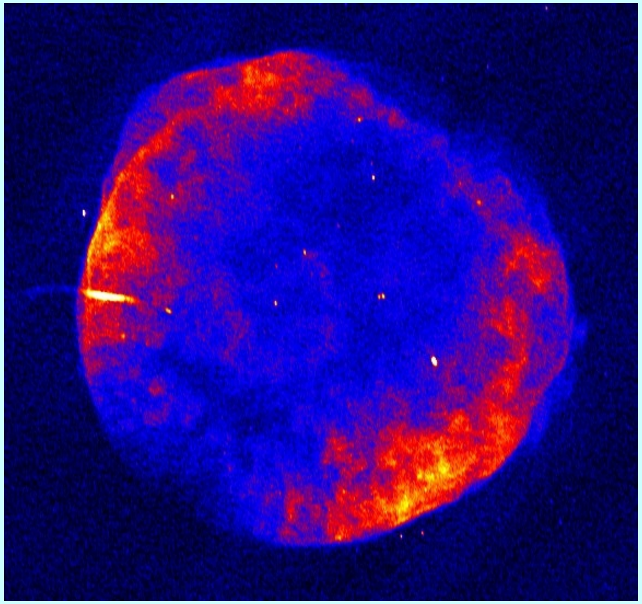
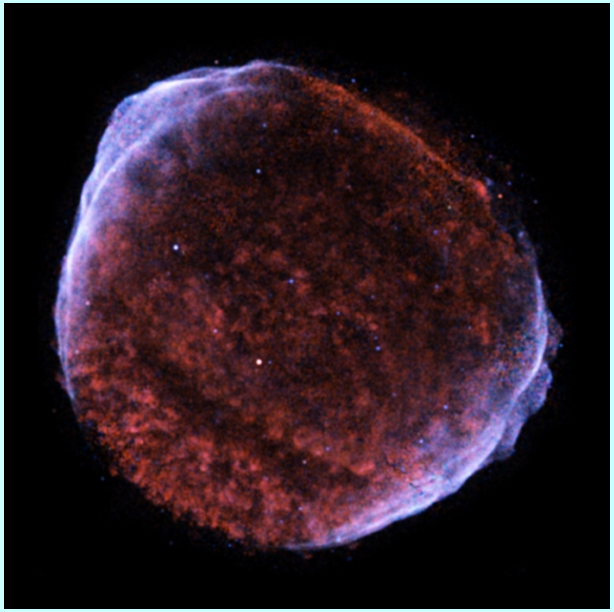
Synchrotron X-rays from Shell Supernova Remnants: Spatial Structure

S. P. Reynolds, NC State U.

1. Introduction: status of observations and modeling
2. Three problems: thin rims, caps vs. belts, azimuthal structure in SN 1006, G1.9+0.3
3. Where we are





Status report: synchrotron X-rays in shell SNRs

1. Four Galactic remnants have X-ray spectra dominated by synchrotron continuum (lines very weak or absent)

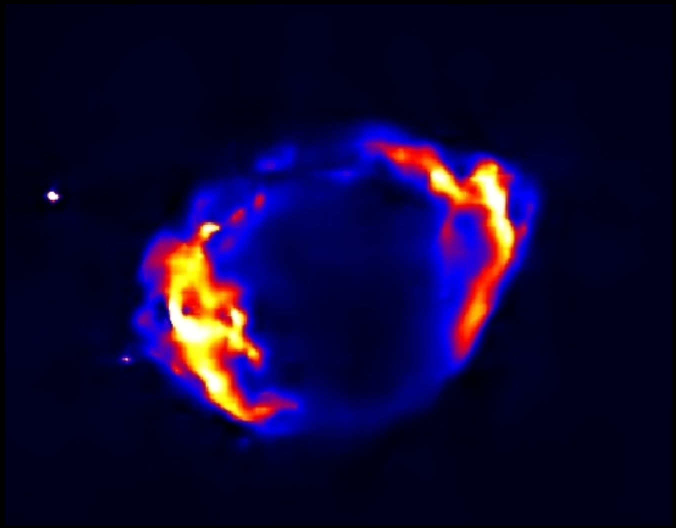
2. Most historical shells have “thin rims” of synchrotron X-rays

3. Most historical shells have hard continua extending above 10 keV in integrated spectra

4. Integrated spectra are well fit by simple models of rolling-off extension of radio spectrum (often indistinguishable from power-laws)

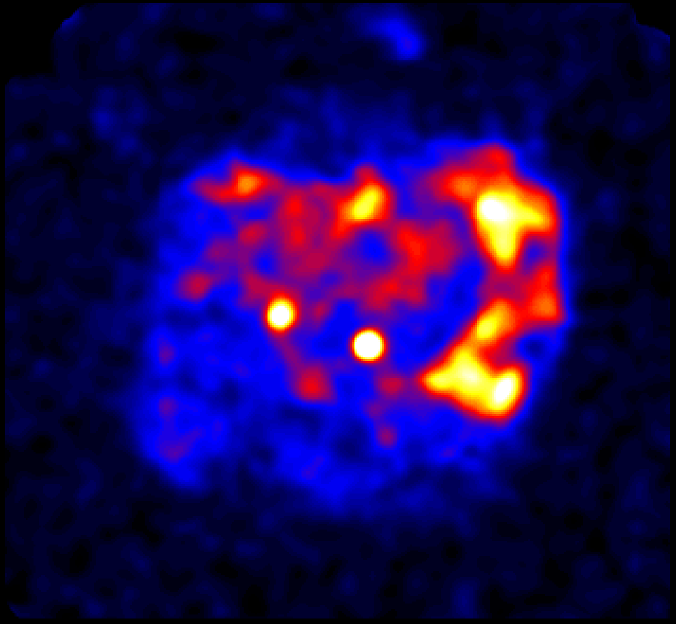
The Big Four: synchrotron X-ray dominated

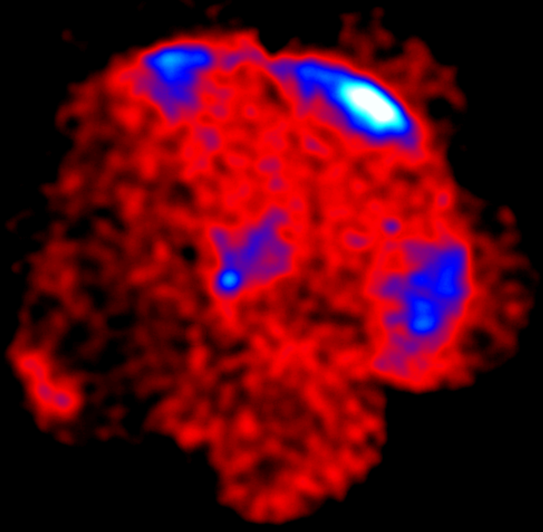
G1.9+0.3:
youngest
SNR!
(Chandra;
Reynolds
et al. 2008)



SN 1006
(Chandra;
CXC)

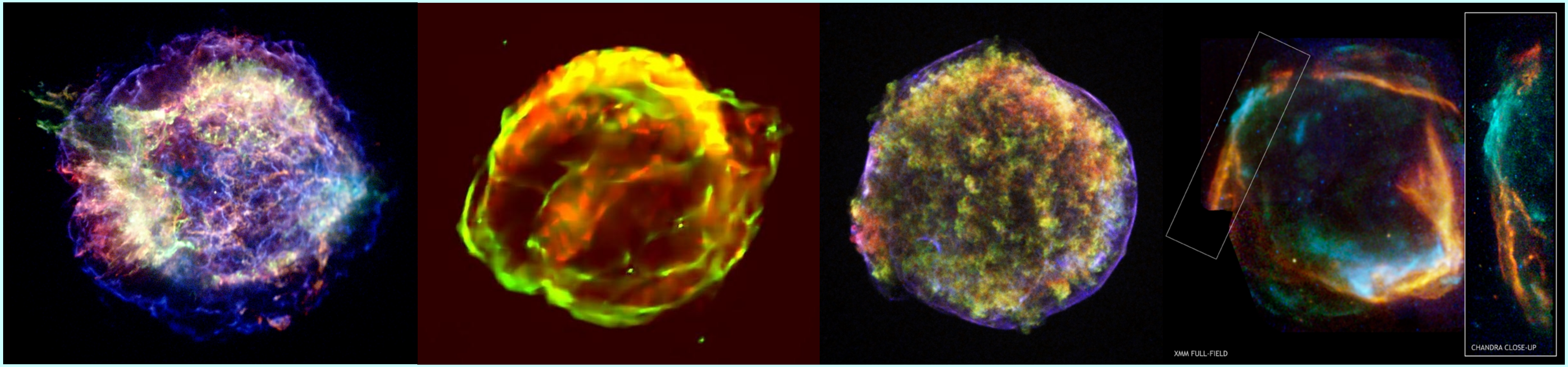
G347.3-0.5
(RX J1713.7-
3946) (ROSAT;
Slane et al.
1999)





