X-ray Polarization in SNRs and PWNe

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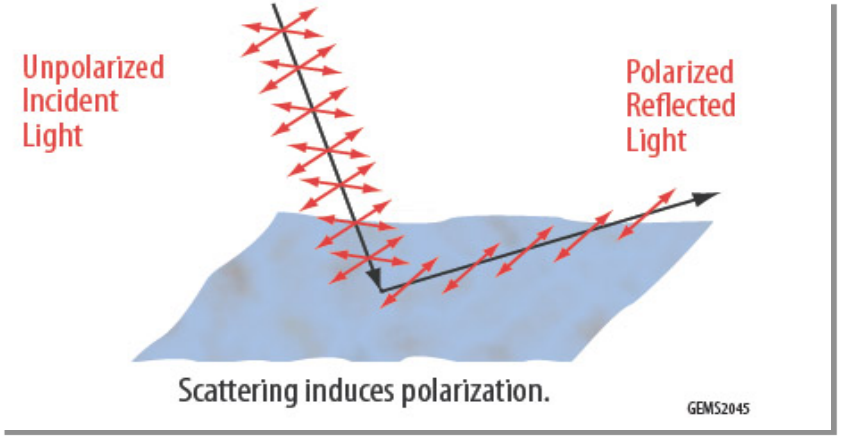
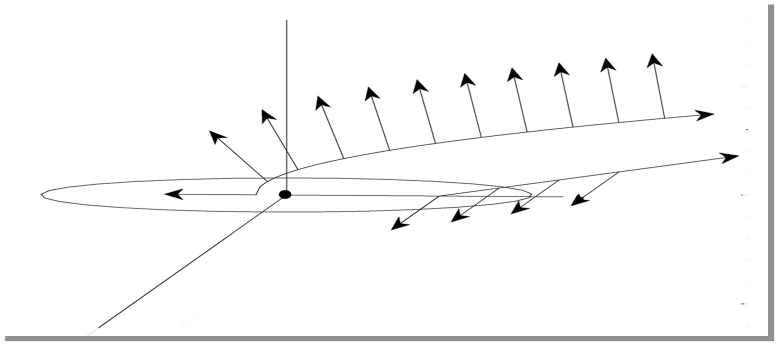
Outline

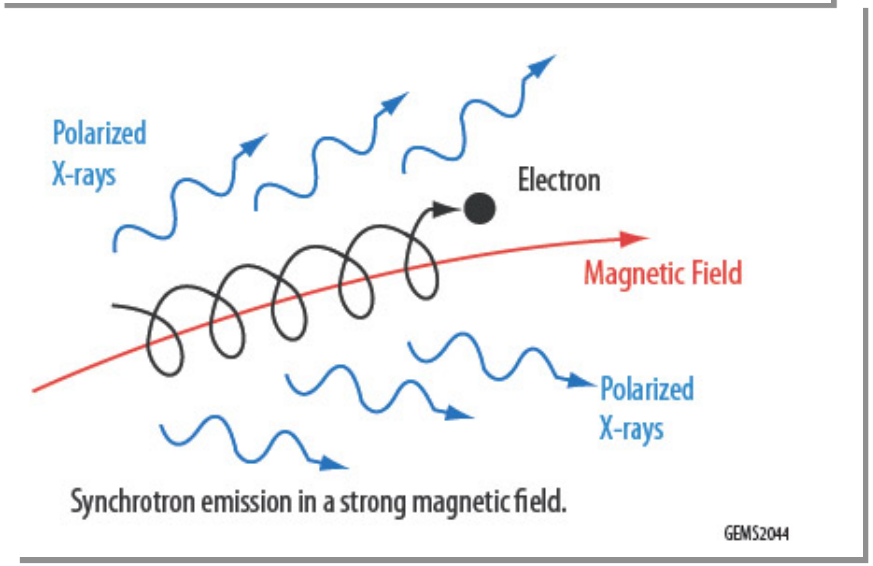
- Polarization processes
- Brief history of X-ray polarization studies
- X-ray polarization in PWNe
- X-ray polarization in SNRs
- Opportunities for X-ray polarization measurements
- What does this have to do with Astro-H?

Polarimetry probes key physics of photon emission and propagation

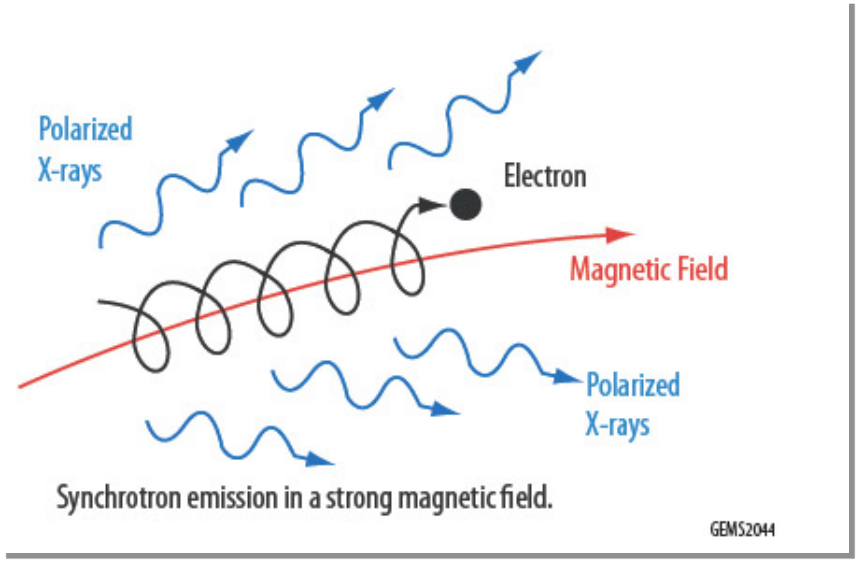
- Polarization measurements allow us to study:
  - ✓ Scattering
  - ✓ Magnetic fields
  - ✓ Strong gravity







Polarized X-rays from SNRs and PWNe arise from synchrotron radiation



- Synchrotron radiation in uniform magnetic field from power law distribution of electrons:
  - Degree of polarization $\Pi = (p + 1) / (p + 7/3)$
  - Spectral index of photons $\alpha = s = (p-1)/2$
- Crab: $s = 1.2 \Rightarrow p = 3.2 \Rightarrow \Pi$ **~0.6**; SN 1006: $s \sim 3 \Rightarrow p = 7 \Rightarrow \Pi$ **~ 0.8**
- In young SNRs, dominant magnetic field direction is radial (from radio obs.)
  - Caused by RT instabilities behind shock, but not fully understood
  - Field measured over larger radial region than producing nonthermal X-rays
- In SNR shells, don't see 80% polarization in radio:
  - Typically see <20% => substantial turbulent component

Difference from radio of X-ray polarization observations in SNRs (& PWNe)

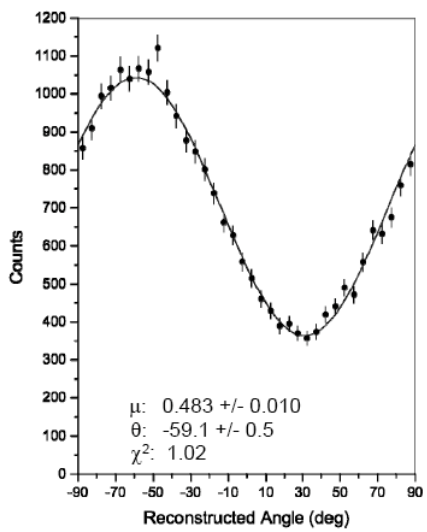
+ Sampling younger (and possibly different) electron population in SNRs & PWNe
+ Sampling different spatial regions in most SNRs and some PWNe
  - Measure whether B field at edge of SNR is different from those seen at longer length scales in radio
+ Measure ordering of B field in region producing nonthermal X-rays
+ No dispersion or depolarization due to ISM – true signal, larger than radio
+ No depolarization by gas within the remnant
  - Strong effect in Cas A – (Anderson et al. 1995)
+ A null result is a good result!

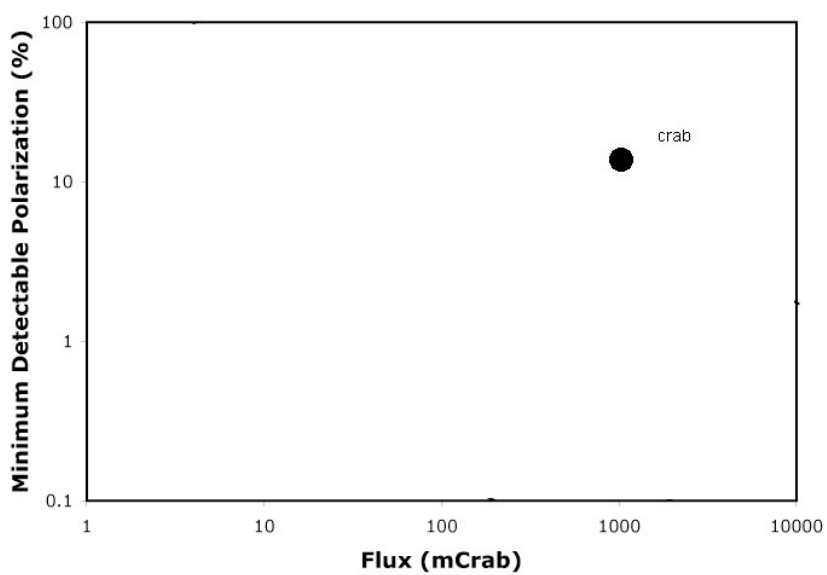
- B field turbulence at shock front => depolarization
- Contamination by thermal emission reduces polarized signal
- Limited number of SNRs – only those with non-thermal X-ray components

Bottom line:
Excitement associated with observing in a new way
Could see something not too exciting; or could see something highly revealing

X-ray Polarimetry has had a sparse history

- Polarization in the X-ray band is almost completely unexplored
- All previous measurements done in the 1970's (sounding rocket, OSO-8)
  - Only *one* has been detected – the Crab Nebula (Novick et al. 1972; Weisskopf et al. 1976, 1978)
  - Upper limits on 10 Galactic binaries >10% (Hughes, Long & Novick 1983)
- Challenging measurements: small signal (typically < 10%), needing <u>many</u> photons to detect
  - Systematics need to be understood and controlled
  - Until recently, detectors lacked either bandpass or high modulation (MDP proportional to $(\sqrt{A}\varepsilon)/\mu$)
  - New photoelectron track reconstruction techniques offer good modulation and QE over a broad band

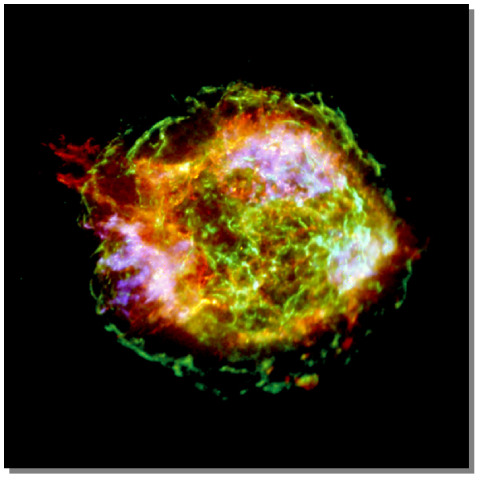




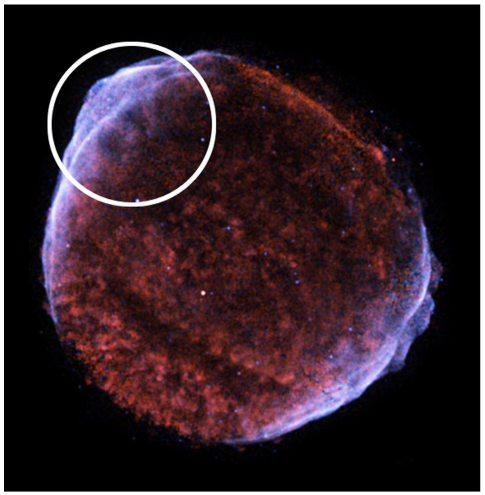
KNOWN SINCE 1972

How Does Cosmic-ray Acceleration Occur in Supernova Remnants?

