Faraday Rotation and stellar Bubbles

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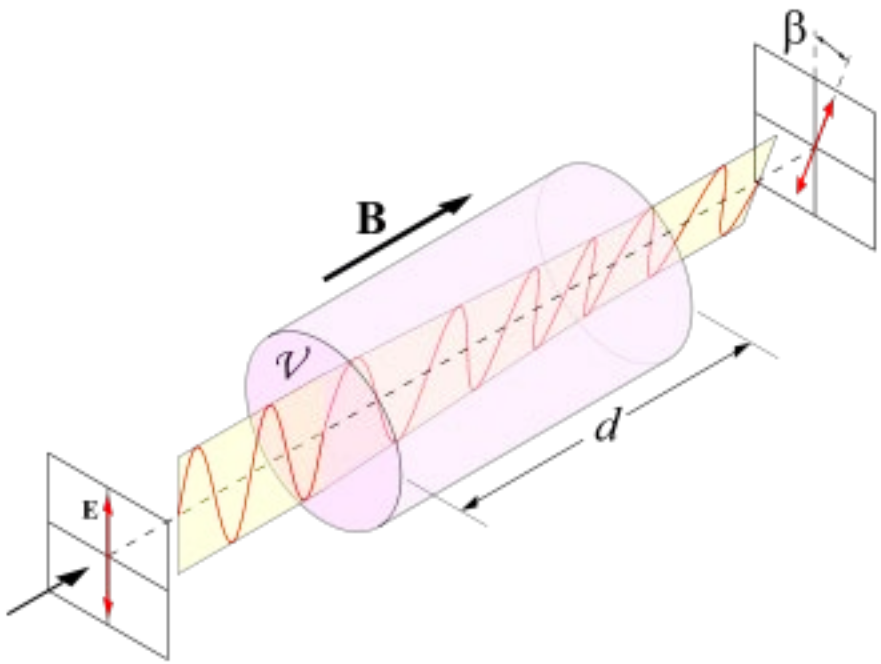
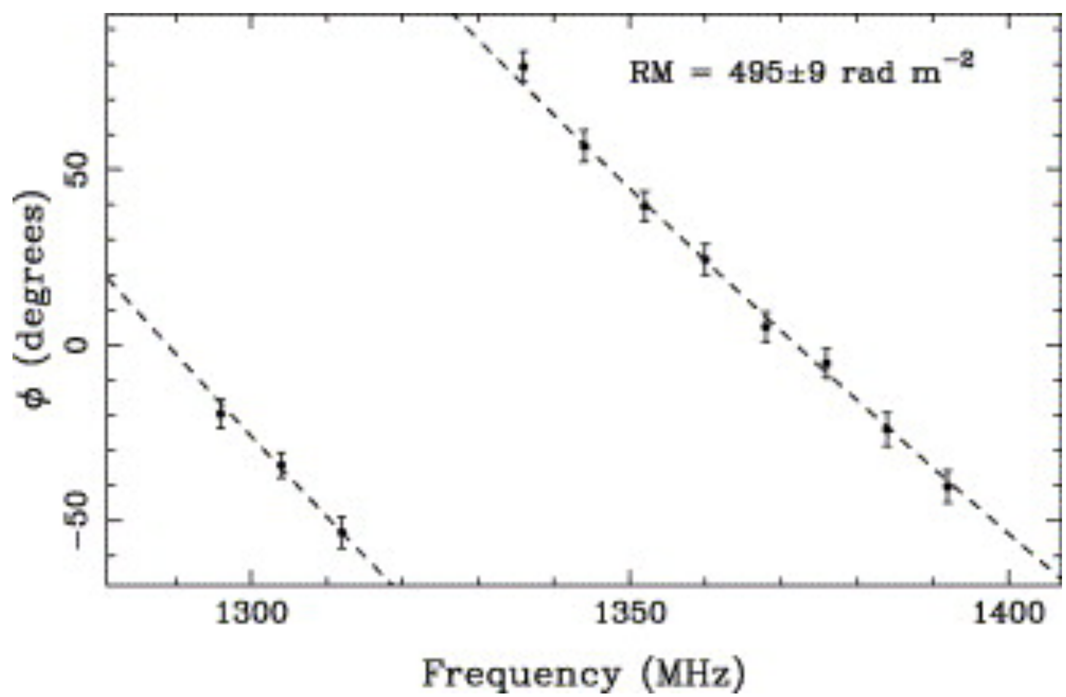


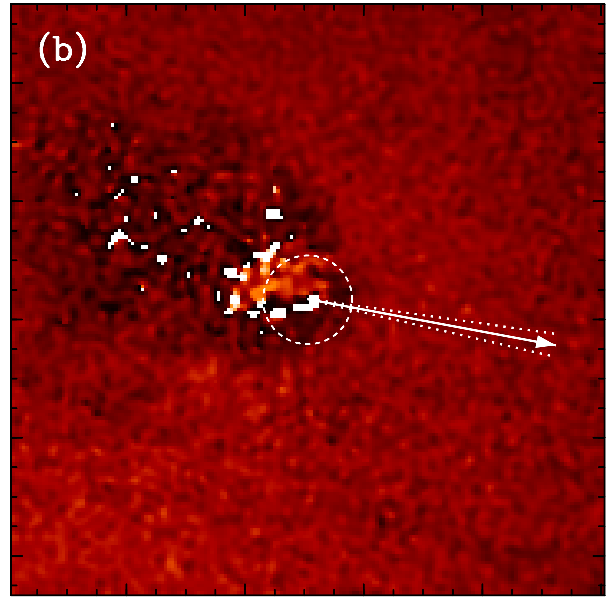
Faraday Rotation

Faraday rotation describes how the position angle (PA) of a background linear polarization signal can be **ROTATED** when passing through a magnetized and ionized medium.