G266.2-1.2
("Vela Jr.")
(ASCA;
Slane et al.
2001)

Thin rims, synchrotron components in other SNRs



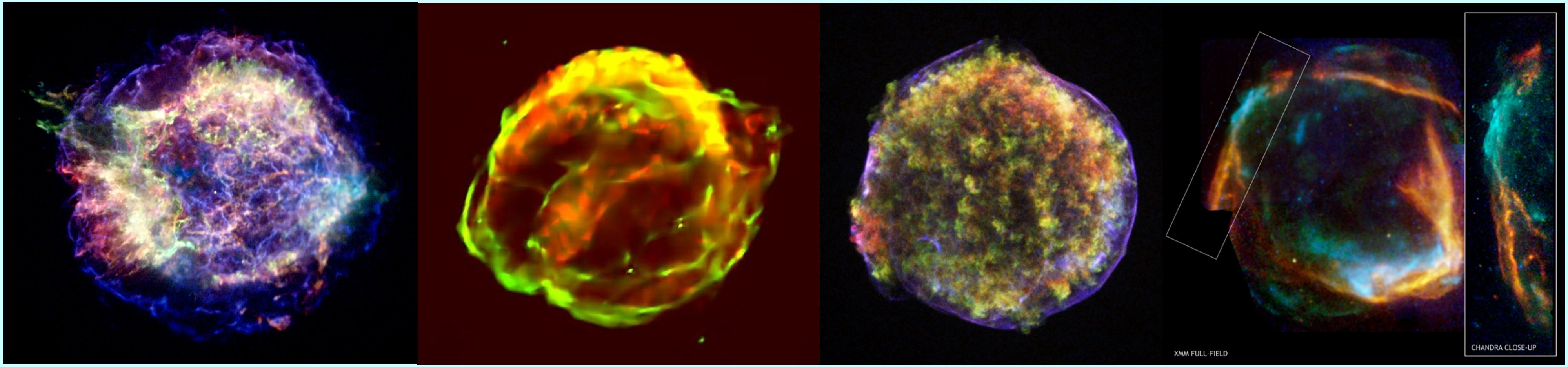
Cas A (SN ~1680)
(Stage et al. 2006)

Kepler (SN 1604)
(Reynolds et al. 2007)

Tycho (SN 1572)
(Warren et al. 2005)

RCW 86 (SN 185?)
(Vink et al. 2008)

Thin rims, synchrotron components in other SNRs

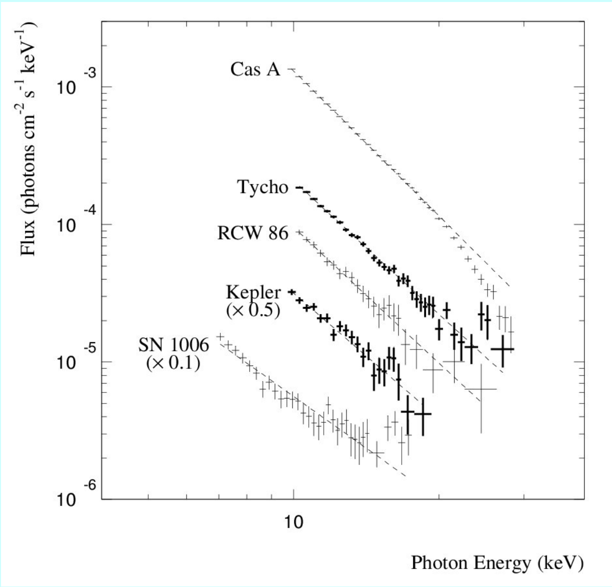


Cas A (SN ~1680)
(Stage et al. 2006)

Kepler (SN 1604)
(Reynolds et al. 2007)

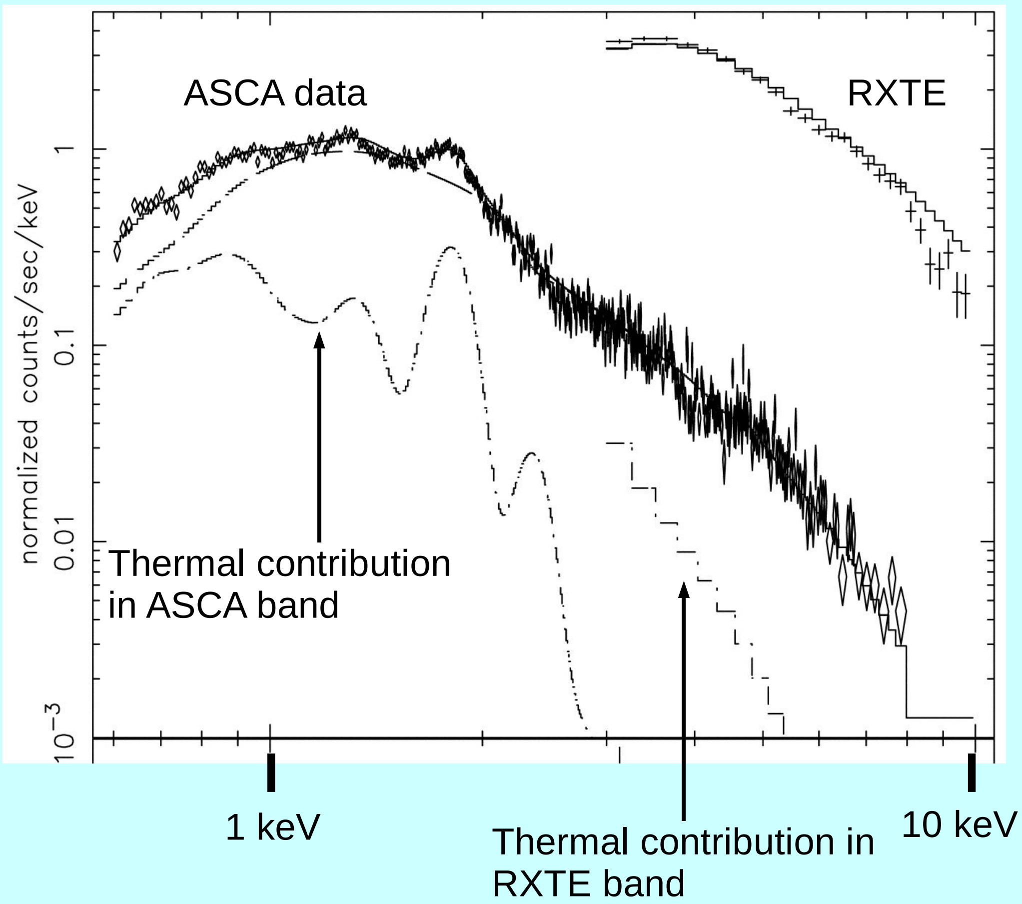
Tycho (SN 1572)
(Warren et al. 2005)

RCW 86 (SN 185?)
(Vink et al. 2008)



Integrated spectra from RXTE PCA of 5 shell SNRs: all show ~ power-law continua above 10 keV (Allen et al. 1999)