- X-ray imaging and spectral observations have shown:
  - Supernova remnant shocks are sources of synchrotron radiation from radio through X-rays
    - The shock thickness implies B fields are amplified
  - The shocks are sources of radiation up to TeV (10^{12} eV) energies
- Questions remain:
  - How are the B fields amplified?
  - Are the B fields tangled or coherent?
- X-ray polarization will tell

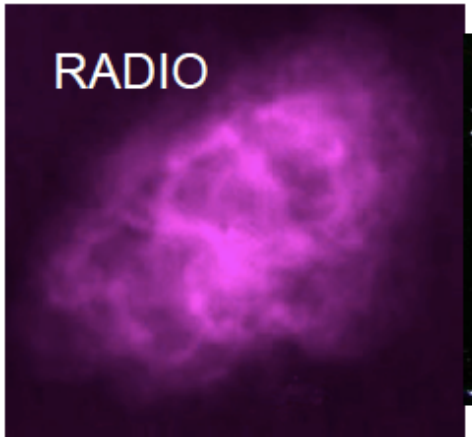


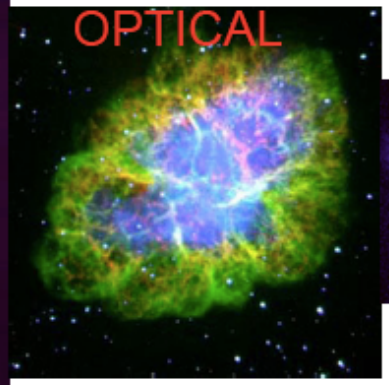
Cas A with Chandra

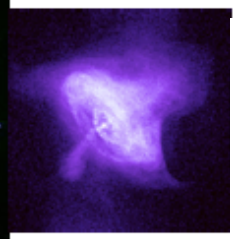


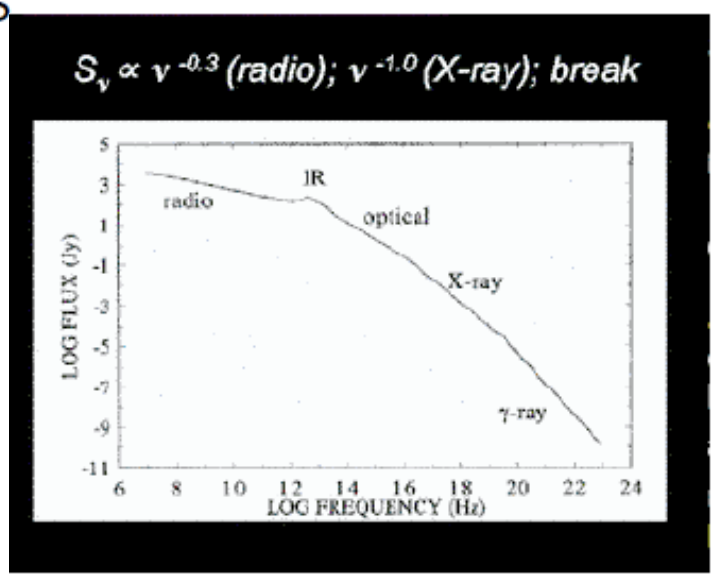
SN1006 with Chandra showing GEMS fov

What can we learn from PWNe?









- Region producing nonthermal X-rays highly structured (disk and jet)
  - Expect high polarization fraction
- Continuous spectrum from radio through X-rays in many but not all PWNe
  - Same population of particles produces both (in general)
- X-ray nebula more compact, reflecting shorter synchrotron lifetime
  - Sample different region
- Need to separate nebular signal from pulsar signal (temporally or spatially)

X-ray polarization observations of the Crab

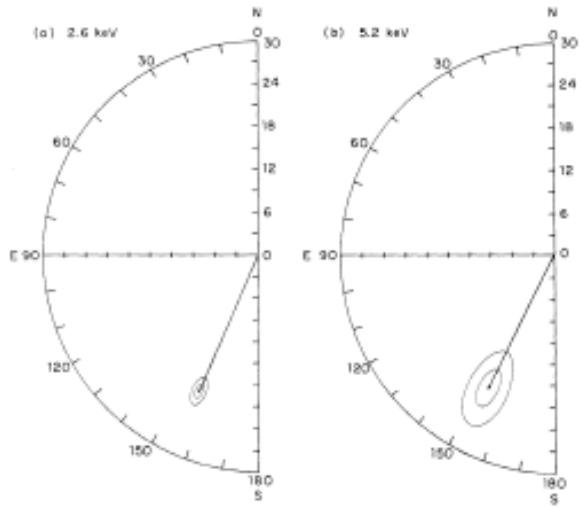


FIG. 3.—The polarization vectors for the Crab Nebula at (*a*) 2.6 keV and (*b*) 5.2 keV. Surrounding the vectors in order of increasing size are the 67% and 99% confidence contours. The radial scale is the polarization in percent.

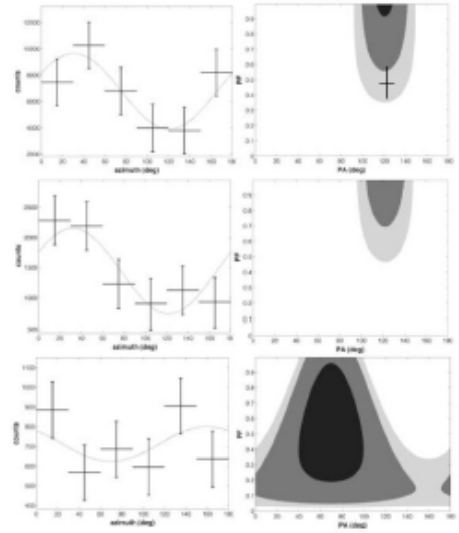


FIG. 2.—Azimuthal profile, modulation angle, PA, and fraction, PF = a_0/a_{100}, measured for the Crab data between 200 and 800 keV, in the off-pulse (*top*), off-pulse and bridge (*middle*), and two-peak (*bottom*) phase intervals. The error bars for the profile are at 1 σ. The 68%, 95%, and 99% confidence regions are shaded from dark to light gray. The SPI result (Dean et al. 2008) is indicated in the top figure by a cross.

- **To measure nebular polarization, need to look a phases when pulsar is "off"**
- X-rays from nebula 19.2%±1.0% polarized at 156.4°±1.4° at 2.6 keV; 19.5%±2.8% polarized at 152.6°±4.0° at 5.2 keV (Weisskopf et al. 1978)
- γ-rays: Off pulse and bridge emission polarized at 122.0°±7.7° (Forot et al. 2008)
  - Consistent with 124°±0.1° projected pulsar rotation angle
  - PF>72% (off pulse) >88% (off pulse plus bridge)
  - Consistent with 77% polarized signal along pulsar rotation axis, maximum
- IBIS measurement probably from particles in equatorial wind near the termination shock.
  Electrons have energy as high as 250-500 TeV, lifetime of 0.85-0.43 year, and do not travel more than 0.09 pc.
- X-rays sample larger region (thus lower fraction); less order (thus different angle)

Polarization in the Crab

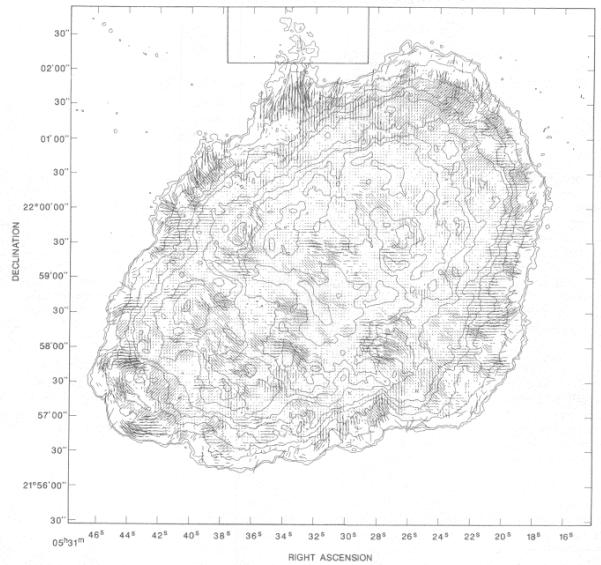


FIG. 2.—The total intensity, percentage polarization, and projected magnetic field orientation at 1410 MHz. The clean beam is as in Fig. 1. The contours represent the total (I) emission at 1410 MHz. Contour levels are at 0.5, 1, 5, 10, 15, 20, 30, 40, 50, 70 and 90% of the peak flux (0.11 Jy beam^{-1}). The length of the vectors represents the percentage polarization, a vector length of 30" indicating 100% polarization. The box indicates the region over which profiles of the "jet" were taken; see Fig. 3.

- Can in principle predict what we will see in X-rays, even without spatial resolution
- If we assume the same population of electrons is responsible for both the radio and X-ray emission, can convolve X-ray surface brightness map with radio polarization map to predict phase angle.
- Polarization fraction cannot be predicted a priori.

Polarization in G54.1+0.3

- Pulsar is dim, making nebular measurement easer.
- Relatively uniform rotation measure distribution
- Typical polarization is 27% at 8.5 GHz and 23% at 4.7 GHz
- Peak polarization ~50% at 8.5 GHz
- Shows different field configuration from Crab
- Large scale radio and X-ray emission distributions very similar, but details near center are very different: **X-ray and radio emission trace two different components of relativistic particles**
- Toroidal and radial components seem to be present; polarization overlapping with X-ray predominantly tangential to pulsar spin axis.

