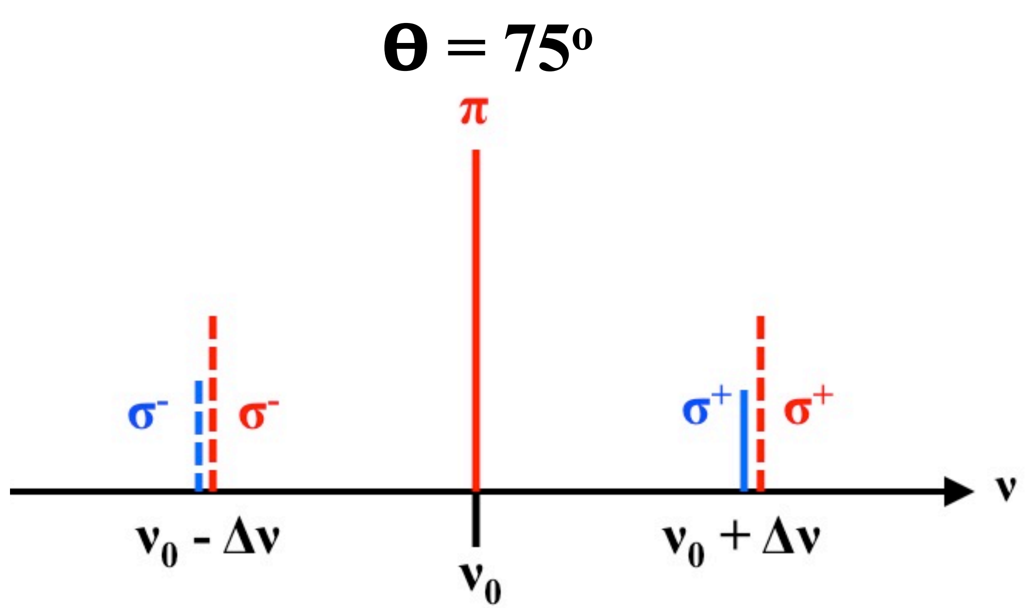


# Appendix A - Classical Model for the Zeeman Effect

- If *spectral line width* >> $\Delta\nu$ (the usual case)

  – However, the *strength* of the circular polarization of σ+ and σ- *declines* as cos(θ), where θ is the angle between the line-of-sight and *B*.



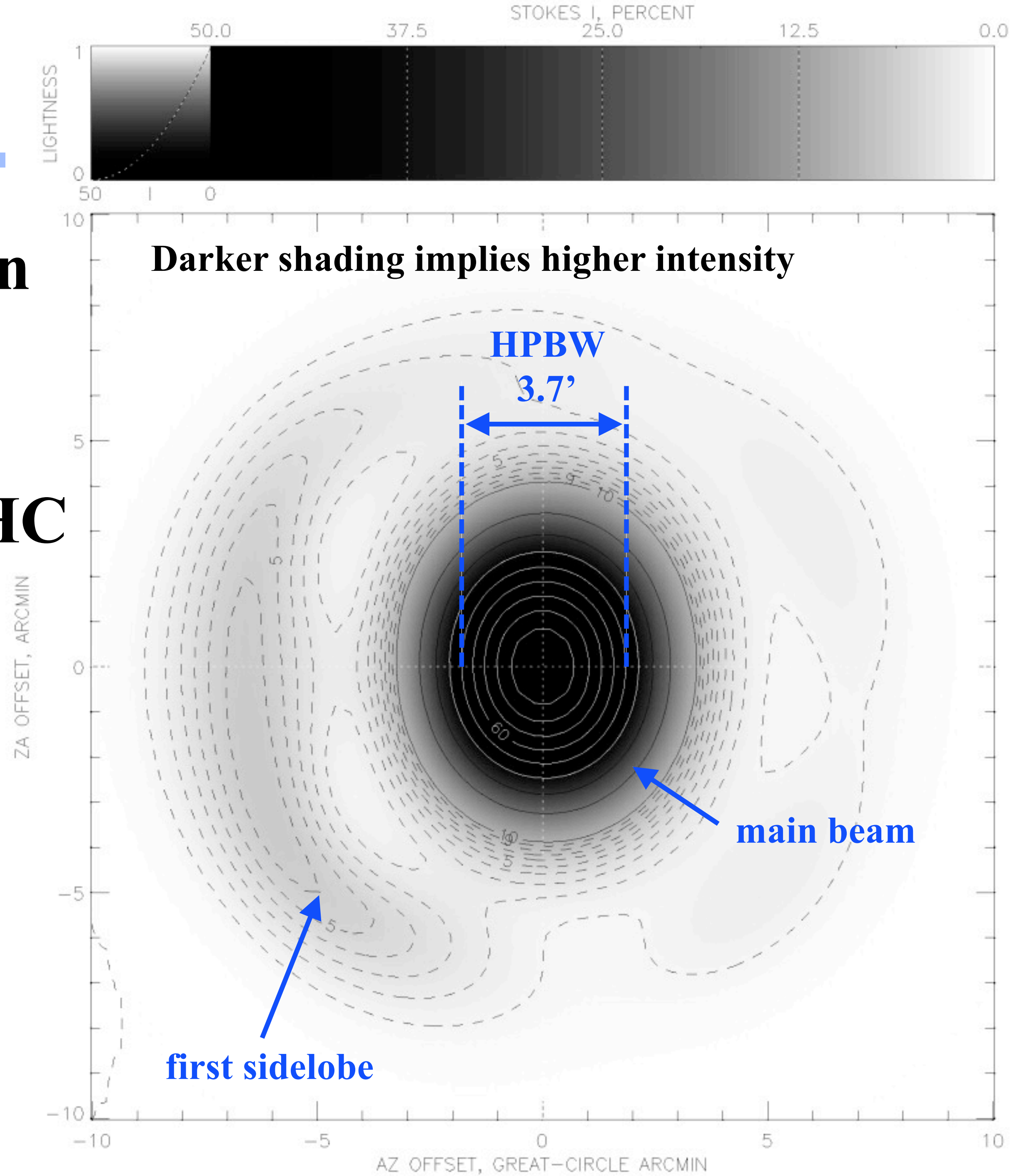
# Appendix A - Classical Model for the Zeeman Effect