Model fit to SN 1006 integrated spectrum

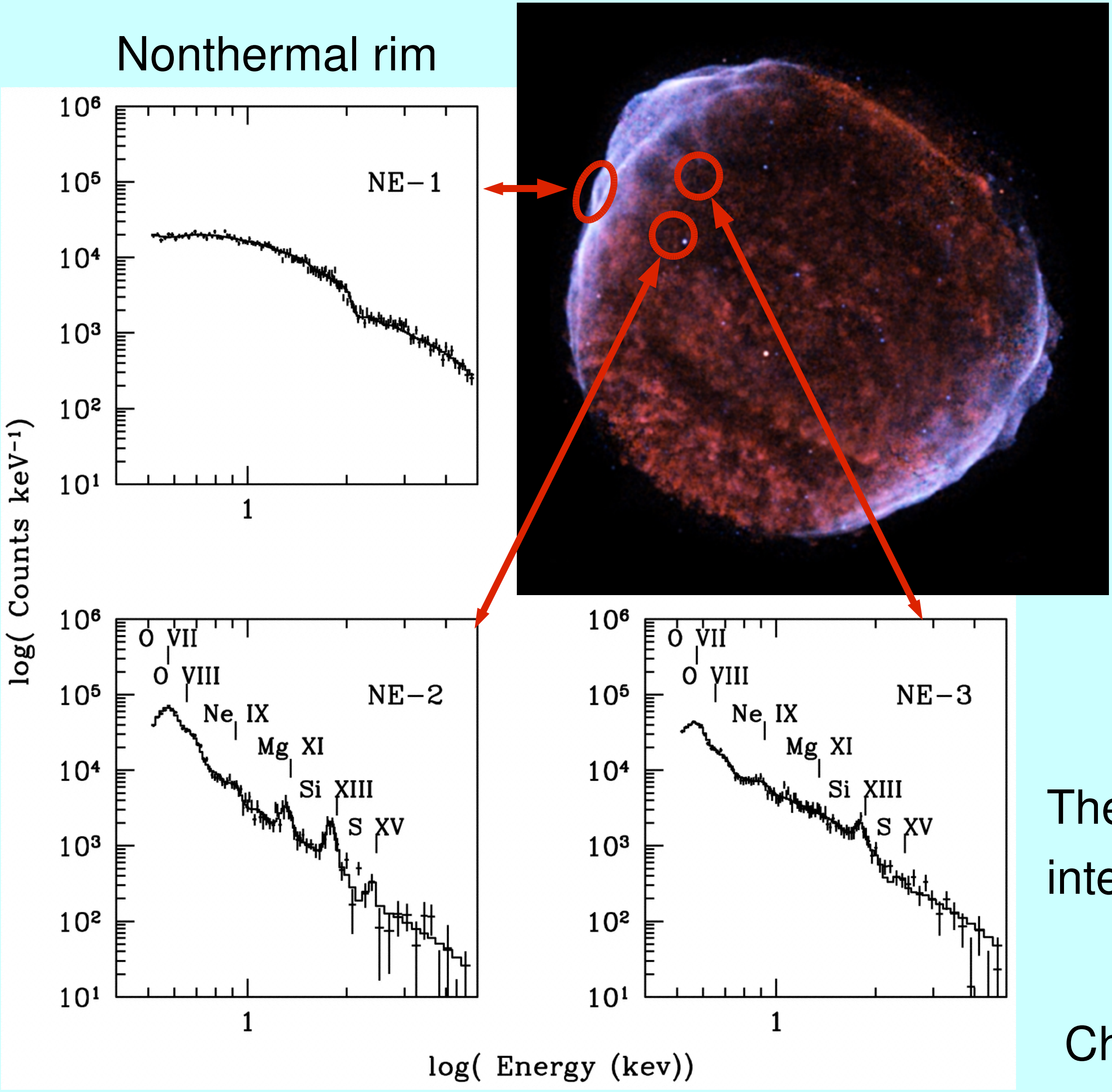


Dyer et al. 2001

Results: Rolloff frequency ~ 3 x 10^{17} Hz (~1.3 keV) gives “maximum” electron energy ~ 30 TeV (*e*-folding energy of exponential cutoff)

Best fit here: Maximum energy set by escape (jump in diffusion coefficient?).

Featureless X-ray spectra



Bright rims: featureless power-laws

Interior: thermal spectrum (prominent O; ejecta. Most Fe not shocked yet)

Thermal interior

Chandra. Long et al. 2003

Maximum energies

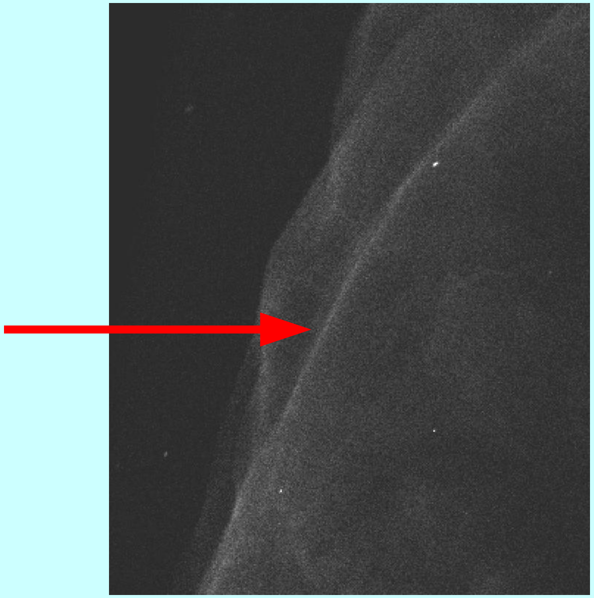
Diffusion: $\kappa \propto$ mfp = ηr_g commonly assumed, so $\kappa \propto 1/B$
Rapid acceleration for high B, v(shock). Cutoffs:

1. age (or size) of remnant: $E_{max} \propto t\, u(\text{shock})^2 B \eta^{-1}$
2. lack of scattering above some λ(MHD): $E_{max} \propto \lambda B$
3. radiative losses: $E_{max} \propto u(\text{shock})\, \eta^{-1/2} B^{-1/2}$

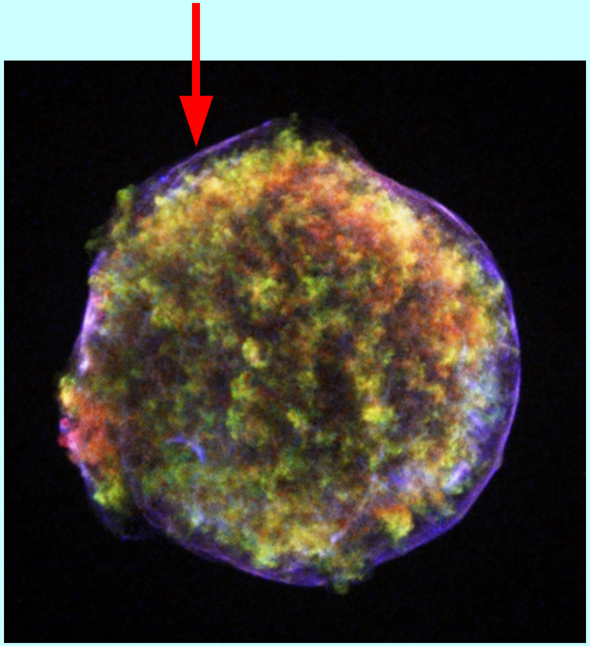
In all cases, easily reach 10 – 100 TeV.

So observing frequency at which spectrum rolls off gives information on remnant properties.

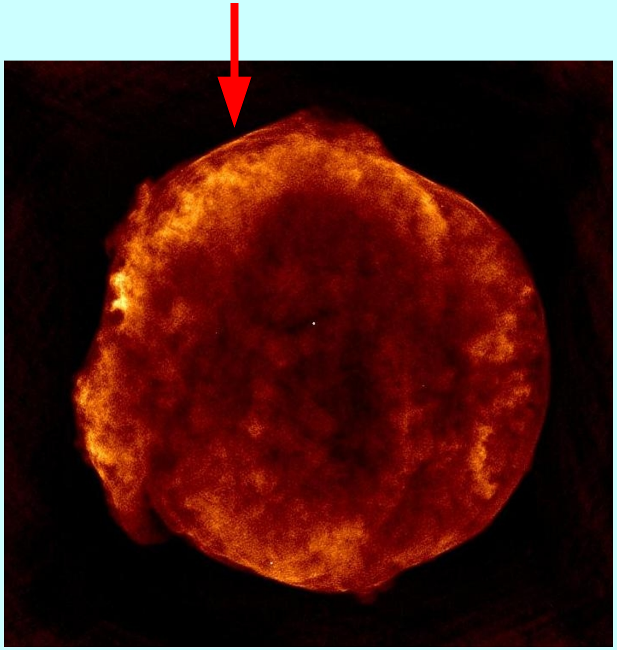
Thin X-ray rims: magnetic-field amplification



SN 1006 (Chandra)



Tycho (Chandra)