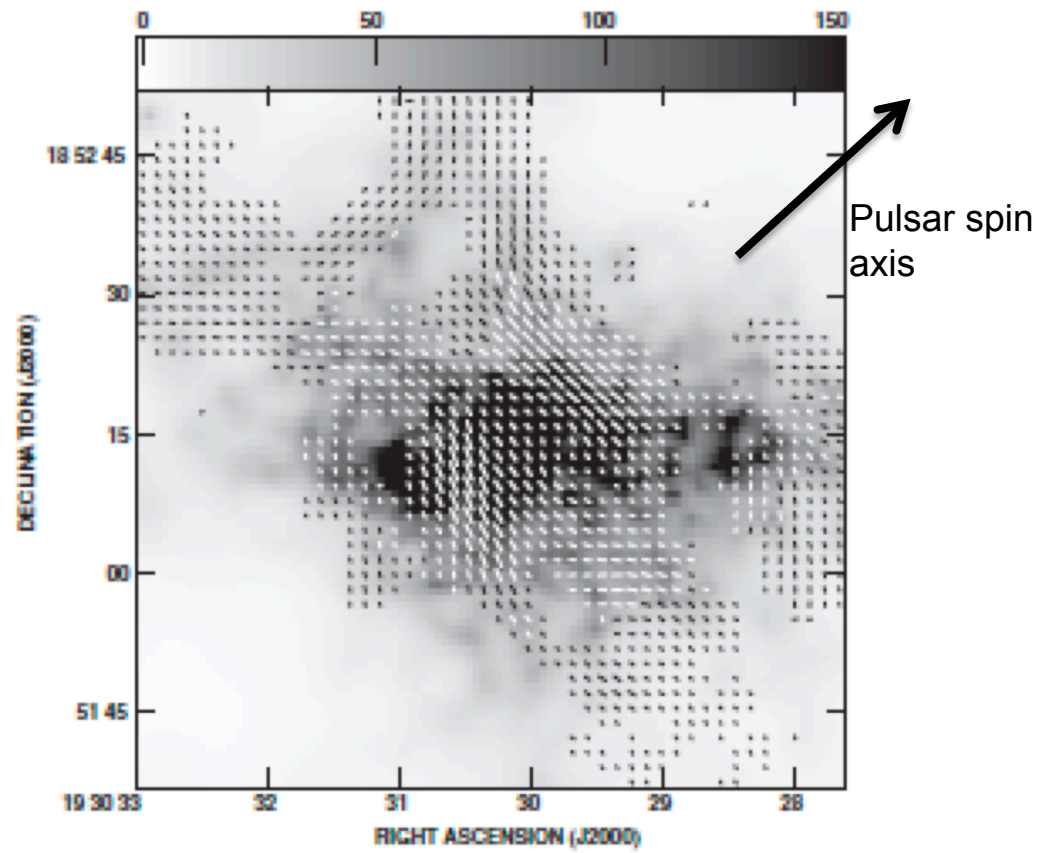
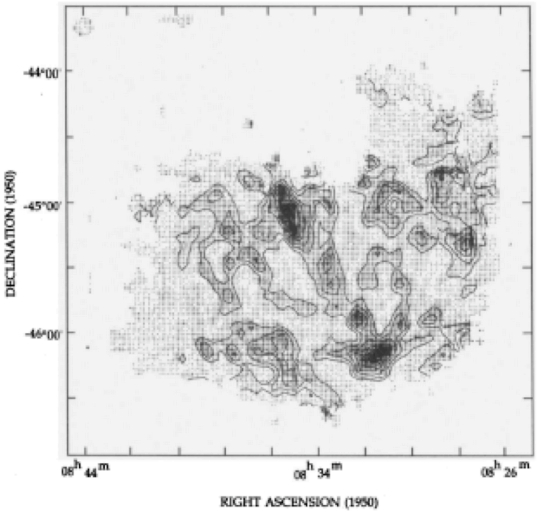


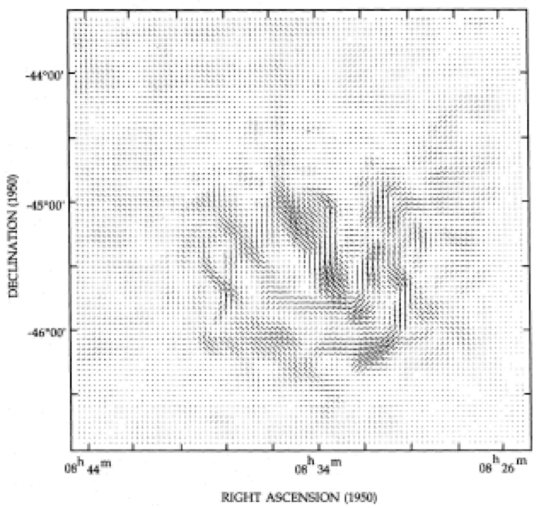
Figure 14. Vectors of the intrinsic magnetic field orientation in G54.1+0.3 from these data (presented in Figure 10) overlaid on grayscale showing the 0.2–10 keV X-ray emission from Lu et al. (2002).

(Lang et al. 2010)

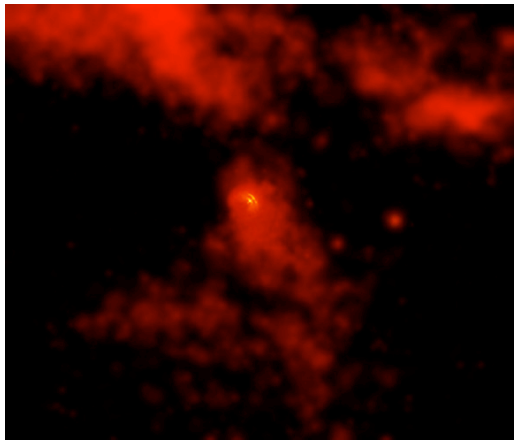
The Vela PWN and Vela X



Polarized intensity



Magnetic field direction



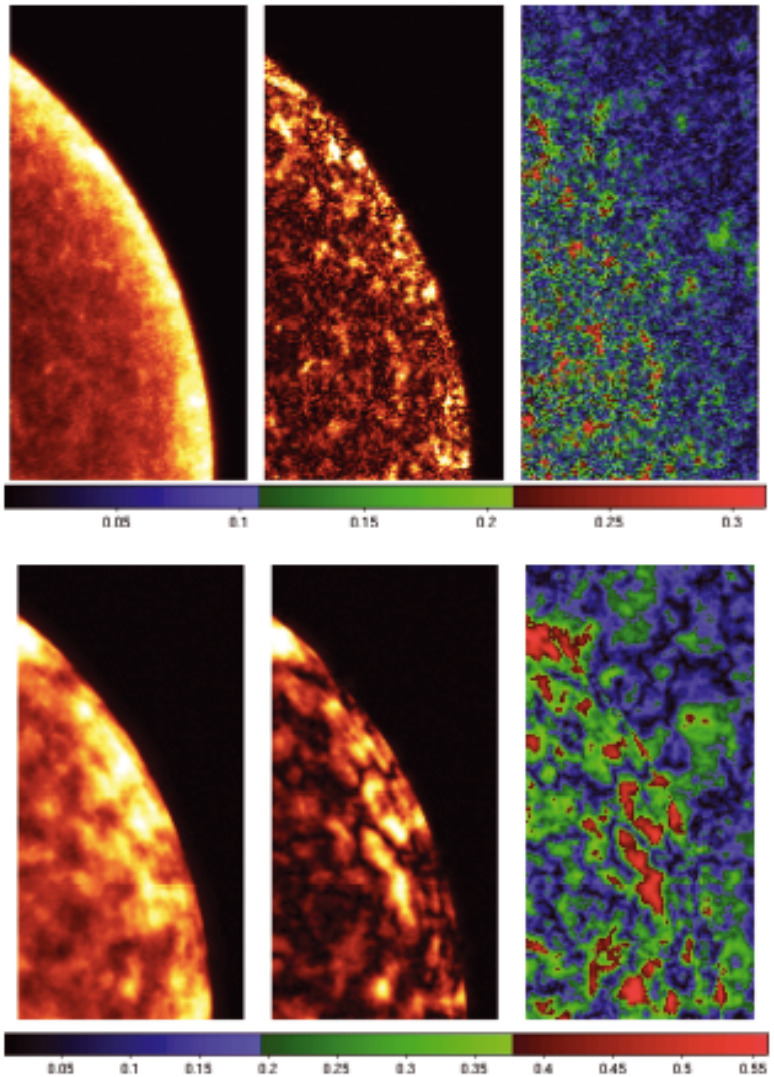
X-ray surface brightness

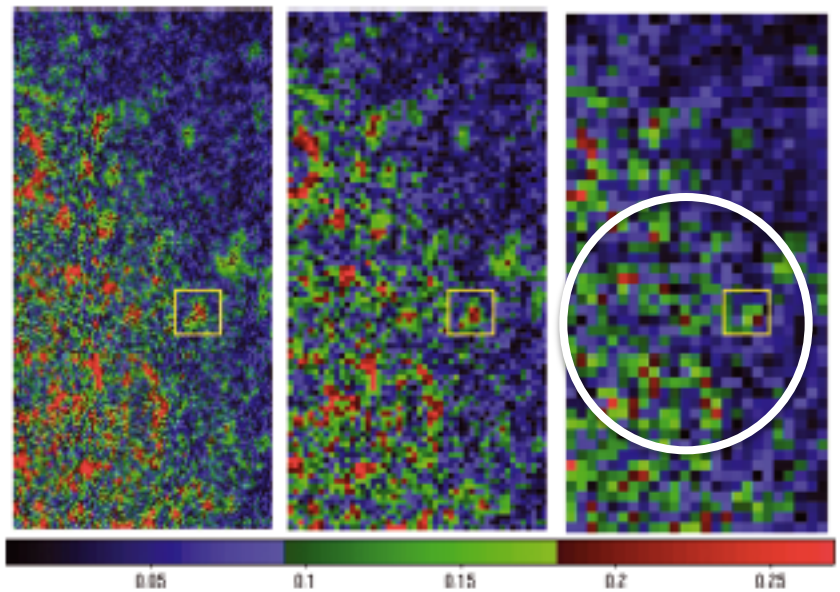
- Vela X (central, radio bright region of Vela SNR, including the PWN)
- Polarized at >40 percent at 8.4 GHz (Milne 1995)
- B-field ordering on few arcmin scales
- Pulsar virtually invisible in 2-10 keV band
- X-ray “jet” is prominent; 15-20% polarized in radio
- “Jet” dominated by nonthermal X-rays above 2 keV (Mori et al.)