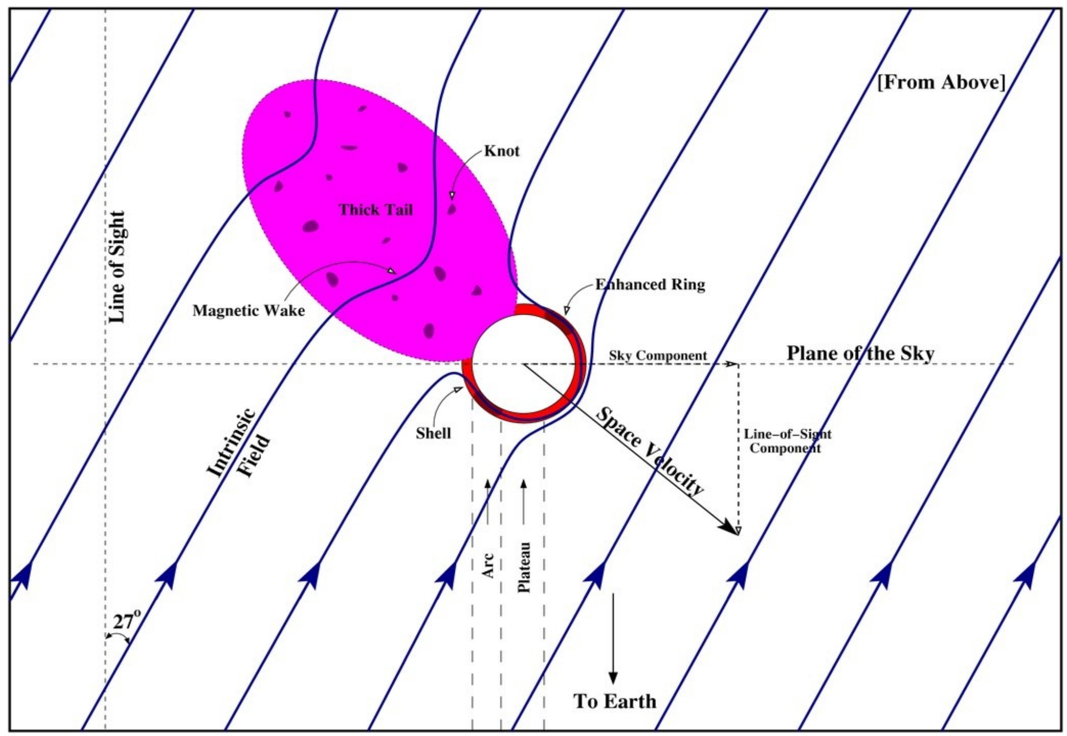
$$\phi = RM \times \lambda^2$$
$$\sim RM \times \nu^2$$