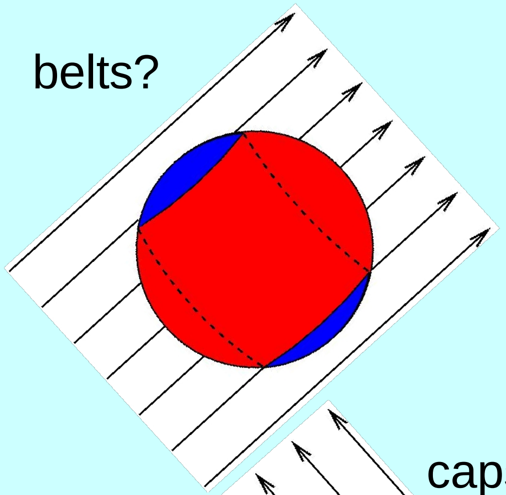
Tycho (radio; VLA)

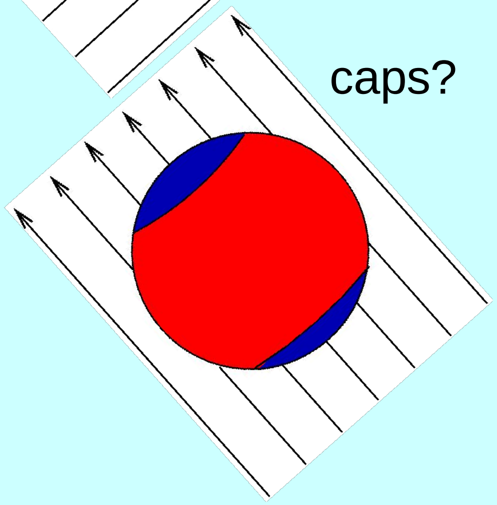
If thickness of rims is due to synchrotron losses, electrons must be depleted rapidly: for observed rim widths w ~ 0.01 pc, need **$B > 200\ (u_{shock}/1000\ \mathrm{km/s})^{2/3}\ (w/0.01\ \mathrm{pc})^{-2/3}\ \mu G$** (without some amplification process, just expect to compress typical interstellar $B \sim 3\ \mu G$ by compression ratio $r \sim 4$).

Similar rims seen in other SNRs (but some rims are thin in radio as well!)

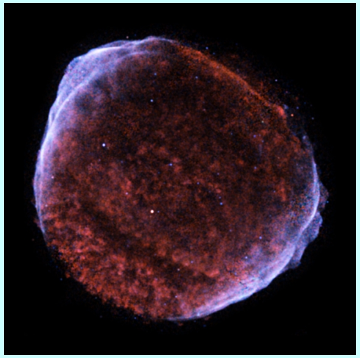
Obliquity dependence: caps or belts?

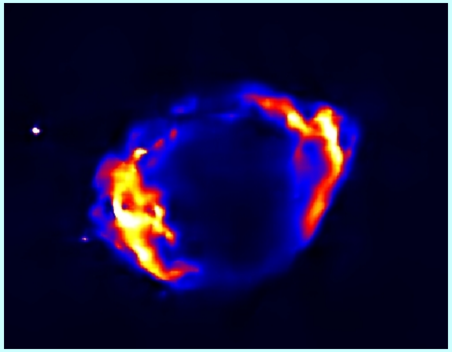
belts?





caps?

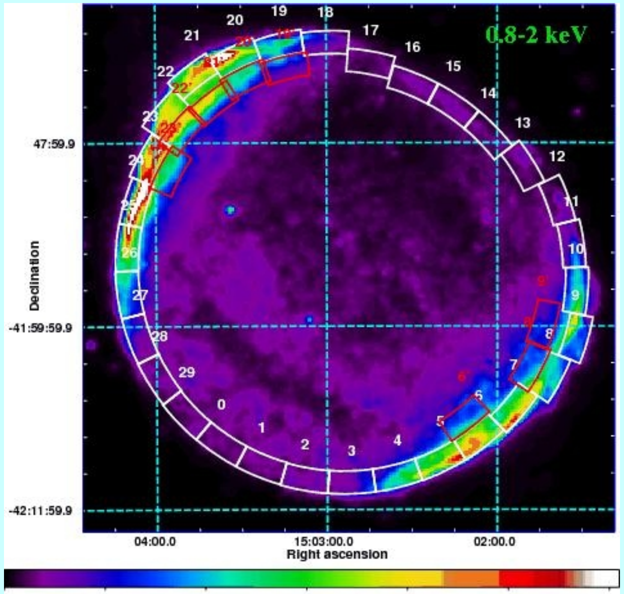


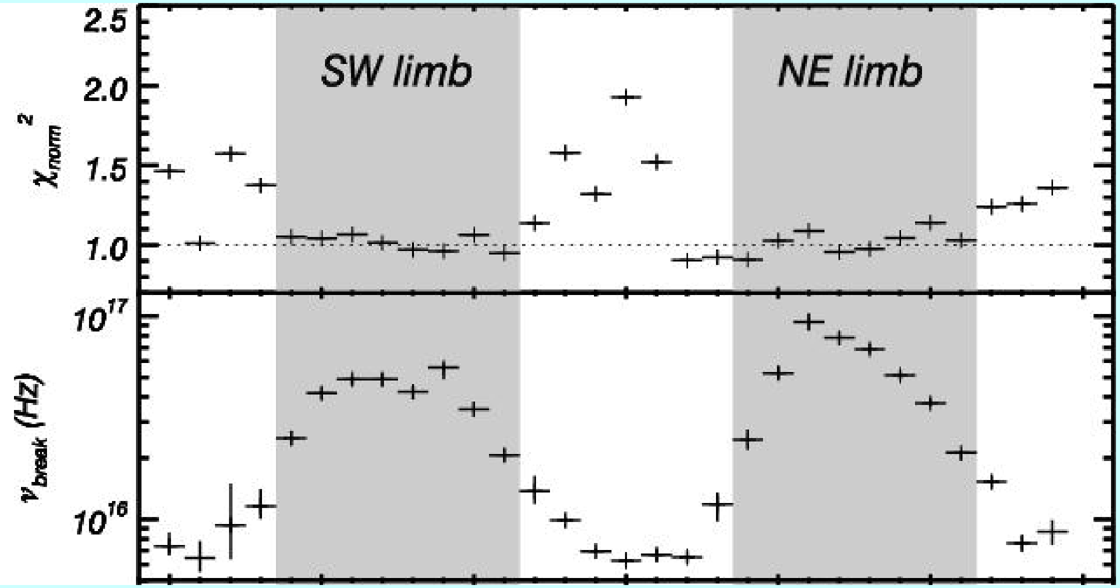


Are bright rims in SN 1006 and G1.9+0.3 due to variations in θ_{Bn} , obliquity angle between shock normal and upstream (undisturbed! ⇒ Type Ia?) magnetic field? If so, are rims caps (θ_{Bn} ~ 0, parallel shocks) or belts (θ_{Bn} ~ 90˚, perpendicular)?

Morphological evidence (Rothenflug et al. 2004, Orlando et al. 2009) supports caps for SN 1006. (But what would end-on view look like?) Both SN 1006 and G1.9+0.3: higher rolloff frequencies in caps. What increases acceleration rate for electrons? (Frequency radiated by electrons with loss-limited E_{max} is independent of B!)