X-ray Polarization in SNRs

- **Detection of polarization will prove synchrotron origin of nonthermal flux**
- Primary magnetic field component in young SNRs is radial (from radio)
- Expect high polarization (up to 80%) from ordered B field at rim
- But field **must** be turbulent if diffusive shock acceleration is to operate
- Turbulence will reduce average polarization (Strohman & Pohl 2009; Bykov 2009)
- Turbulence can also produce locally high B-field fluctuations
  - Results in locally high X-ray polarization
  - X-rays particularly sensitive, since degree of polarization sensitive to electron spectral index, and those producing X-rays in exponential rolloff tail
  - Fluctuations, thus flux and polarization will be **time variable**
- **Imaging polarization measurements can be used to determine degree and spatial scale of B field fluctuations**
  - Radio modeling suggests $\delta B<B$ in young SNRs (Strohman & Pohl 2009)
  - Radio polarization too large to be produced by purely stochastic fields; must be ordered component

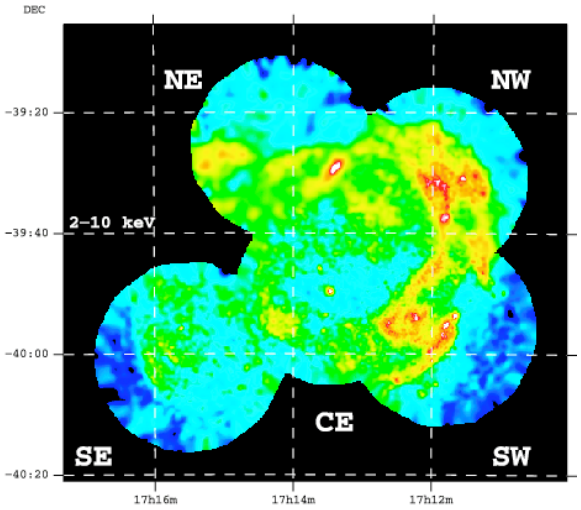
Polarization could be dominated by short term B-field fluctuations (Bykov et al. 2009)

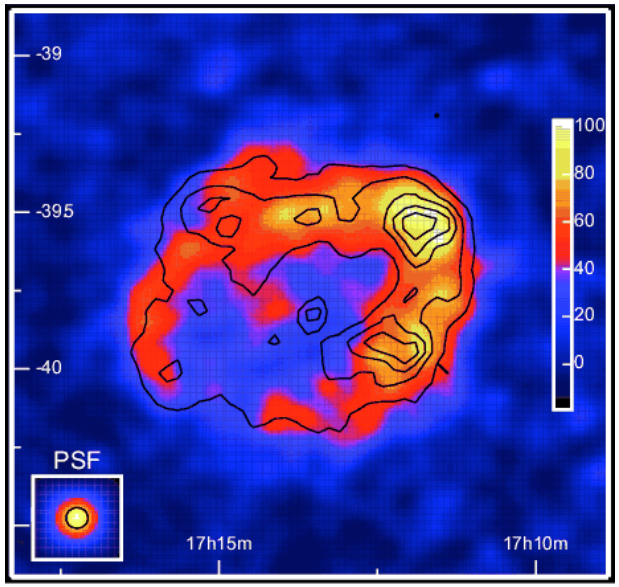


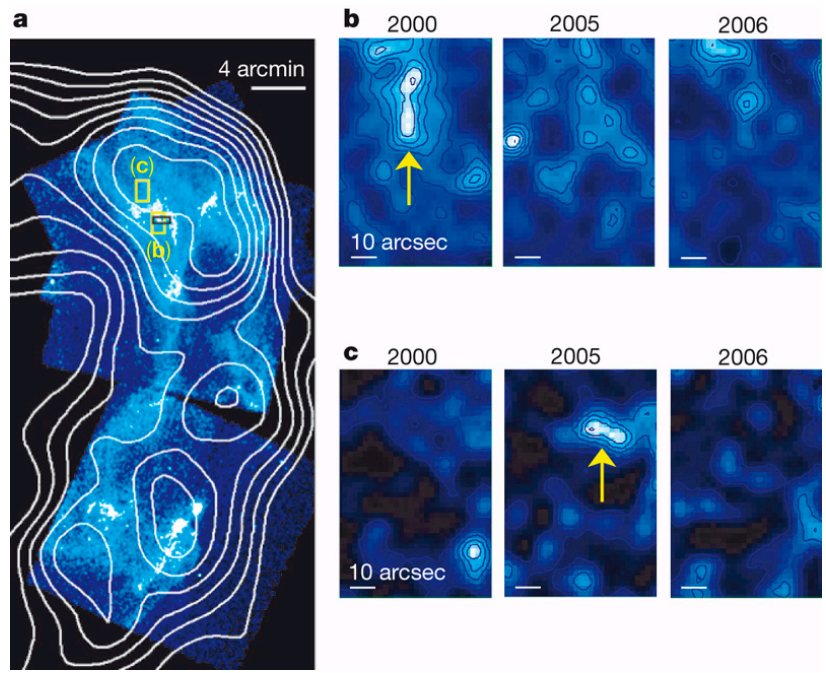


- Polarization at 5 keV from purely stochastic B field
- Strong dependence on electron spectrum
- Random polarization directions
- Strength of polarization dependent on angular resolution
- Polarization will be time variable

RX J1713.7-3946: Poster child for twinkling polarization

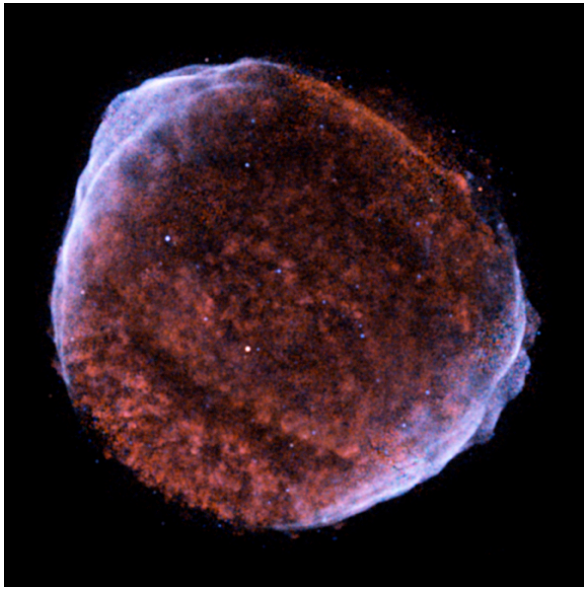


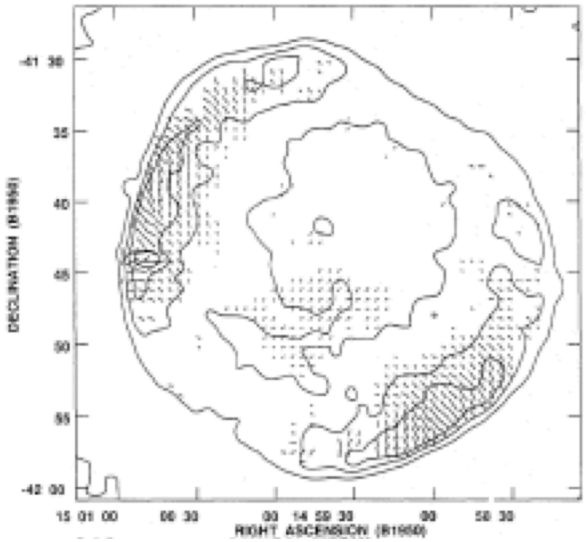




- Spectrum is entirely nonthermal
- Stimulus for Bykov et al. model
- Small features have 1y timescales (Uchiyama et al. 2007)
- These features should be highly polarized

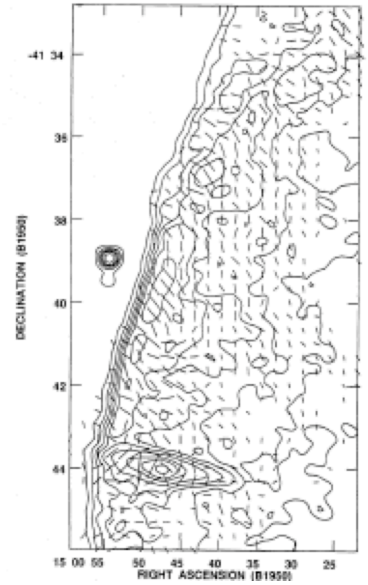
SN 1006 could be different

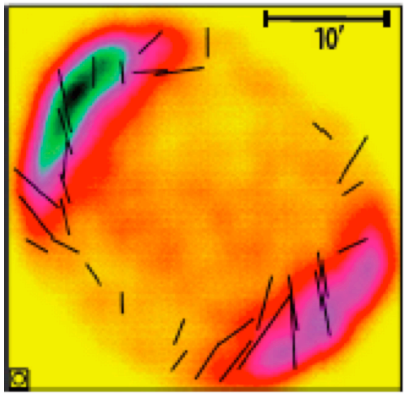




- Intrinsic magnetic field is radial, as expected in young SNR
- Relatively well ordered but some evidence of structure
- Average polarization only 13%, peak of 30%
- Polarized fraction suggests field is mostly disordered, with only 20% of the total magnetic energy density in the radial component
- Radio ordered field polarization would be 71% (X-ray >80%)
- Radio and X-ray probe different scales
  - X-ray synchrotron originates only in outermost shock region
  - *No evidence of X-ray variability* (<10%).
  - Is field there more ordered?

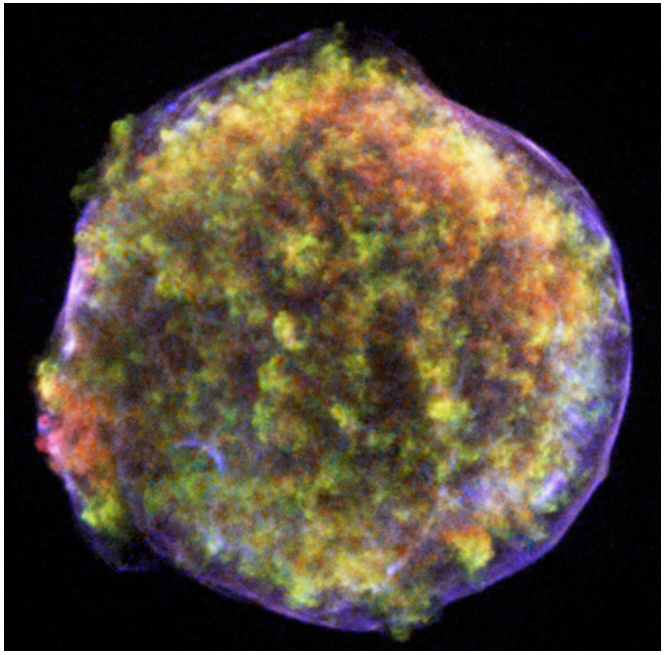
Reynolds & Gilmore 1993

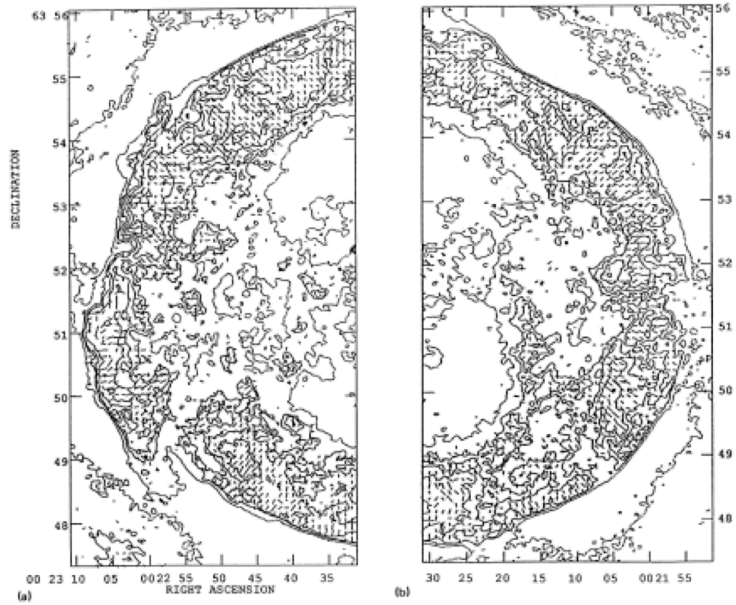




X-ray image of SN1006 showing the position angles and strengths of the X-ray polarization vectors (black bars) assuming it is the same as the polarization measured in the radio band.