Faraday in a Planetary Nebula



Map of the polarization PA

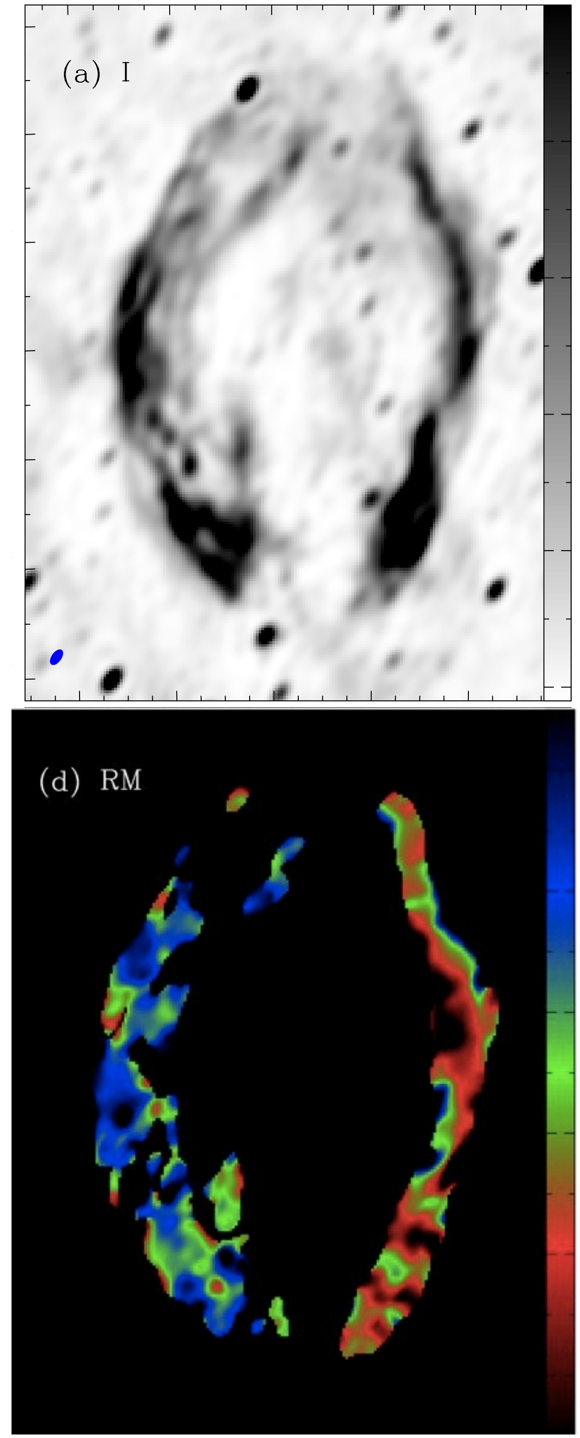


(from Faraday Rotation in the Tail of the Planetary Nebula DeHt 5, Ransom et al., 2010, ApJ, 724, 946)

Faraday in a Supernova Remnant

Upper shows a grayscale image of the SN remnant. Lower shows the rotation measure distribution (RM) associated with Faraday rotation across the remnant. Note especially the antisymmetric PA rotation pattern (positive vs negative.).

(from Faraday Rotation of the Supernova Remnant G296.5+10.0: Evidence for a Magnetized Progenitor Wind, Harvey-Smith et al., 2010, ApJ, 712, 1157)



A New Formulation for Bubbles

$$OLD: \quad \Delta\psi = RM \times \lambda^2$$

$$\text{where } RM = 0.81 \text{rad/m}^2 \int n_e B_{\parallel} dz$$

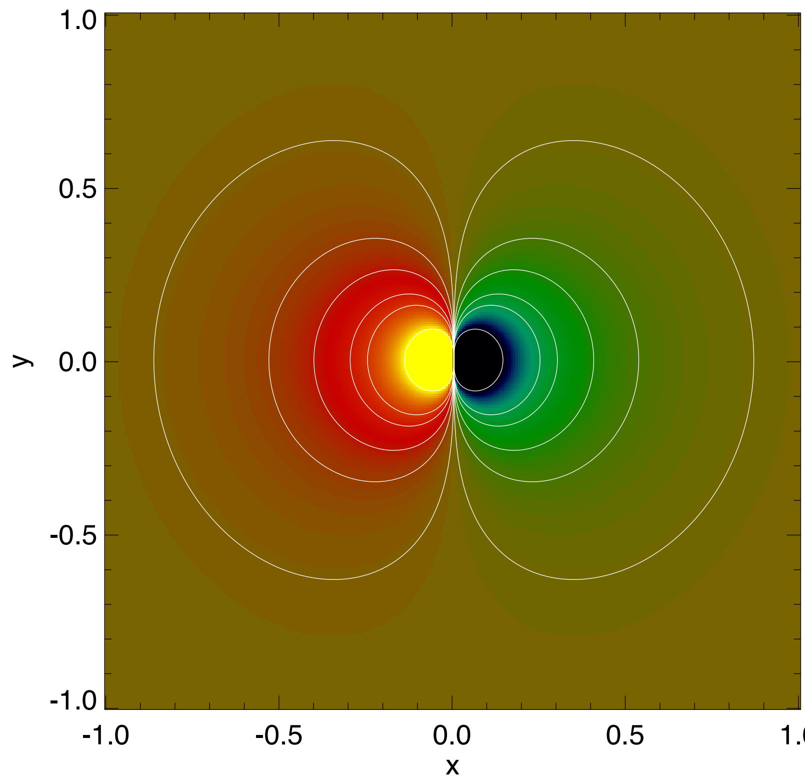
$$NEW: \quad \Delta\psi_{bub} = \frac{\pi}{z_{bub}(\lambda)} \int \left(\frac{n_e}{n_0}\right)\left(\frac{B_{\parallel}}{B_0}\right) dz$$

Azimuthal Stellar Magnetic Field

- The lowest order stellar field that might exist to large radius is azimuthal, B_φ.
- Adopt:

  $B_\varphi = (R/r)\sin(\theta)$
- Then the PA maps (at fixed λ) are of the form:

$$\psi_{meas} = \psi_{ISM} - \delta\psi_{ISM} + \psi_{Bub}$$



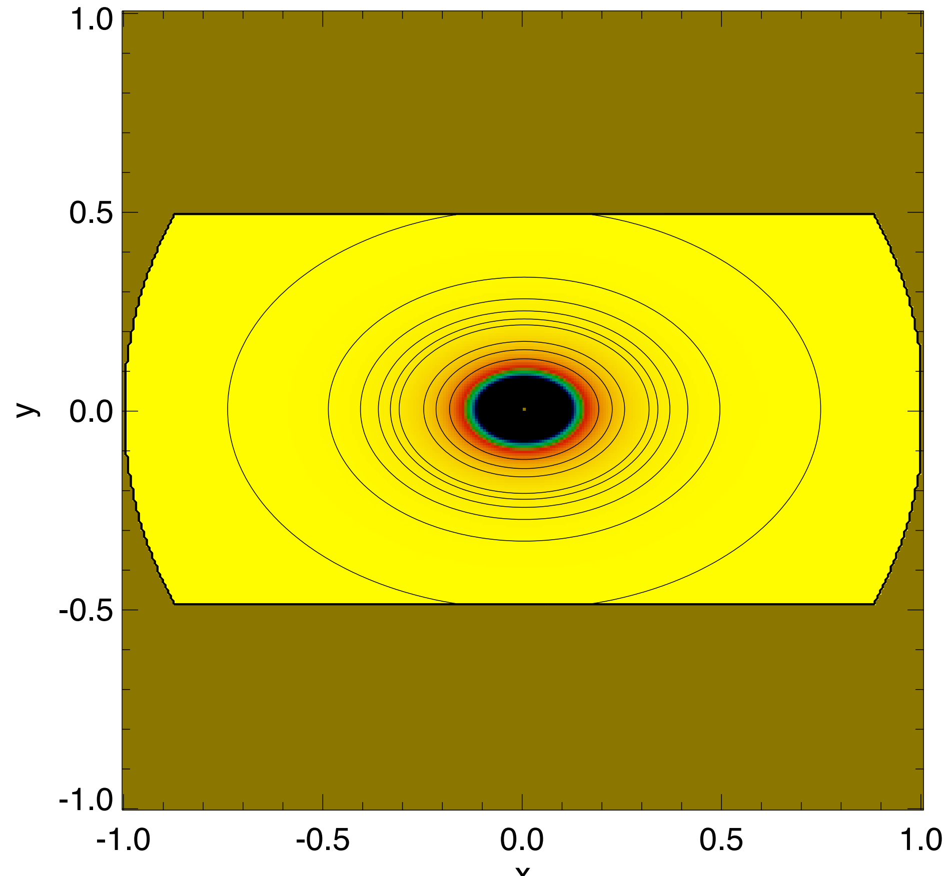
Position angle (PA) map for an azimuthal field and $1/r^2$ wind density; "1" is the bubble radius; opposing colors signify a change in the sign of the PA rotation

Split Monopole Stellar Magnetic Field

- The next lowest order stellar field is the split monopole, B_r.
- Adopt:

  $B_r = \pm (R/r)^2$
- For a bubble seen at arbitrary inclination, sightlines failing to intercept the magnetic equator produce two hemispheres of:

  $\psi = \psi_{ISM} - \delta\psi_{ISM}$

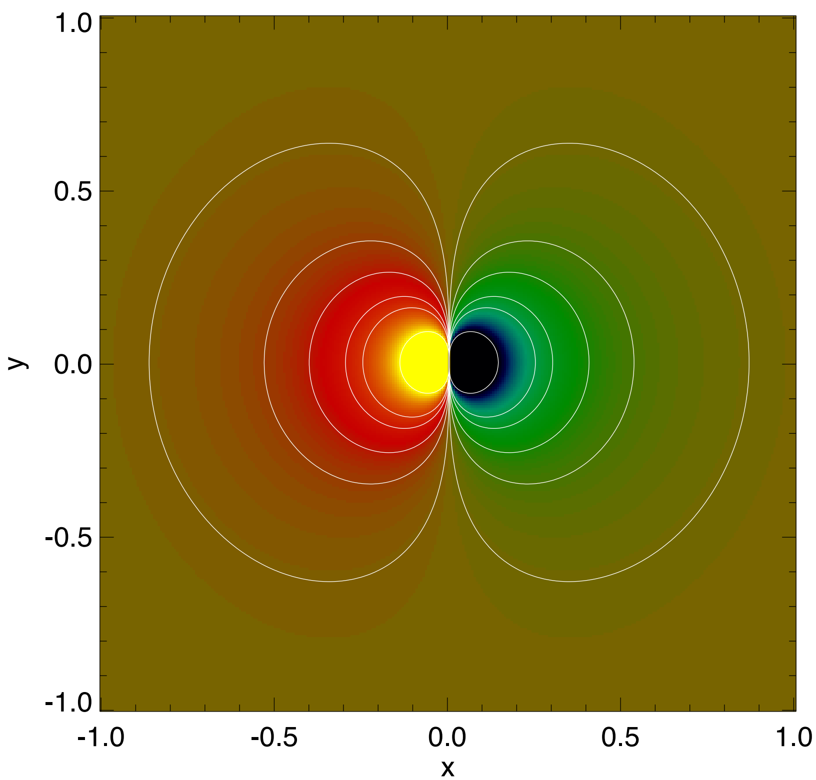


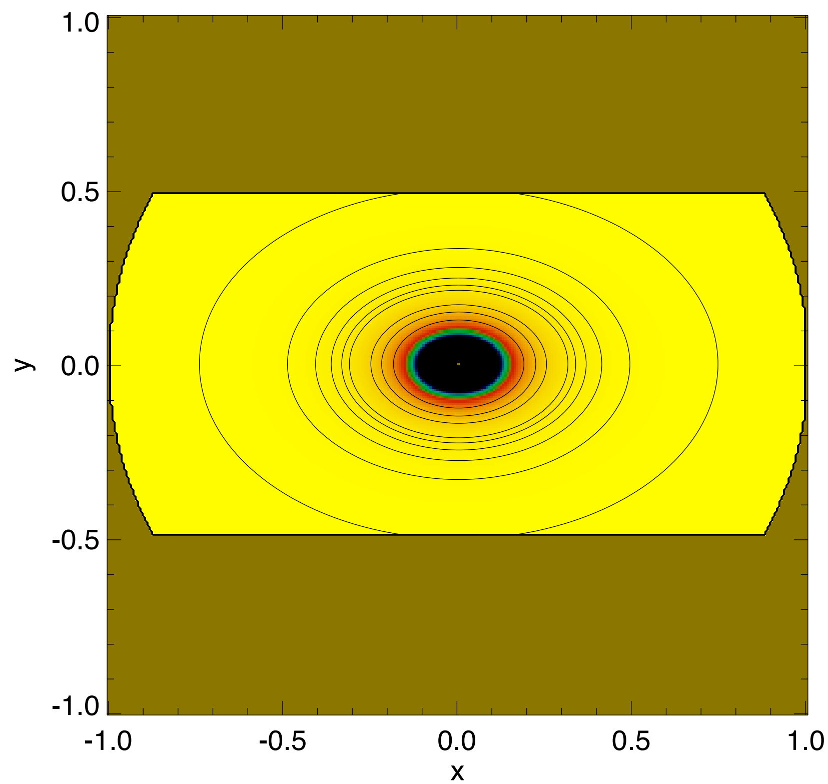
Position angle (PA) map for a split monopole field and $1/r^2$ wind density.

Recap:

(Note: both cases are analytic)

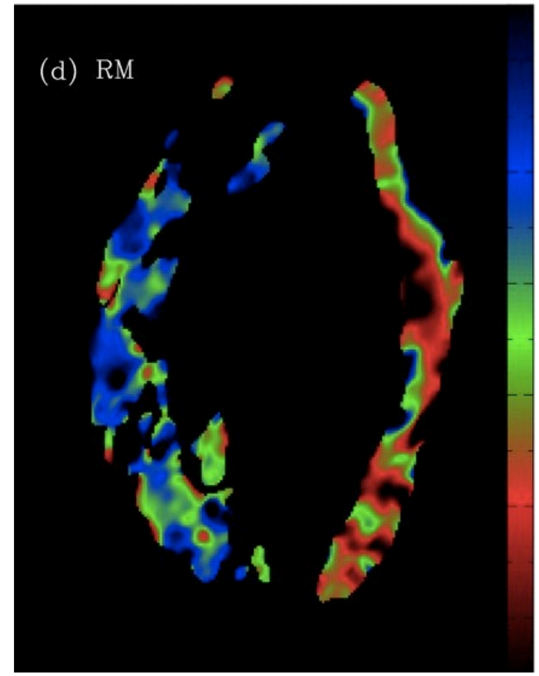
- **Azimuthal**: Antisymmetric (sign flip) in PA.
  - Morphology INDEPENDENT of inclination.
- **Split Monopole**: Single signed in PA.
  - Truncated hemispheres that are inclination dependent.
  - Pole-on view is centro-symmetric.
  - Edge-on results in NO NET contribution by the stellar field.

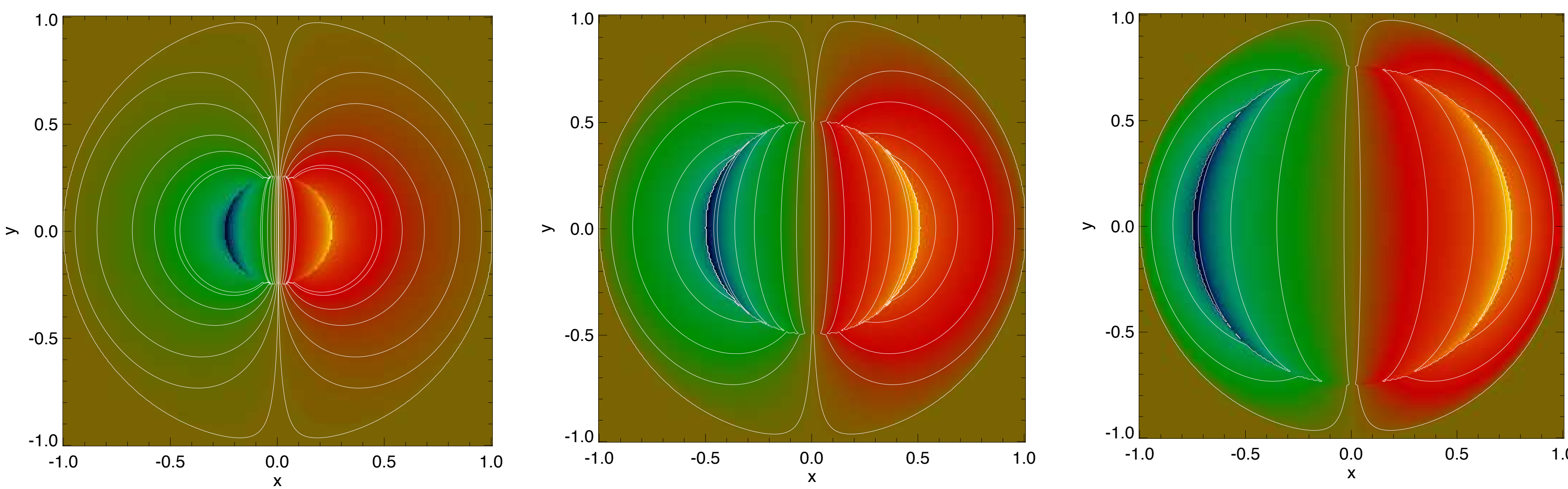




Swept Up Azimuthal Field

- Insert cavities of 25%, 50%, and 75% of the bubble radius.
- Outline of the inner radius appears as a consequence of a rapidly varying path length through the magnetized shell for these sightlines.
- Morphology independent of inclination, but amplitude of PA scales like *sin (i)*