Variation of rolloff frequency with azimuth

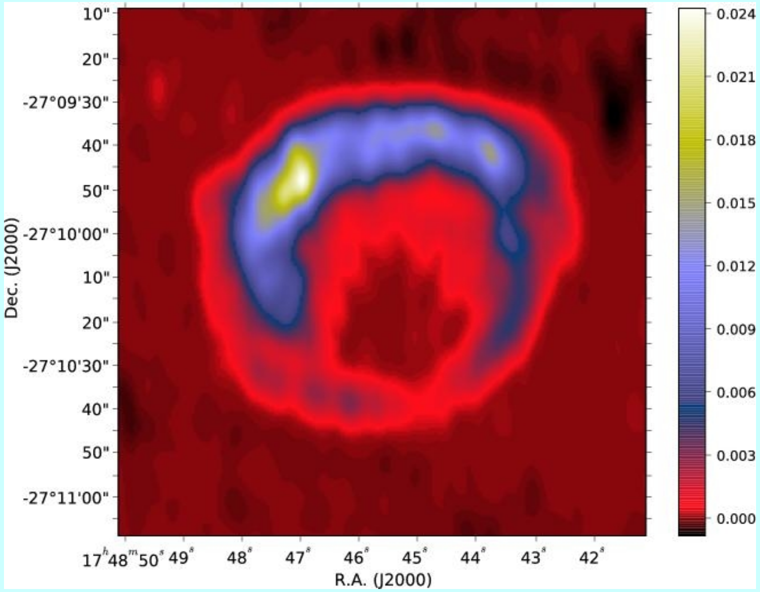




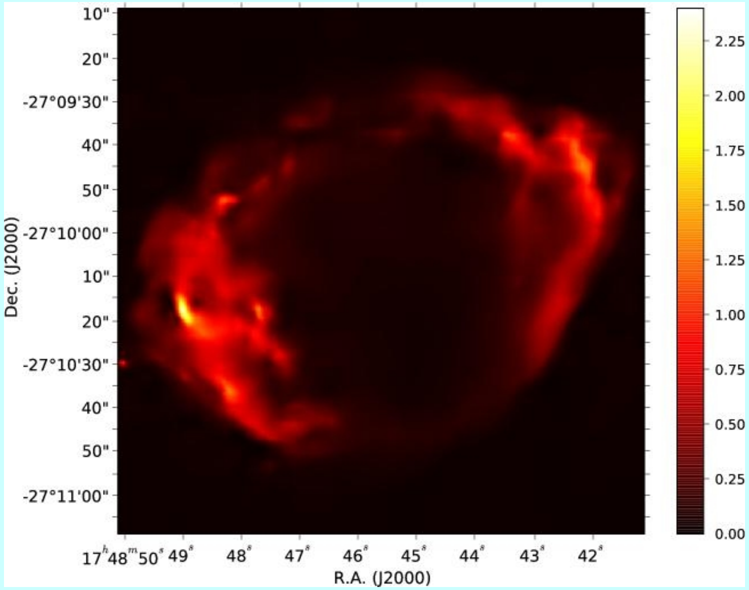
Miceli et al. 2009 A&A, 501, 239: *XMM-Newton* data

Rolloff frequency varies by factor ~10; highest where rims are brightest

G1.9+0.3: the youngest Galactic SNR



Radio (VLA 1985)



Chandra (2007) (platelet smoothed)

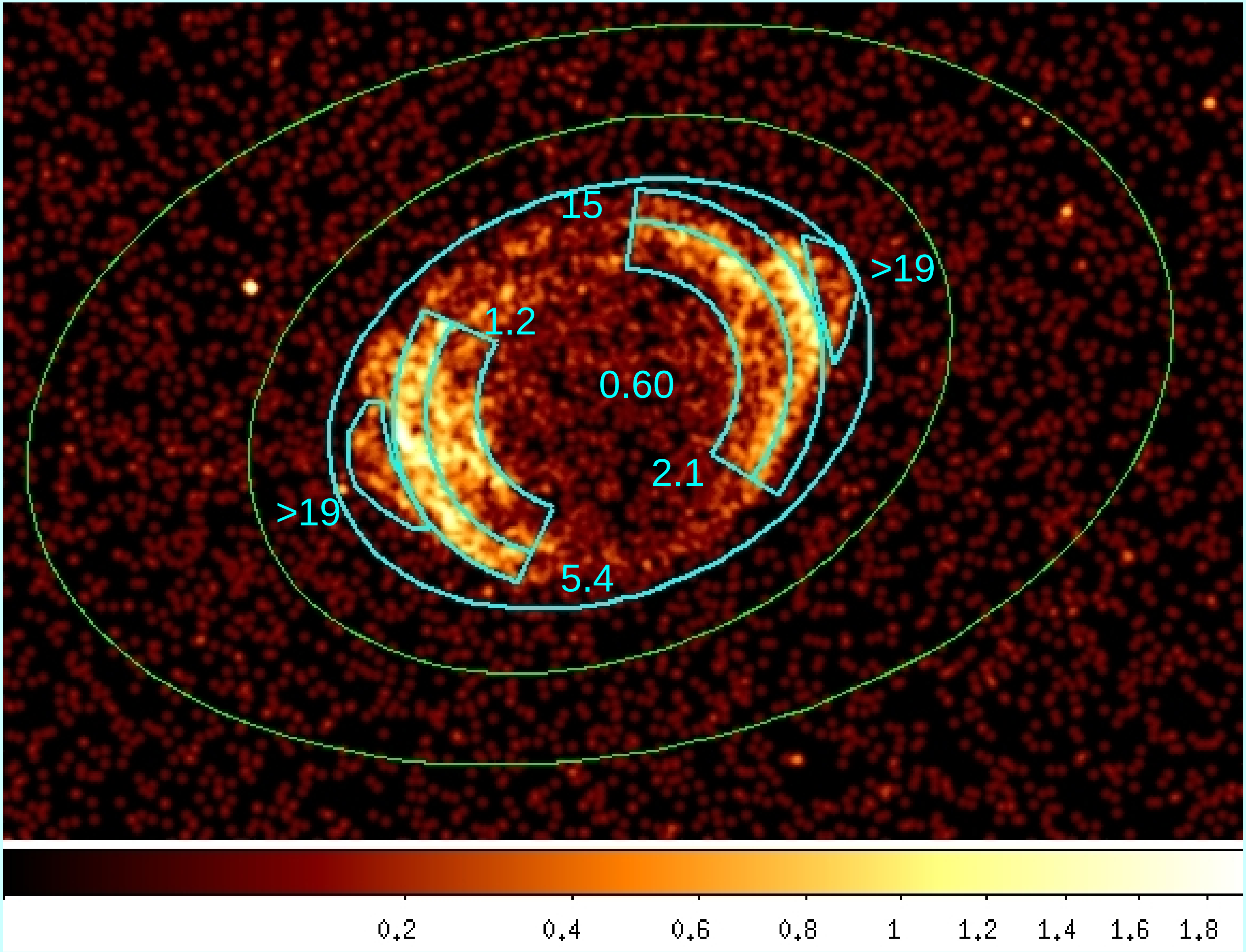
Angular diameter ~ 100". Radio flux (1 GHz) ~ 0.9 Jy; $\alpha \sim -0.65$.

Discovered in search for young SNRs (Green & Gull 1984).

2007 Chandra observation compared with 1985 radio observation:

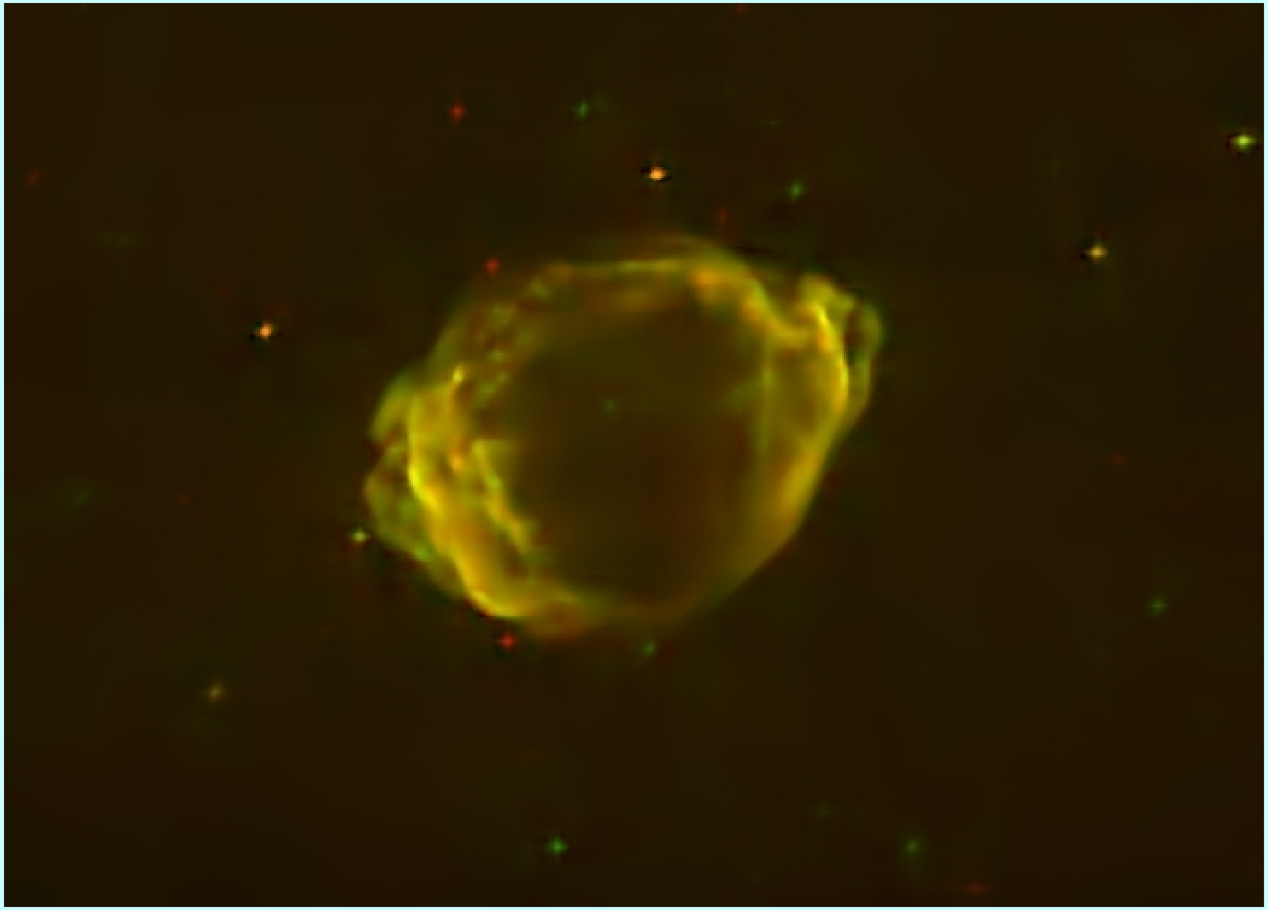
X-ray size larger by 16%! Age < 140 yr (~ 100 yr with deceleration)!