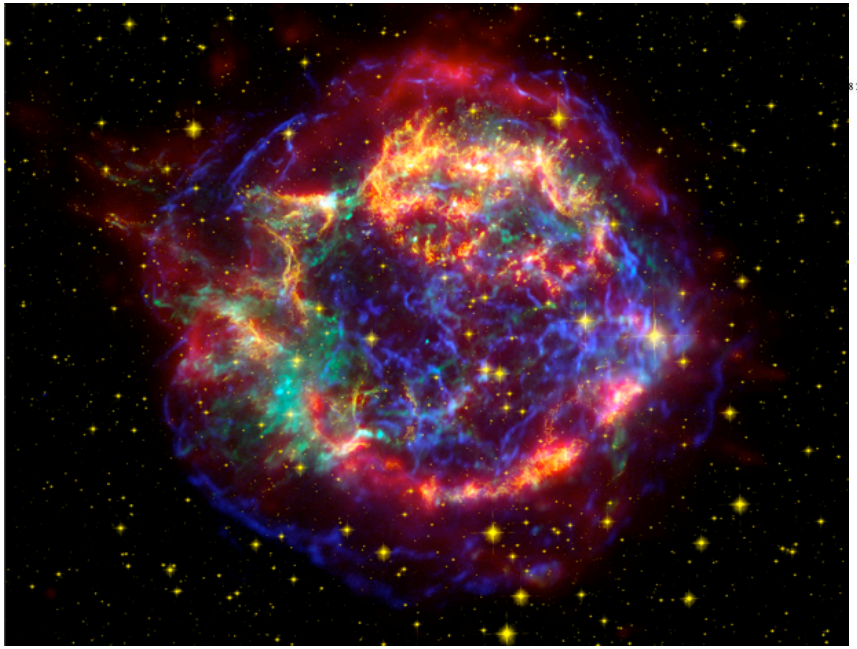
Tycho

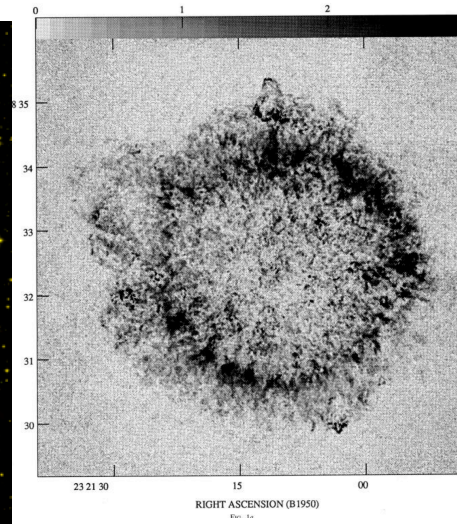


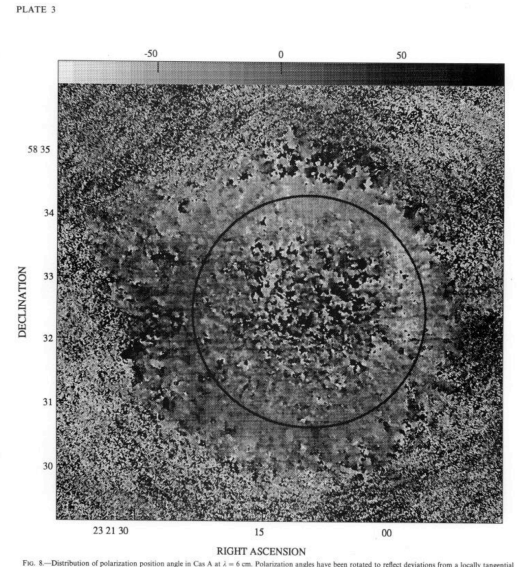


- Polarized intensity strongest on rim and falls more markedly than the total intensity (Dickel et al. 1991). B-field at rim is not strictly radial
- Polarized radio intensity appears to have a cell like structure, with a characteristic size of ~0.2 pc (15 arcsec). The polarization cells are not necessarily coincident with total intensity features. High polarization intensity sometimes occurs near the edges of bright regions of total intensity, but no formal correlation.
- Regions having a high degree of local magnetic field organization tend to have strong polarized intensity (Wood et al. 1992)
- In X-rays, we will only see outer rim, where radio polarized intensity is highest

Polarization in Cas A







- Strong radial pattern in radio (Anderson et al. 1995)
- Strong depolarization coupling with hot gas
- X-ray synchrotron comes from different region
  - Cas A does not have radio bright outer rim
  - If can isolate shell may see something different
  - Substantial contamination of rim nonthermal emission by thermal gas

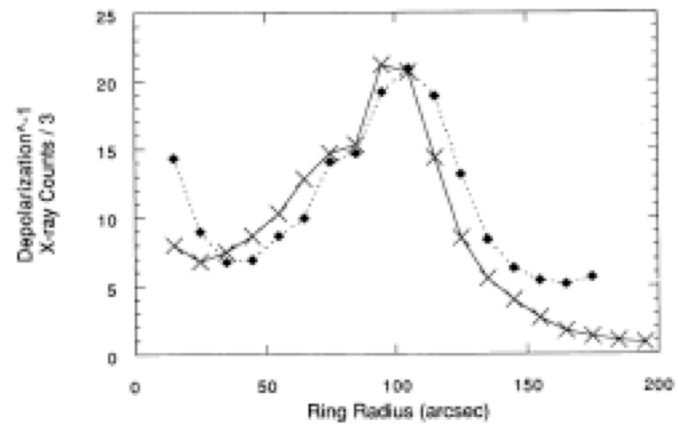


FIG. 4.—Depolarization^{-1} = %pol(λ = 6 cm)/%pol(λ = 20 cm) and X-ray brightness (*ROSAT*/HRI) averaged over azimuthal rings and plotted as a function of radial distance from the center of the remnant.

The very young SNR G1.9+03

- Newly discovered SNR shows rapid expansion consistent with being ~100 yrs old
- X-ray spectrum is largely nonthermal, but radio and X-ray surface brightness is anticorrelated
- Radio polarization has yet to be measured

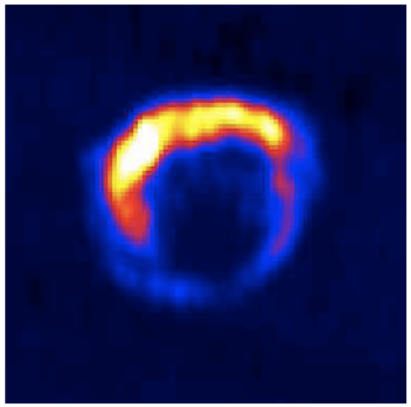


FIG. 1.— Radio image of G1.9+0.3 (Green 2004): VLA at 1.5 GHz. Resolution $9''.4 \times 7''.2$.

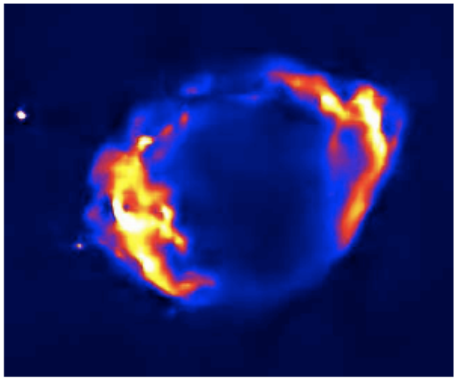
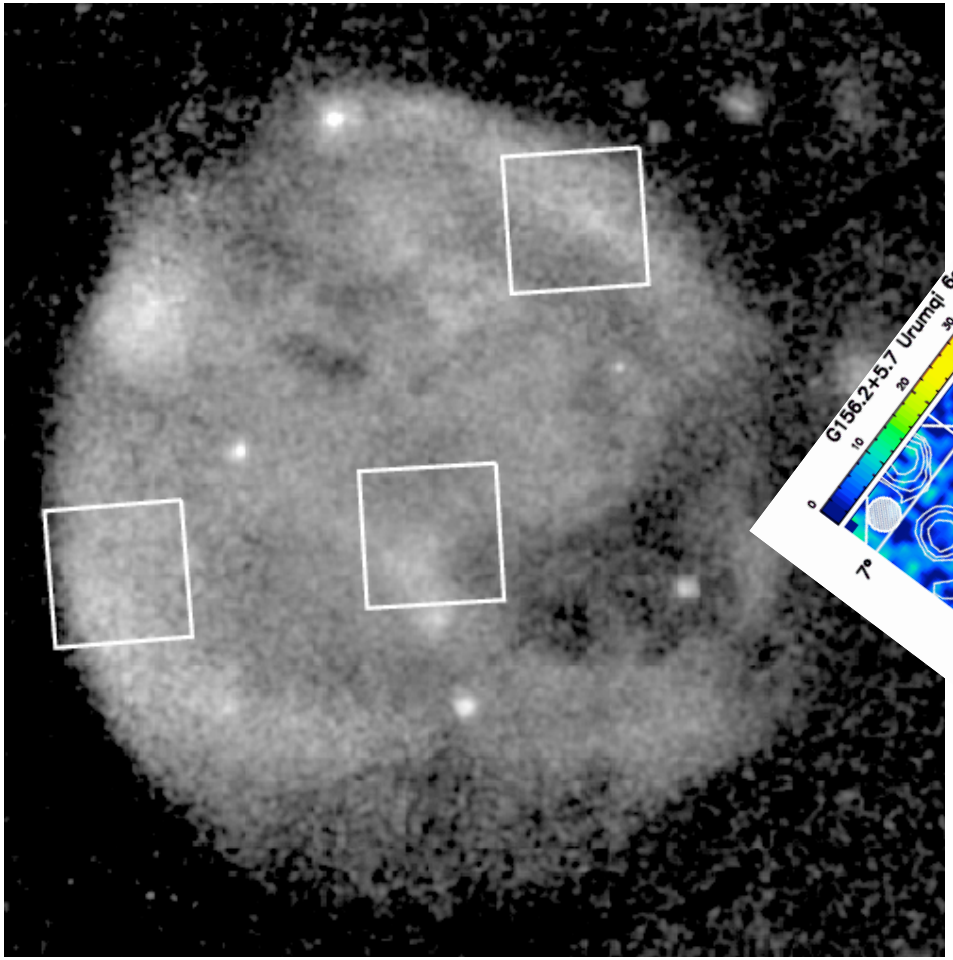
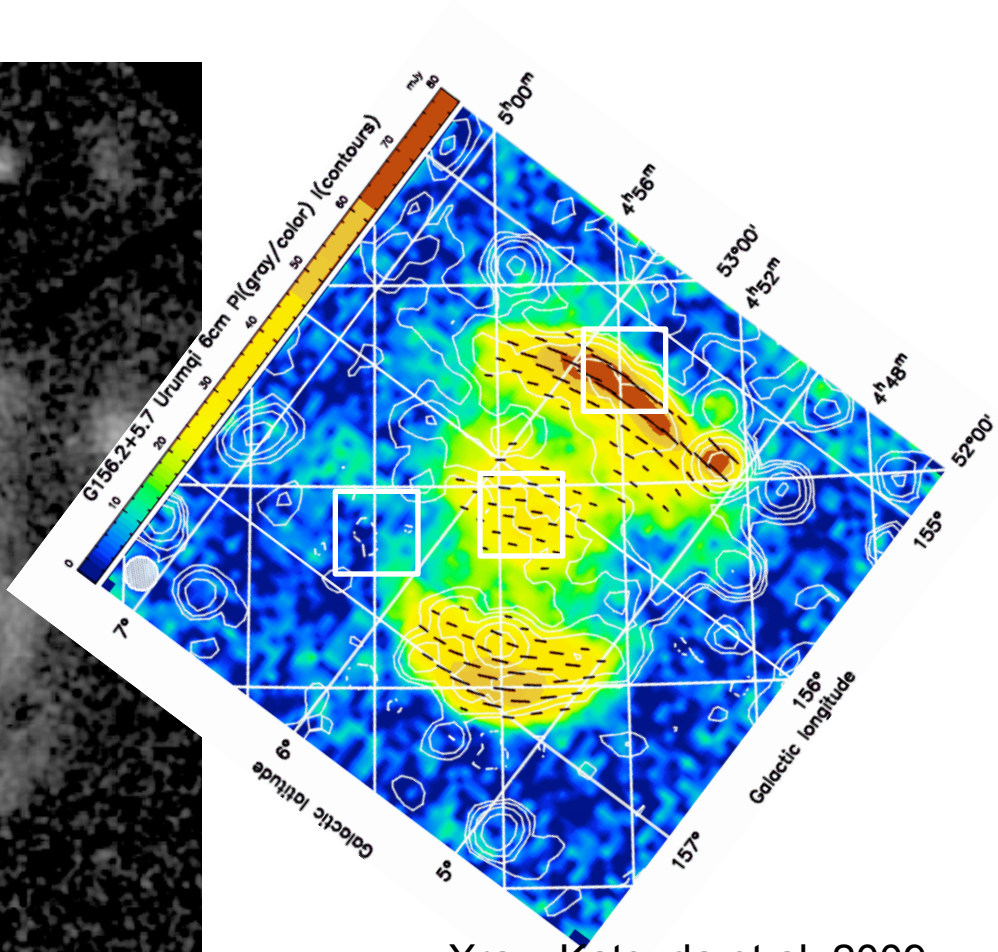