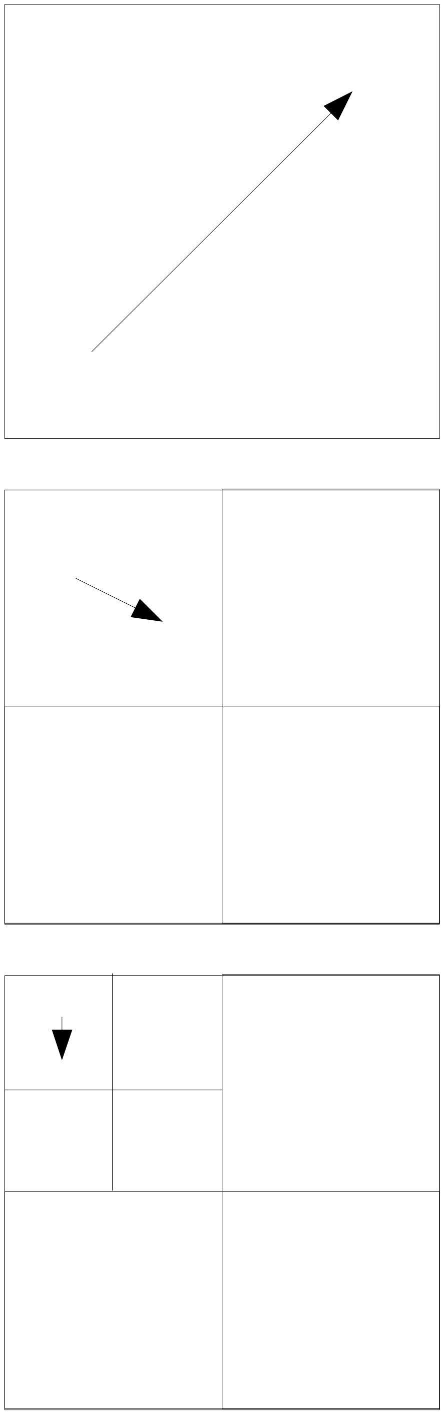


Faraday in an Ionization Front

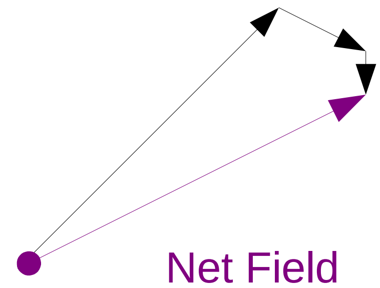
- A different scenario is to consider an ionization front, such as from a supernova or an HII region (e.g., Savage, Spangler, & Fischer 2012, astroph/1206.5173 on the Rosette Neb).
- For a time-dependent front (like a SN), the idea is to imagine an event that ionizes a magnetized yet (mostly) neutral region of the ISM leading to <u>evolving</u> Faraday rotation maps.
- Presents an opportunity to extract information about the interstellar field as the front sweeps by it.

How to Set the Magnetic Field

The magnetic field of the ISM appears to consist of two roughly equal-strength components: a uniform one and a random one, each at around several μG.



Construction of the random field component based on subgroups. Each one contributes a field of random direction but diminishing strength.

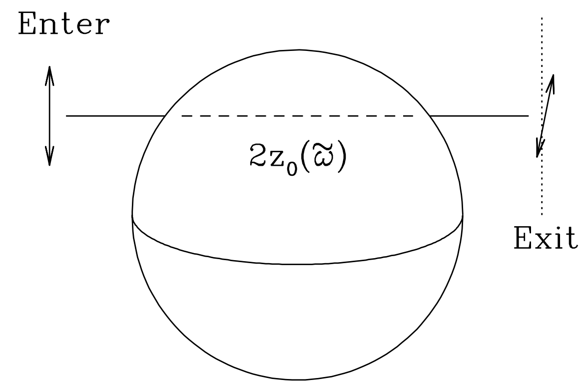


Deviations from the Trivial

For a spherical bubble with a uniform magnetic field and constant density, the PA rotation is trivial.