X-ray Spectral Variations



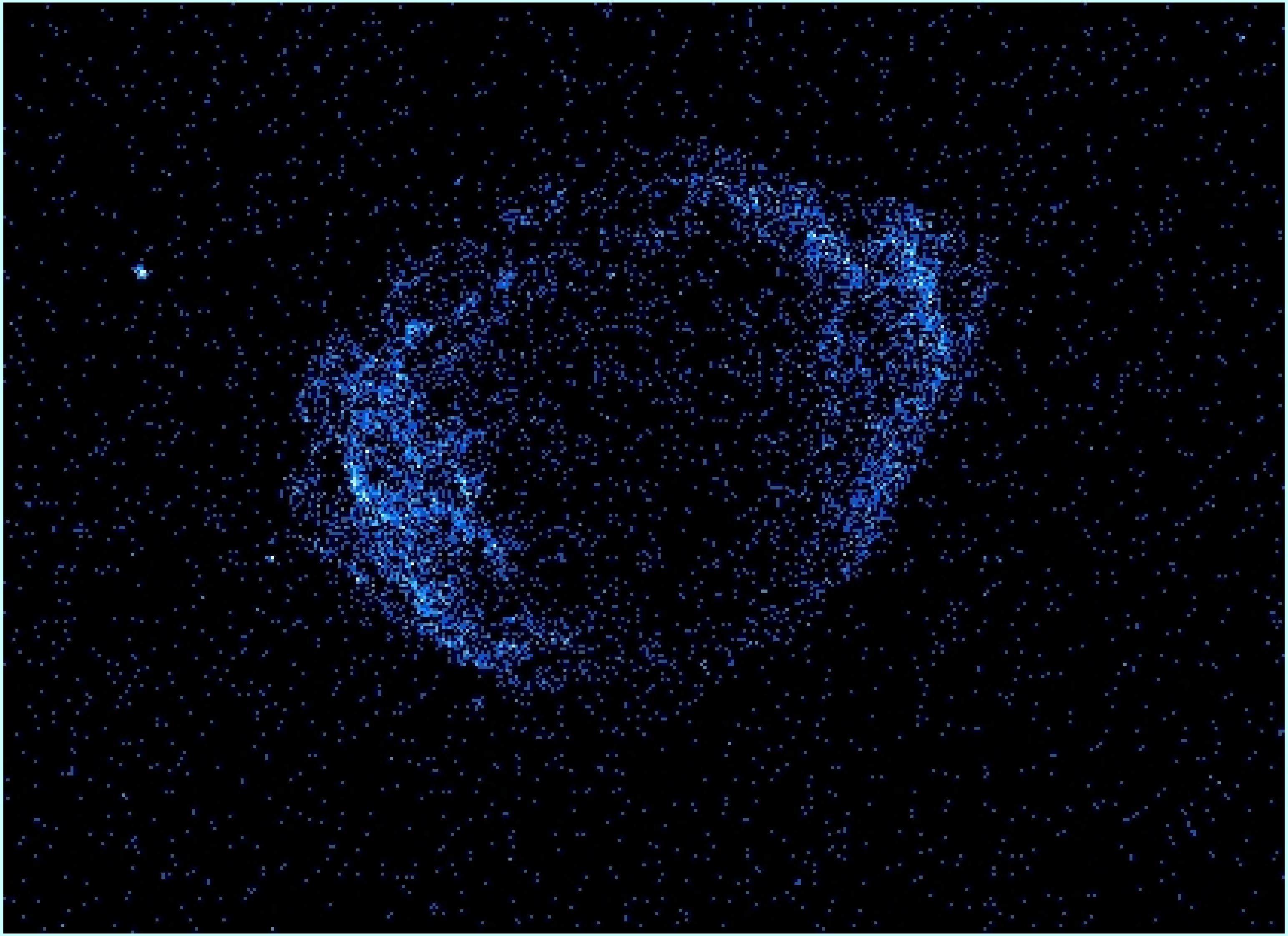
Break frequency increases outward along the bipolar X-ray axis

Two-color 2009 Chandra Image



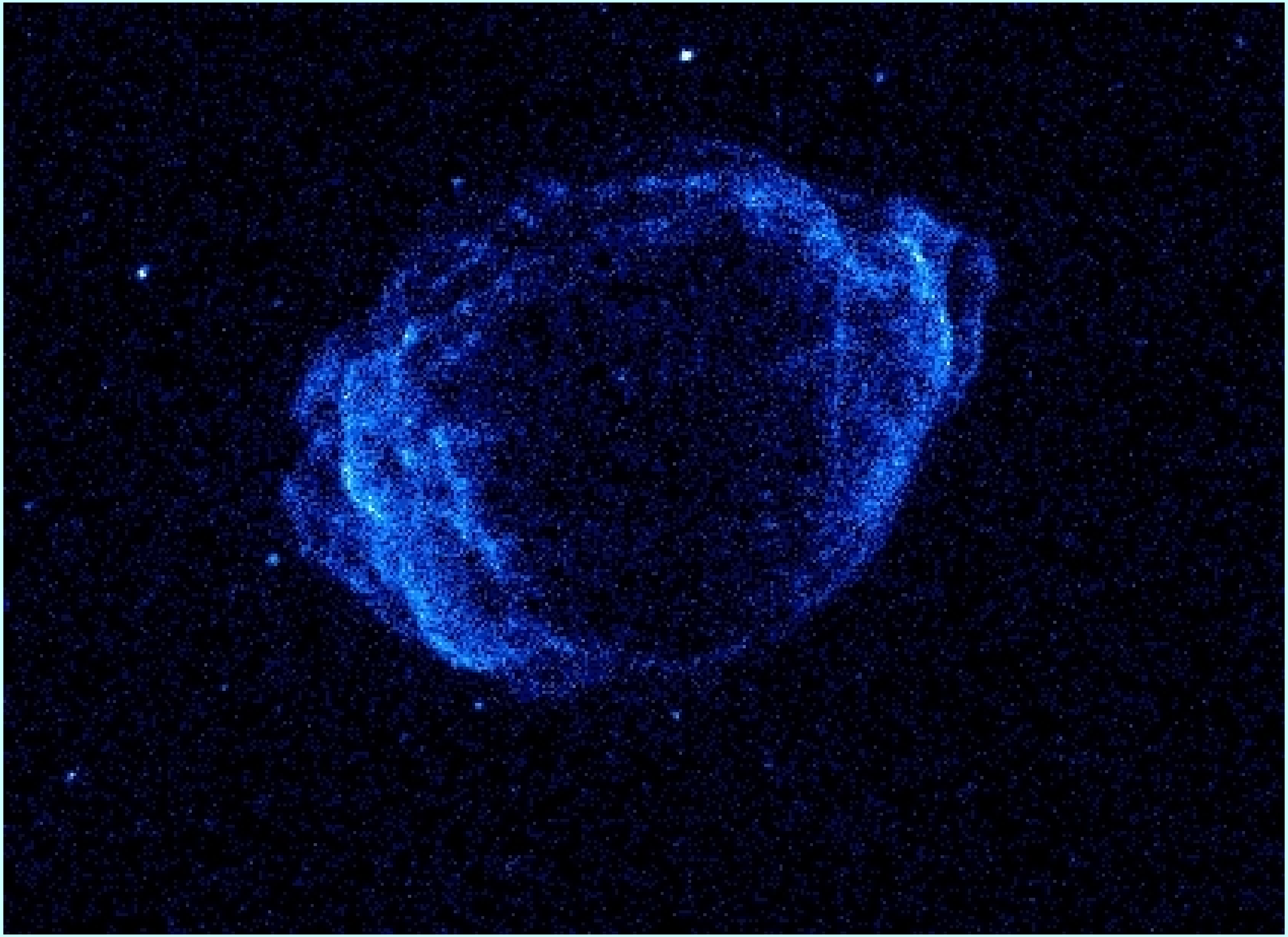
Red: 1-3.5 keV, Green: 3.5-7 keV. Spectral variations are apparent