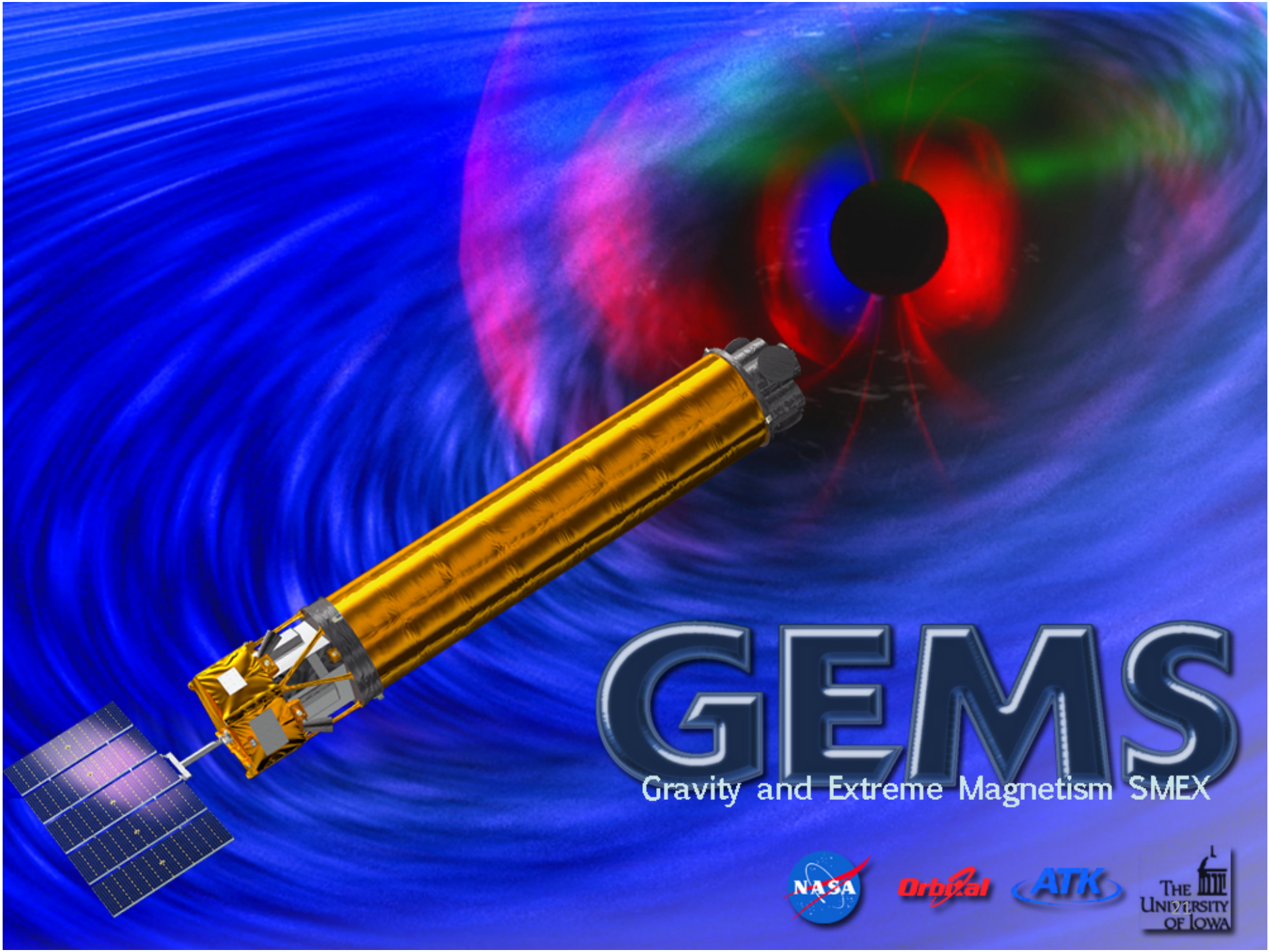
FIG. 2.— *Chandra* image of G1.9+0.3, platelet smoothed (Willett 2007). Colors are intensities only, between 1.5 and 6 keV.

G156.2+5.7: An evolved SNR showing a nonthermal shock





Xray: Katsuda et al. 2009
Radio Xu et al. 2008


GEMS
Gravity and Extreme Magnetism SMEX
NASA
Orbital
ATK
The University of Iowa

GEMS will open the frontier of X-ray polarimetry

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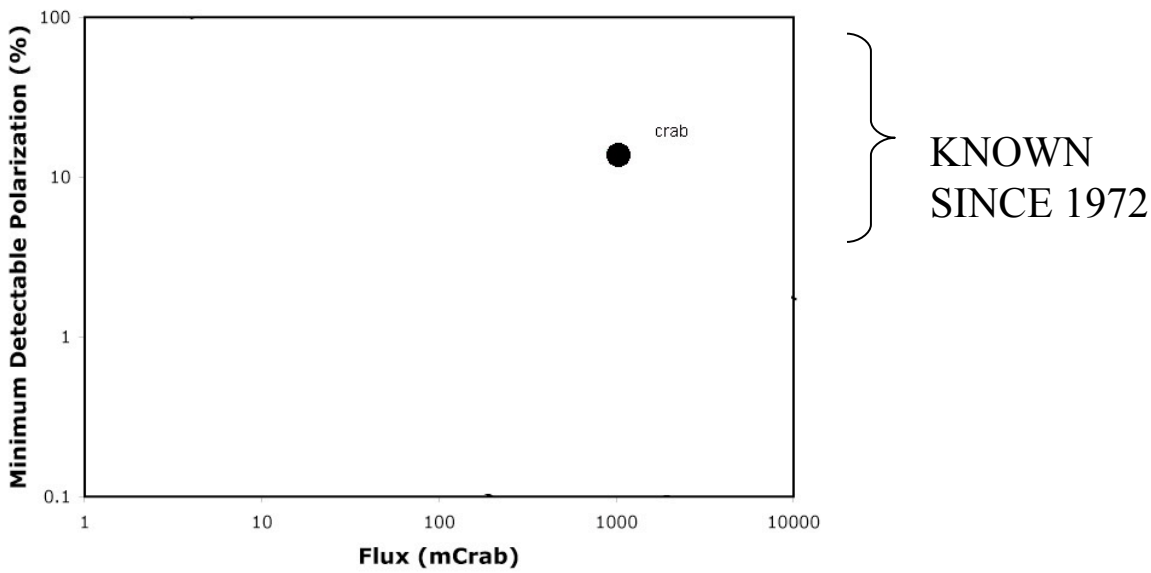
- Polarization in the X-ray band is almost completely unexplored: only *one* object outside the solar system has been previously detected
- GEMS will be ~100x more sensitive than any previous instrument and will be able to study *dozens* of sources
- *Discoveries* can be expected: about black holes, neutron stars, supernova remnants



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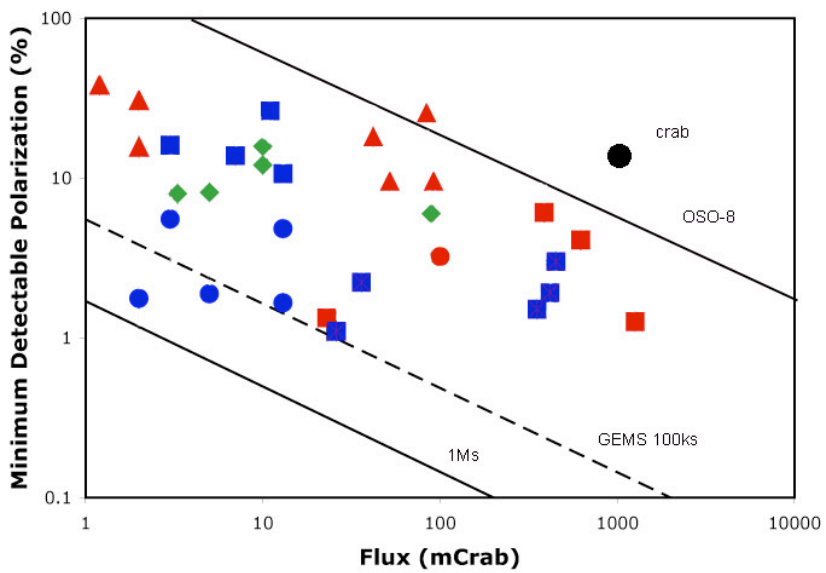
- GEMS targets include Crab, SN 1006, Cas A, RX J1713.7-3946, Vela (+GO program)