$$\Delta\psi \sim \mu_0 B_0 \times 2z_0(\varpi)$$

$$\text{where } z_0 = \sqrt{R^2 - \varpi^2}$$

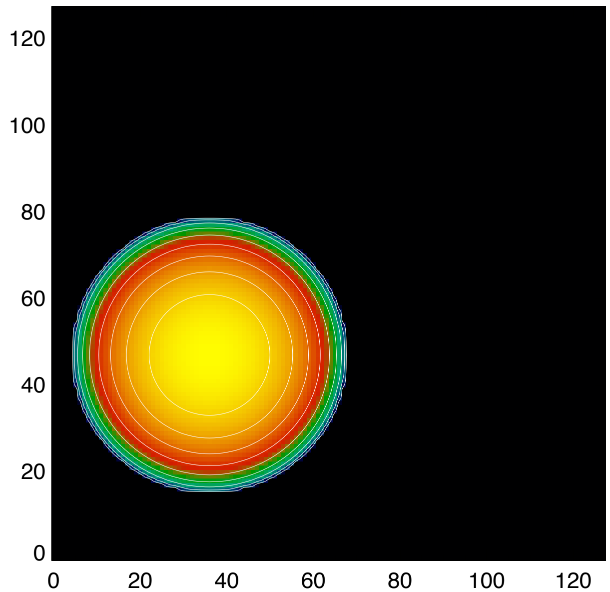


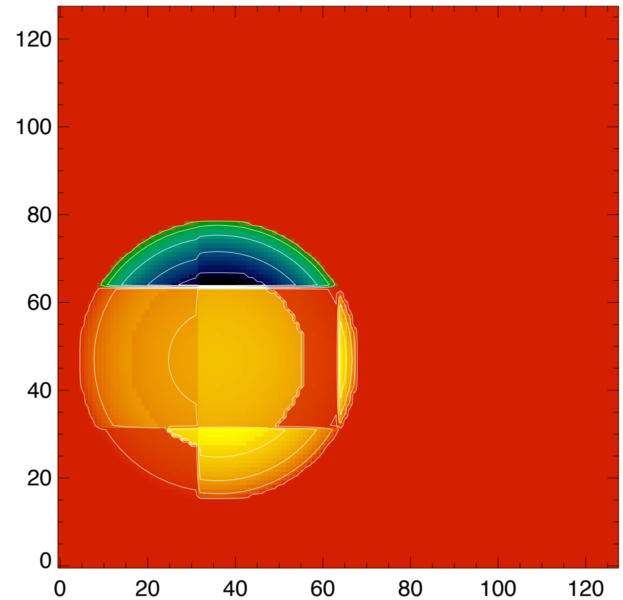
The presence of a random field creates deviations from this simple pattern.

Considering that at different scales for the random component, (a) the field gets weaker and (b) the field is always randomly oriented, then only the strongest fields at the largest scales survive (primarily) to produce deviations from the uniform field case.

Results for Ionized Bubbles

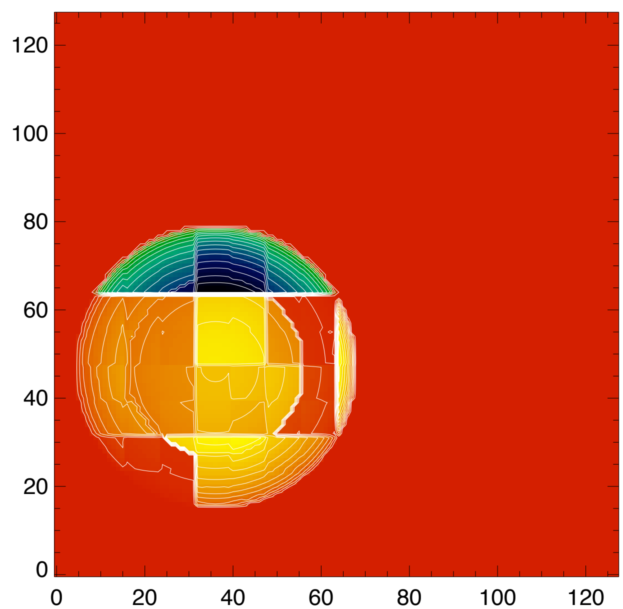
1 group
(1 cell)

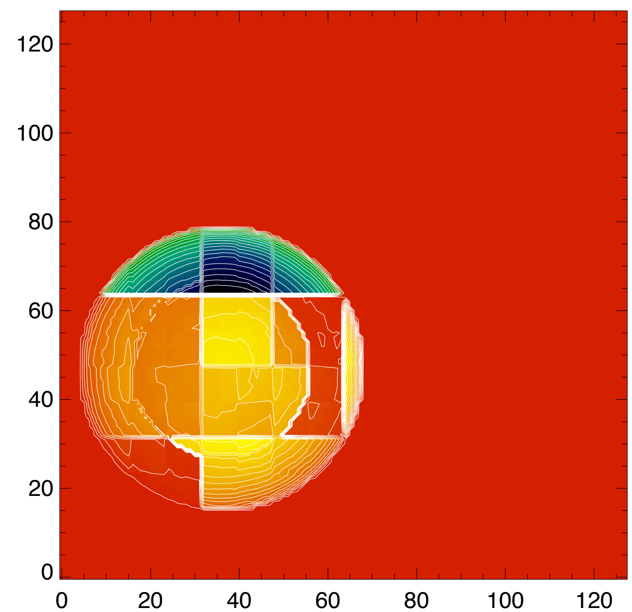




2 groups
(4^3 cells)

4 groups
(16^3 cells)