- **If *spectral line width* >> $\Delta\nu$ (the usual case)**
  - So the measured Stokes V profile is proportional *both* to *B* and cos(θ).
  - In effect, the measured Stokes V is proportional to the *line-of sight component of the magnetic field* $B_{los}$ = *B* cos(θ).

# Appendix B - Beam Squint

- **Arecibo beam pattern** **(at 1175 MHz)**

- **Stokes I = RHC + LHC**

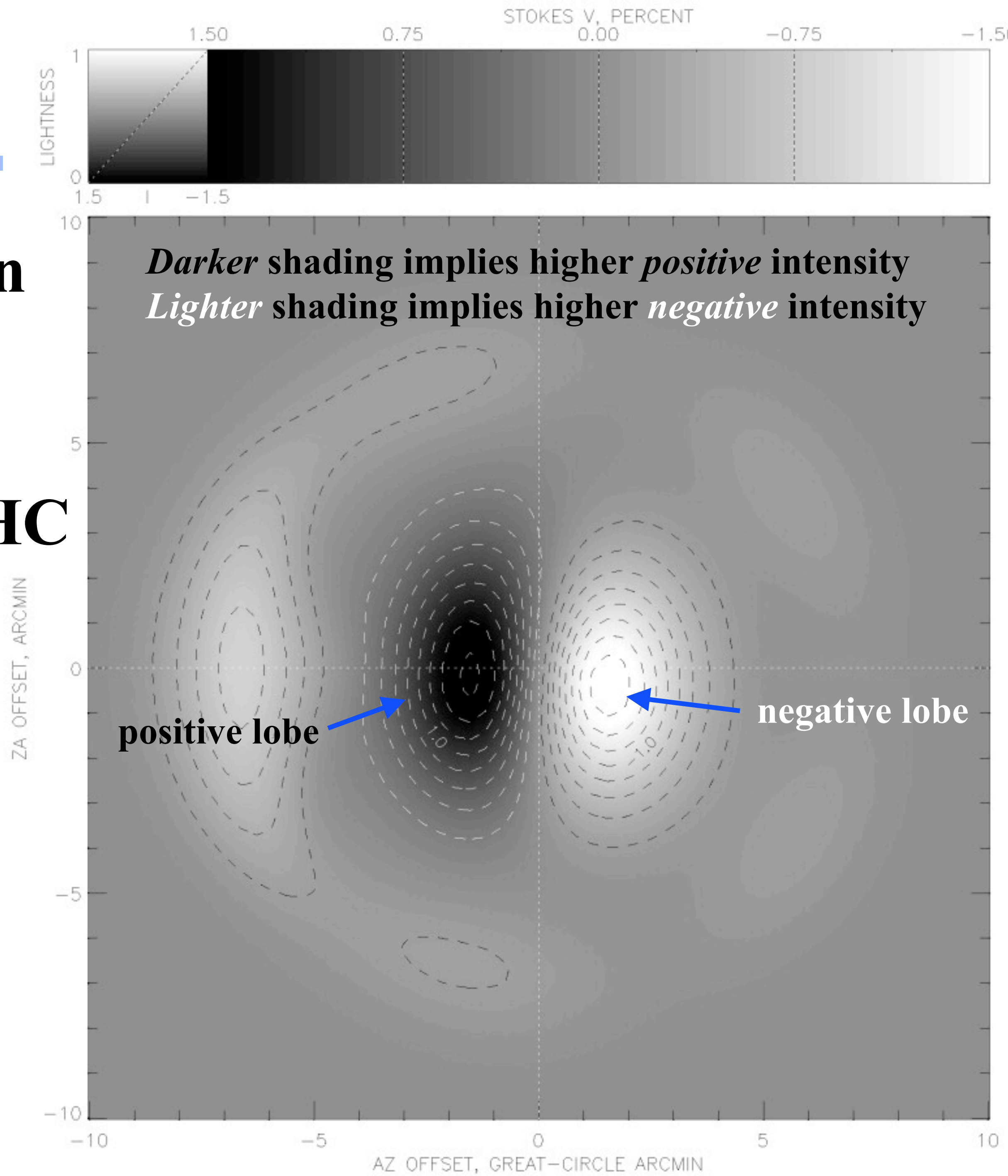



Heiles+ PASP, 2001

# Appendix B - Beam Squint

- **Arecibo beam pattern**
  **(at 1175 MHz)**

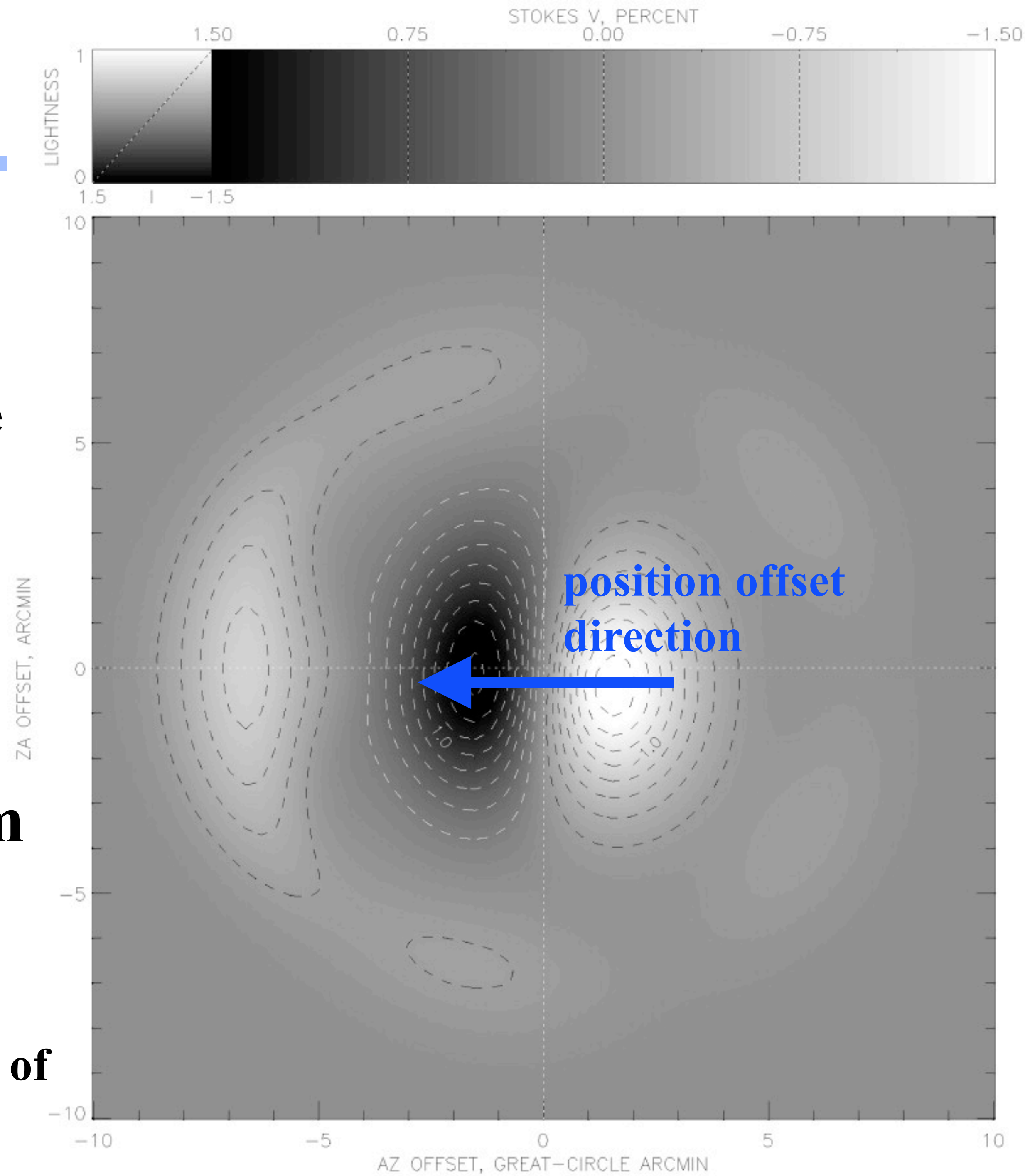
- **Stokes V = RHC - LHC**




Heiles+ PASP, 2001

# Appendix B - Beam Squint

- Stokes V pattern is equivalent to a small *position offset** of the telescope beams in RHC and LHC polarizations.
- Effect is called “beam squint”.




*Position offset typically ≈ 1% of HPBW

# Appendix B - Beam Squint

- **If the spectral line source has a *velocity gradient on the sky*, then the RHC & LHC beams (offset from each other) sample the line at slightly different velocities (hence, frequencies).**

- **This instrumental effect exactly mimics the Zeeman effect.**