Targets with known fluxes, polarization estimates

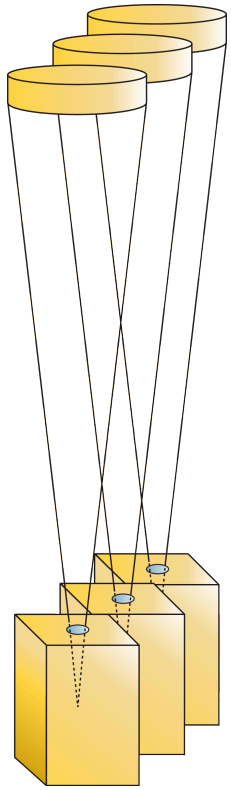


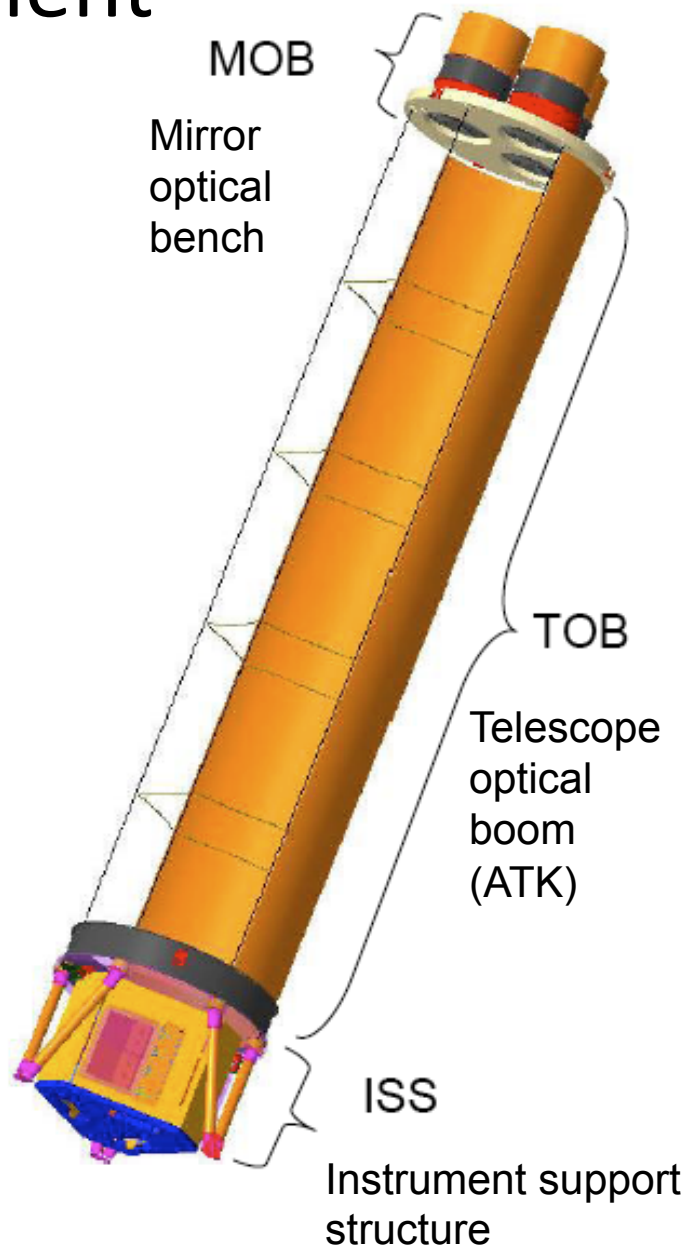
KNOWN SINCE 1972

NEW TERRITORY

X-Ray Polarimeter Instrument

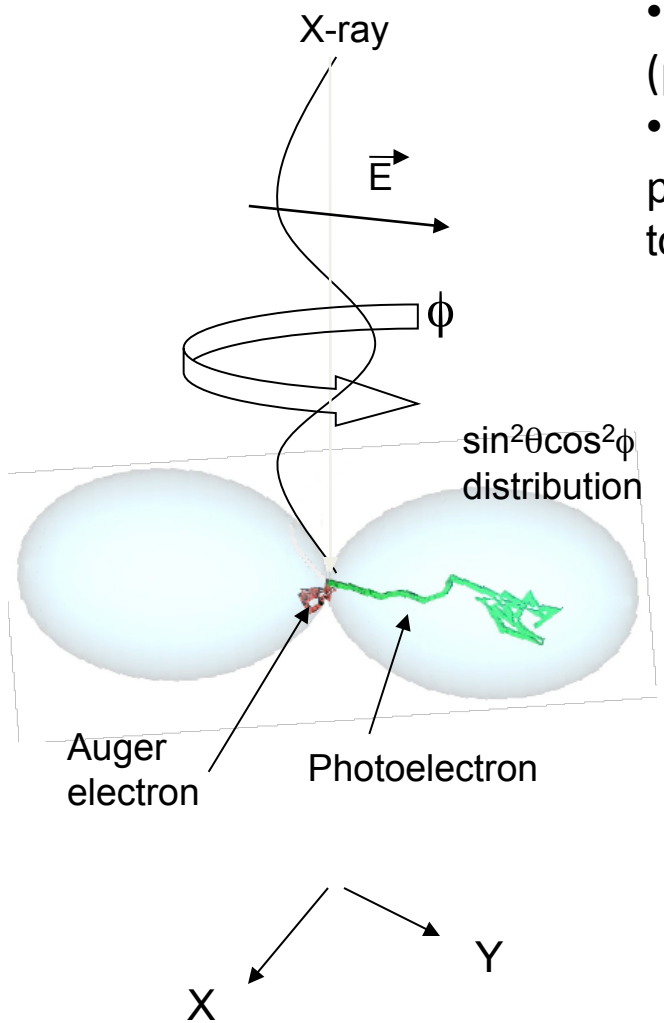
- 2-10 keV range
- Mirrors with 4.5 m focal length (a Suzaku mirror, but 33 cm diameter versus 40 cm)
- Time projection chamber Polarimeters image photoelectron tracks
    - High QE
    - Moderate energy resolution
- 3 independent and identical telescopes (mirror and polarimeter pairs)
- Instrument rotates at 1 rpm to remove systematics

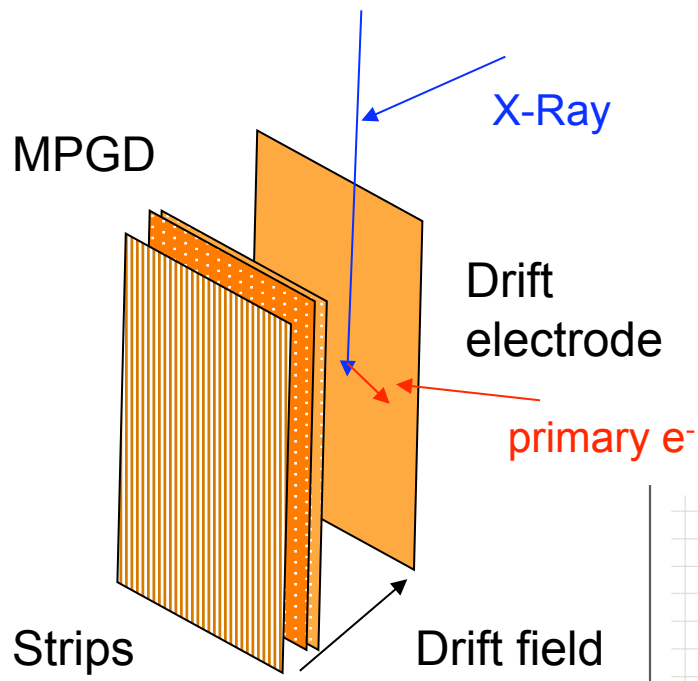


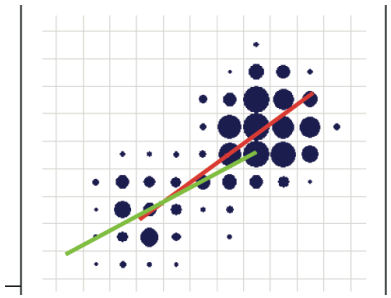


Time Projection Chamber Polarimeter

- Measures the projection of the electron track in the X-Y plane with time and space measurements
- Like all polarimeters, measures electric field vector (perpendicular to B field)
- $\cos^2\Phi$ distribution requires many photons to establish polarization angle; low polarization requires many photons to establish polarized intensity

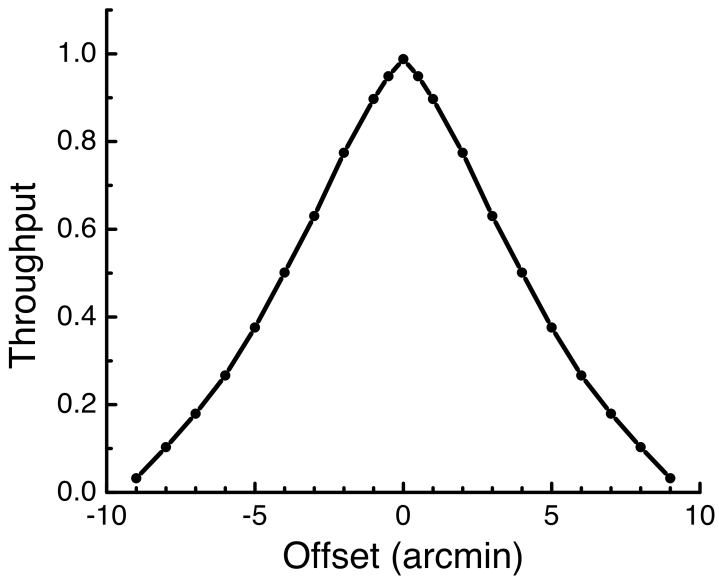






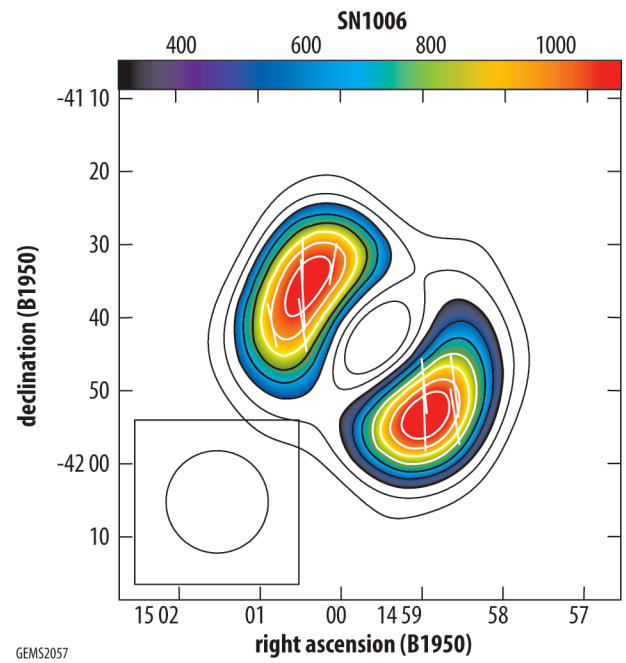
While the sky is not imaged, XPI has a useful field of view

Mirror and aperture geometry combine with the point spread function to give a field of view ~ 11 arc min



Response of current design

Convolution of telescope FoV and ASCA image of SN1006 shows the contributions of the hemispheres