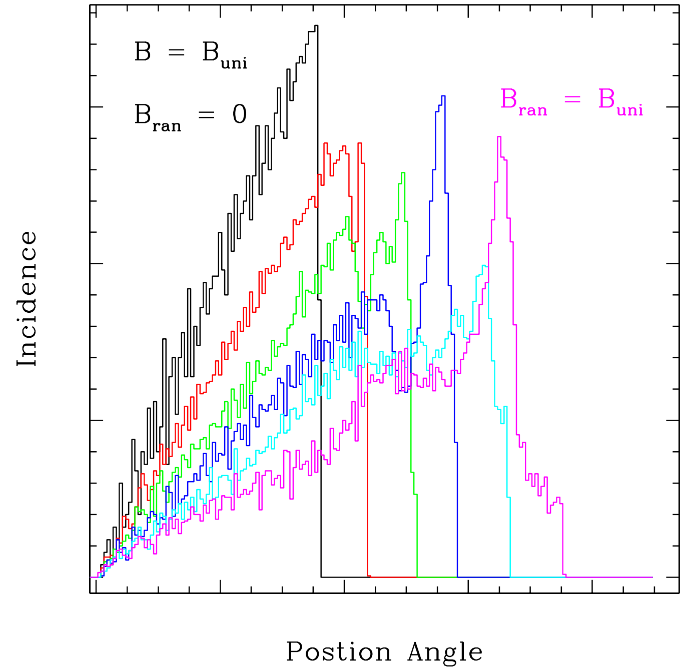
5 groups
(32^3 cells)

Building a Baseline for Analysis

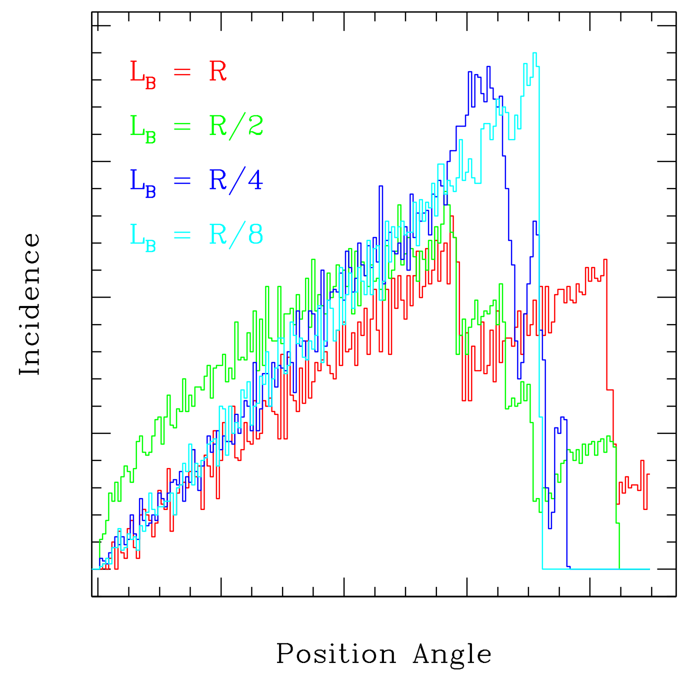
- What does an observer do with a map of PA values across the face of a projected bubble? Might make a histogram for the incidence $dN/\Delta\psi$ vs $\Delta\psi$.
- Take the case of the uniform field as a baseline of reference :

$$\Delta\psi \sim \sqrt{R^2 - \varpi^2}$$

$$\frac{dN}{d\Delta\psi} \sim \varpi \frac{d\varpi}{\Delta\psi} \sim \Delta\psi$$



Top Turbulent Scale Length vs Bubble Radius



Pushing the Envelope

(*pun intended!*)

- Faraday rotation studies are conducted in static situations. In other words spatial PA maps are produced, but not time-varying ones.
- There is the possibility of observing variable Faraday rotation for an evolving ionization front from a SN. The ISM field is static, but the ionized bubble grows. For a given pixel, one has $z_0 = z_0(t)$ for the pathlength, and so different field scale lengths are sampled in t.
- The space-based radio interferometer Radio Astron will have 37 μas resolution at 18 cm. An ionized bubble of just 1 LY radius corresponds to ~30 resolution elements at a distance of 100 Mpc (e.g., the Coma cluster).

Summary

- **Stellar Bubbles:**
  - An azimuthal stellar magnetic field produces an antisymmetric PA map (in the sense of PA rotation) irrespective of viewing inclination.
  - The PA map for a split monopole is distinctly different, consisting of one sign for the PA and radically different morphology.
  - Models for a “swept up” field were presented (i.e., field free cavities) that qualitatively reproduce observations of a SN remnant.
- **Ionization Fronts:**
  - For a reasonable “turbulent” random field component, it is the largest spatial scale that tends to dominate modifications to the Faraday rotation signal for the uniform field.
  - Potentially new novel way to discern the ISM field using an evolving ionization front.

Scale for an Azimuthal Field

$$PA = 7.8^o \frac{\left(\frac{B_*}{100G}\right)\left(\frac{R_*}{10R_o}\right)\left(\frac{\dot{M}/\mu}{10^{-6}M_o/yr}\right)}{\left(\frac{\mathrm{v}}{1000\ \mathrm{km/s}}\right)\left(\frac{R_{bub}}{1\ \mathrm{pc}}\right)^2} \times \left(\frac{\lambda}{30\ \mathrm{cm}}\right)^2$$

Converting PA Maps to RM Maps

$$\text{PA Map: } \Delta\psi_{bub} = \frac{\pi}{z_0(\lambda)} \int \left(\frac{n_e}{n_0}\right)\left(\frac{B_{\parallel}}{B_0}\right) dz$$

$$RM \text{ Map: } \mathrm{RM} = \left[\frac{\pi / \lambda_0^2}{z_0(\lambda_0)} \int \left(\frac{n_e}{n_0}\right)\left(\frac{B_{\parallel}}{B_0}\right) dz\right]$$

because $\Delta\psi_{bub} = RM \times \lambda^2$