2007



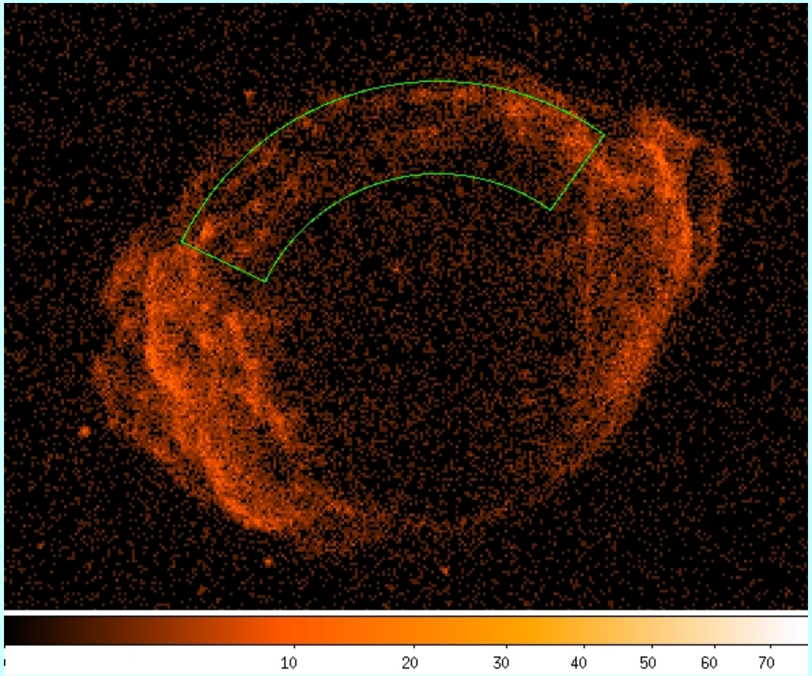
smaller

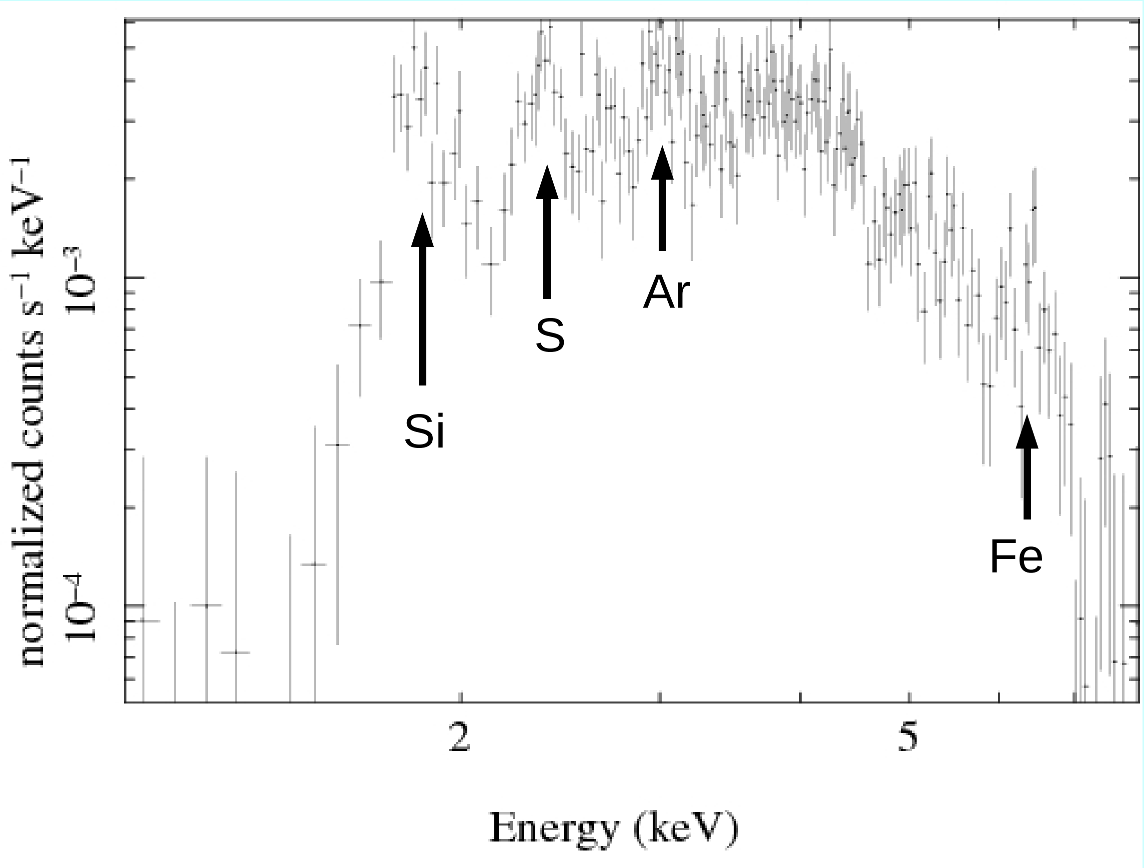
2009



bigger

Thermal X-ray emission: powerful diagnostics





See He-like states of Si, S, Ar, Ca. Very strong Fe K: width 26,000 km/s!

Deeper observations can further constrain shock velocity, density

Problem: Azimuthal variations in rolloff

1. Observations: In both SN 1006 and G1.9+0.3, *wide range* of rolloff frequencies, higher in brighter regions.
2. Best explanation for bilateral symmetry in either: magnetic obliquity variations (so G1.9+0.3 must also be Type Ia!)
3. Loss-limited electron acceleration has rolloff *independent of B*

So how is the observed factor ~ 10 variation in rolloff with azimuth produced?

Brightness variations can be produced by varying *B*; expect θ_{Bn} dependence of magnetic-field amplification in nonlinear models

Rolloff variations require variations in *acceleration rate*

Rolloff frequencies

$$h\nu_{\rm roll}({\rm age}) \sim 0.4 \left(\frac{u_{\rm sh}}{3000 \ {\rm km \ s^{-1}}}\right)^4 \left(\frac{t}{1000 \ {\rm yr}}\right)^2 \left(\frac{B}{10 \ \mu{\rm G}}\right)^3 (\eta R_J)^{-2} \ \text{keV}$$

$$h\nu_{\rm roll}({\rm loss}) \sim 2 \left(\frac{u_{\rm sh}}{3000 \ {\rm km \ s^{-1}}}\right)^2 (\eta R_J)^{-1} \ \text{keV} \quad \textit{independent} \text{ of } B!$$

$$h\nu_{\rm roll}({\rm esc}) \sim 2 \left(\frac{B}{10 \ \mu{\rm G}}\right)^3 \lambda_{17}^2 \ \text{keV}$$

Here $R_J(\theta_{\rm Bn}, \eta, r) \equiv \tau_{\rm acc}(\theta_{\rm Bn})/\tau_{\rm acc}(\theta_{\rm Bn} = 90^\circ)$.