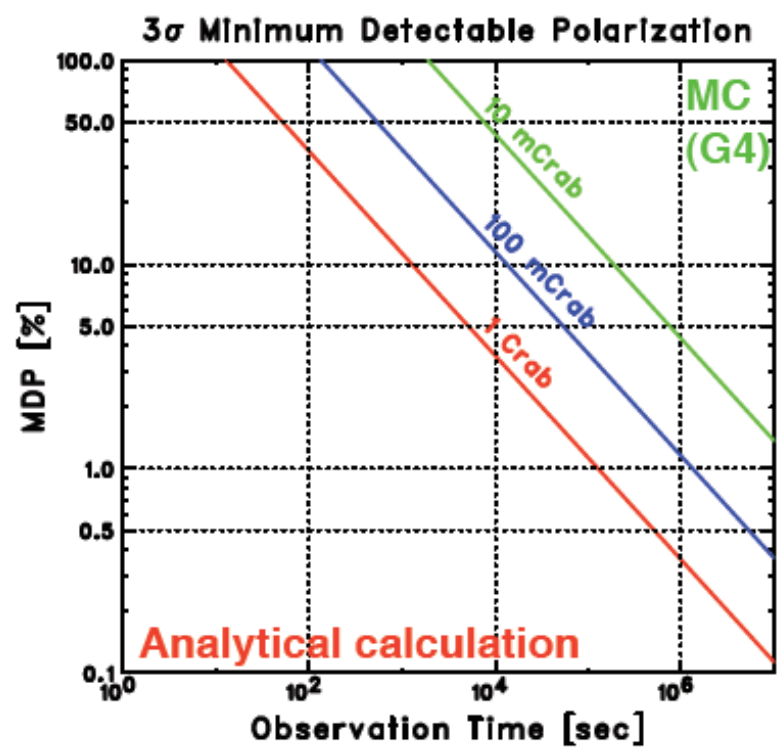
Expect ~10% polarization signal from SN 1006, even with contamination from thermal X-rays

The Astro-H SGD is polarization sensitive!

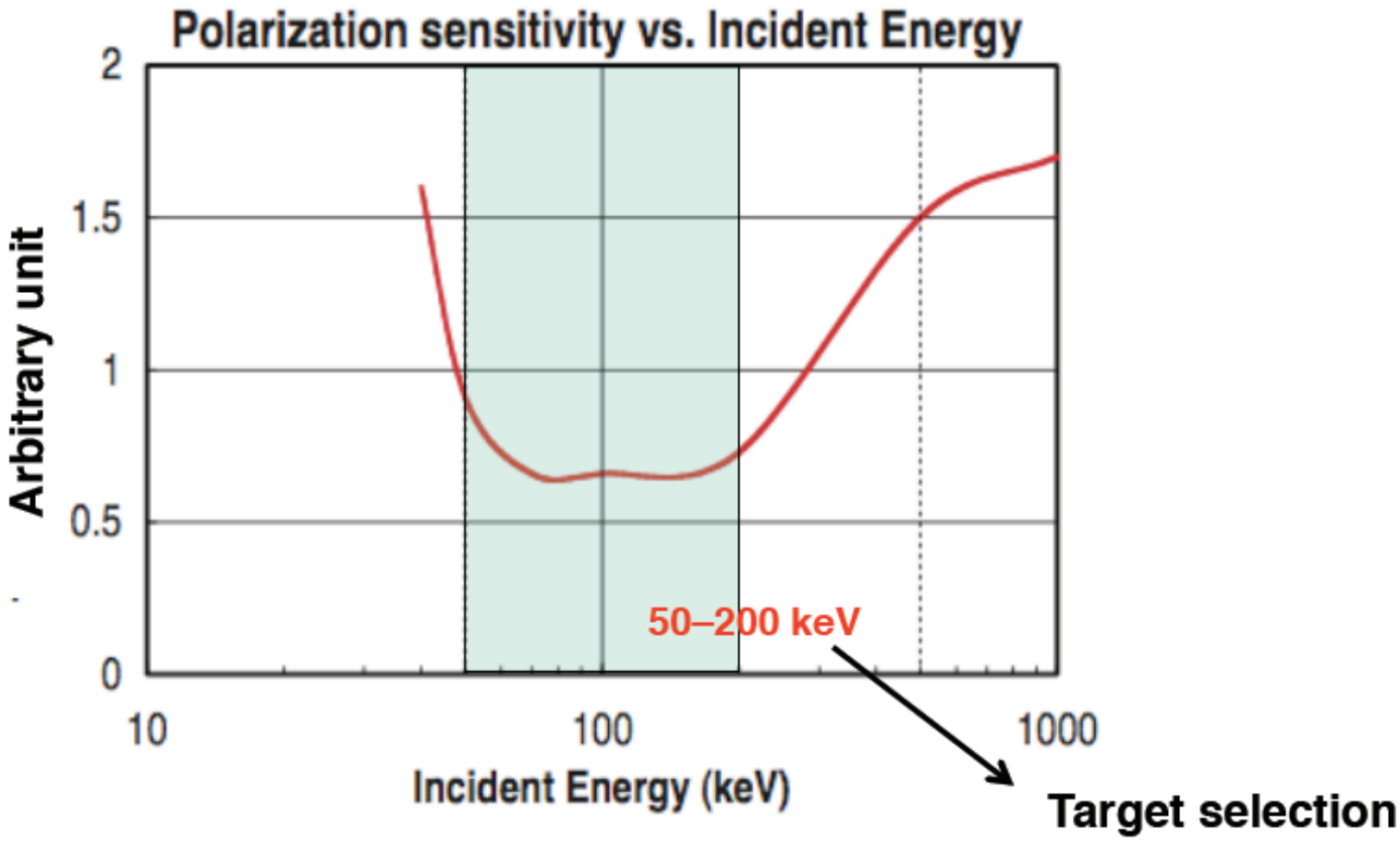
- **3σ MDP (Minimum Detectable Polarization):** $11\%/\sqrt{t_{\rm obs}}$ (1 Crab)
  - $t_{\rm obs}$: observation time in ks — $36\%/\sqrt{t_{\rm obs}}$ (0.1 Crab)
  - BG taken into account (assumed no modulation)
  - N_γ: number of incident photons in 50–200 keV
- **Energy or phase (pulse, orbit) dependence for bright sources**

Simulation results (EGS4)

Source	Observation time	N_γ	3σ MDP
Crab	5 ks	85,900	6.0%
Cygnus X-1 soft state	25 ks	92,800	6.4%
X0115+63	25 ks	52,400	8.5%
Mk501 flare	100 ks	56,400	8.2%

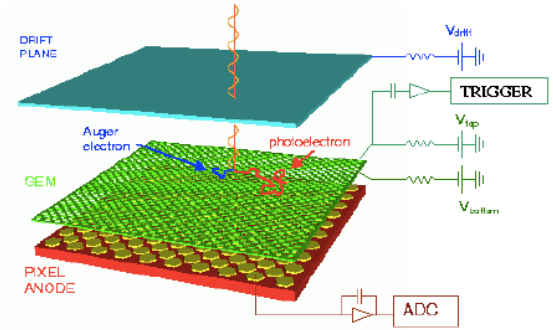


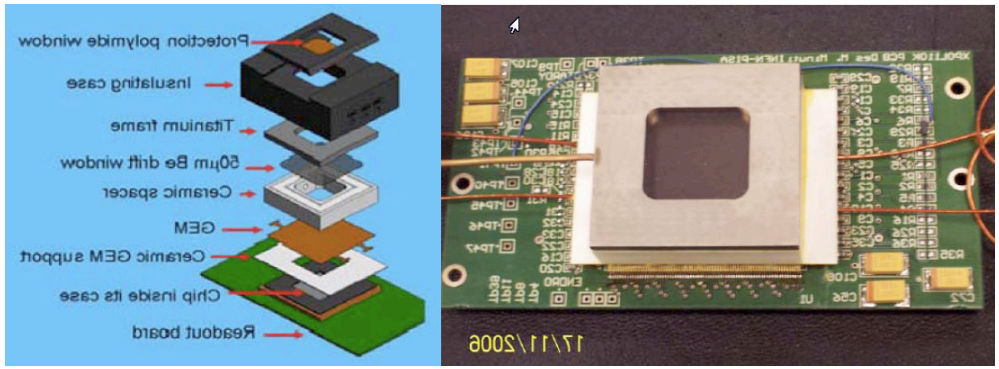
SGD polarization sensitivity

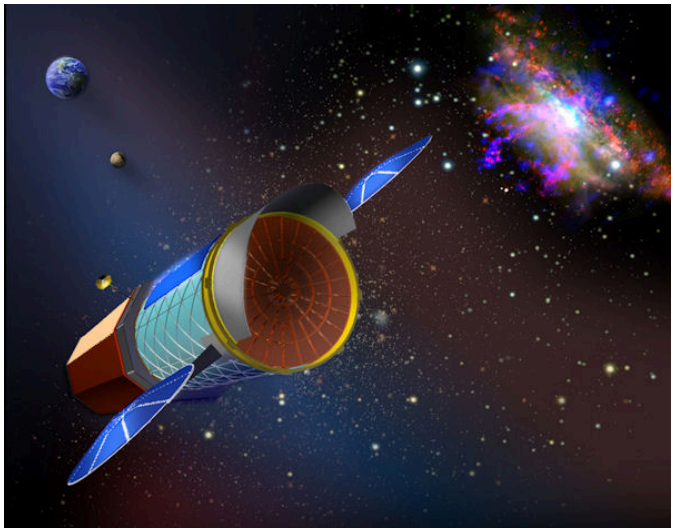


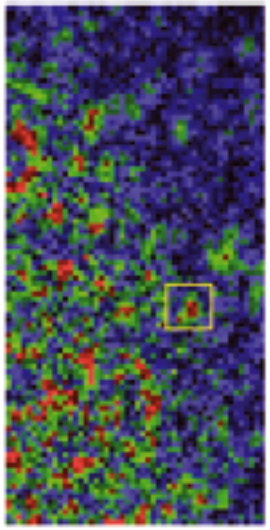
- The SGD is sensitive in a band very different from GEMS
- The two provide complementary measurements

XPOL – Imaging polarimetry on IXO









- IXO will carry an *imaging* X-ray polarimeter with ~5 arcsec angular resolution and 2.5 arcmin field of view
- Modest QE detector, but huge collecting area leads to very high polarization sensitivity

What does this have to do with Astro-H?

- Astro-H SGD will detect polarization from the Crab, possibly others
- GEMS + SGD offer broad band polarimetry
- GEMS provides constraints on B-field geometry and turbulence. Together with broad band spectra from Astro-H, these will provide input for next generation of models of synchrotron emission and diffusive shock acceleration
- In PWNe GEMS and SGD sample different regions
  - Variations in polarized fraction and polarization angle provide insight into magnetic field geometry
- As with all new capabilities, we will find new ways to combine Astro-H and GEMS

Conclusions

- With GEMS, SGD, (and IXO), the era of X-ray polarimetry is about to begin
- We expect detectable polarization signals from PWNe and from nonthermal shocks in SNRs
- For PWNe, should be able to predict polarization direction from comparison of X-ray (Chandra) images and detailed radio polarization maps
- For SNR shells, can constrain magnetic field parameters (fluctuation spectrum), and compare with models
- Polarization information will help us understand the origin of the broad band X-ray spectra to be measured by Astro-H
- There will be many surprises!