Operative value from loss mechanism giving lowest $E_{\rm max}$

Origin of acceleration-rate variations

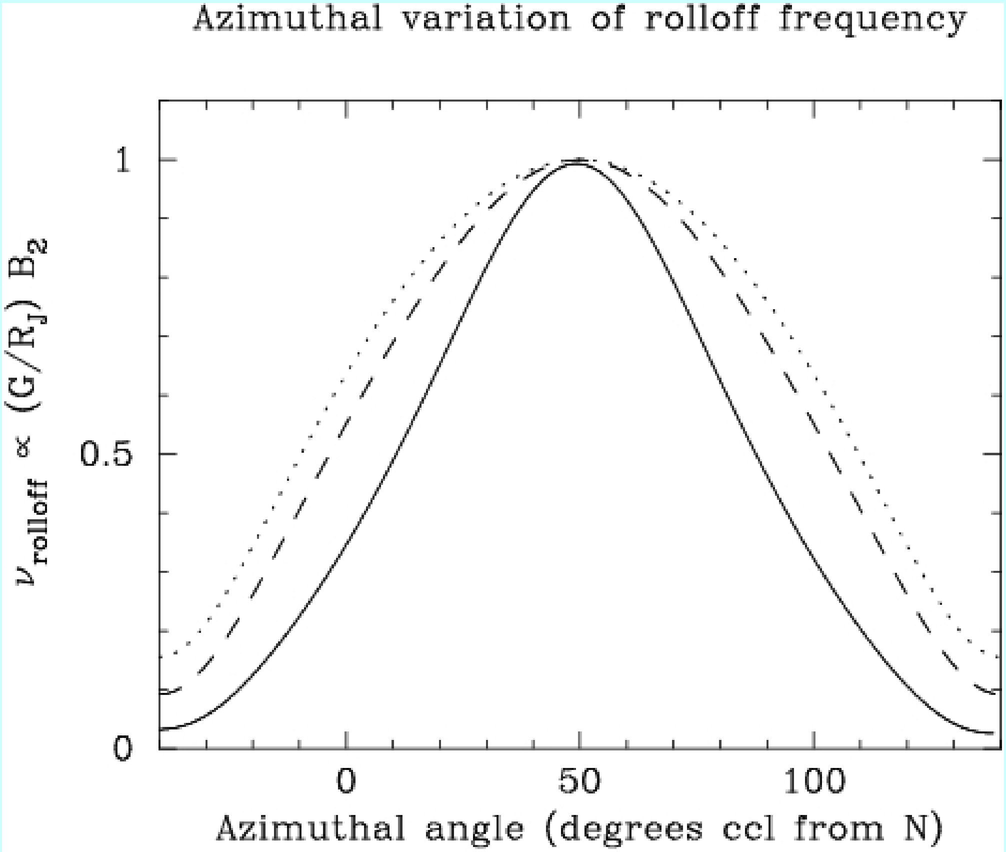
$\tau(\text{acc}) \propto \kappa \propto \eta r_g c/3$ along B
Across B: effective mfp ~ r_g

Combine:
$\kappa \propto [\eta r_g c/3](\cos^2\theta_{Bn} + \sin^2\theta_{Bn}/(1+\eta^2))$.

(As η rises, slow parallel acceleration compared to perpendicular, which is always Bohm)

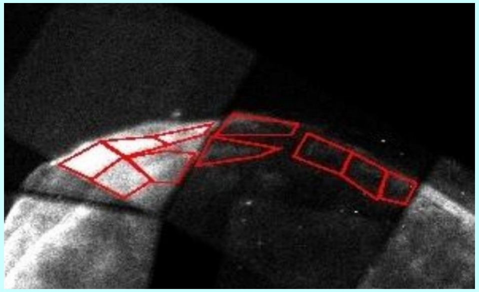
Further: different residence times in preshock and postshock regions gives additional θ_{Bn}-dependence as well as dependence on compression ratio *r*, magnetic field *B*

Can easily achieve factor 10 variation with θ_{Bn}, even for modest departures of gyrofactor η from 1.

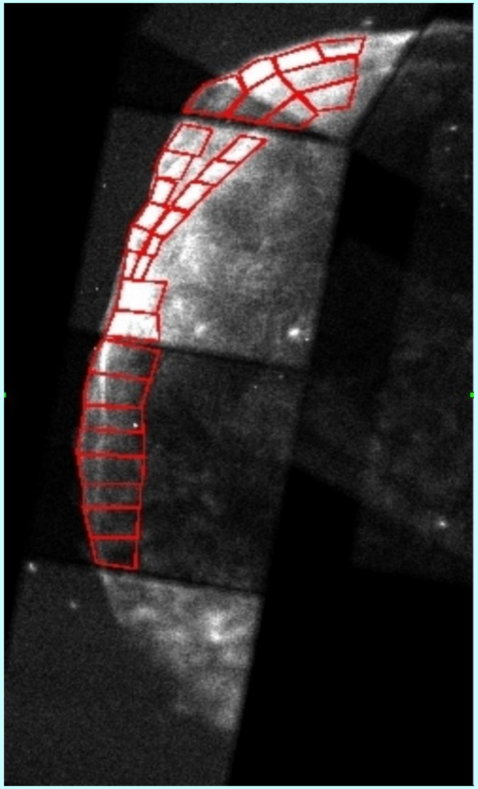


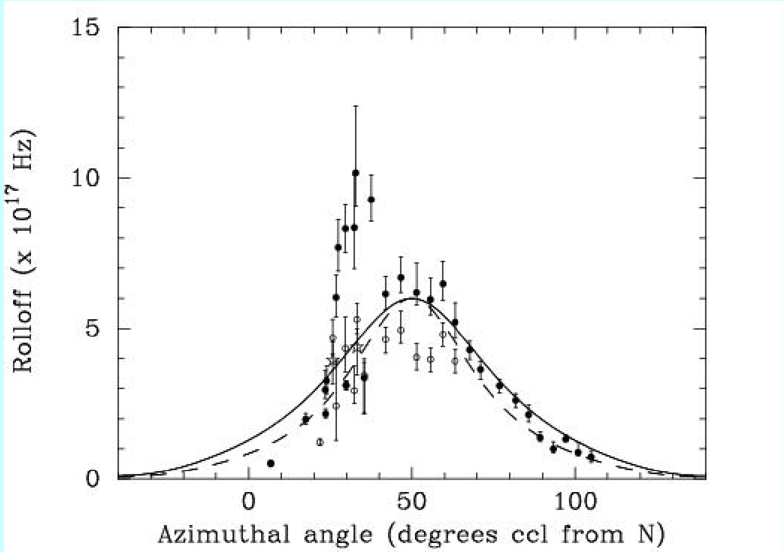
Loss−limited models. Gyrofactor $\eta = 2$.
Solid line, $B_1 = 1\ \mu G$, dashed, $B_1 = 3.2\ \mu G$,
dotted, $B_1 = 10\ \mu G$

Modeling azimuthal variations in SN 1006



SN 1006: dependence of rolloff frequency on azimuthal position (McFarland, SPR, Borkowski, 2004 HEAD)





Filled circles: outer rim. Open circles: inner filaments.
Open stars: intermediate regions.
Loss−limited models: solid line, η = 2; dashed, η = 3

Models: loss-limited, more rapid acceleration where shock is perpendicular

Describes inner shell well

NE “extension”: higher rolloff values

Loss-limited acceleration: rolloff frequency is *independent* of *B*

Another explanation?

Previous explanation requires well-ordered *B* upstream, “belts” in SN 1006, efficient *injection* where shock is perpendicular (radio is brightest there too!)

But: If electron acceleration is not loss-limited, *B* dependence can produce the higher rolloffs in rims which can again be caps. Correlation with brightness is naturally explained.

Consequences:

1. The inferred E_{max} ~ 30 TeV applies to ions too!
2. Thin rims must now be produced by some kind of decay away of mean *B*.

Conclusions

1. Spatial structure of synchrotron X-rays contains important information on the physics of shock acceleration and magnetic-field amplification.

Conclusions

1. Spatial structure of synchrotron X-rays contains important information on the physics of shock acceleration and magnetic-field amplification.
2. “Thin rims” may require disappearance of B as well as of electrons (due to losses).

Conclusions

1. Spatial structure of synchrotron X-rays contains important information on the physics of shock acceleration and magnetic-field amplification.
2. “Thin rims” may require disappearance of *B* as well as of electrons (due to losses).
3. Bilateral symmetry of nonthermal X-rays in SN 1006 and G1.9+0.3 is most easily explained by obliquity variations as shock encounters roughly uniform *B*.

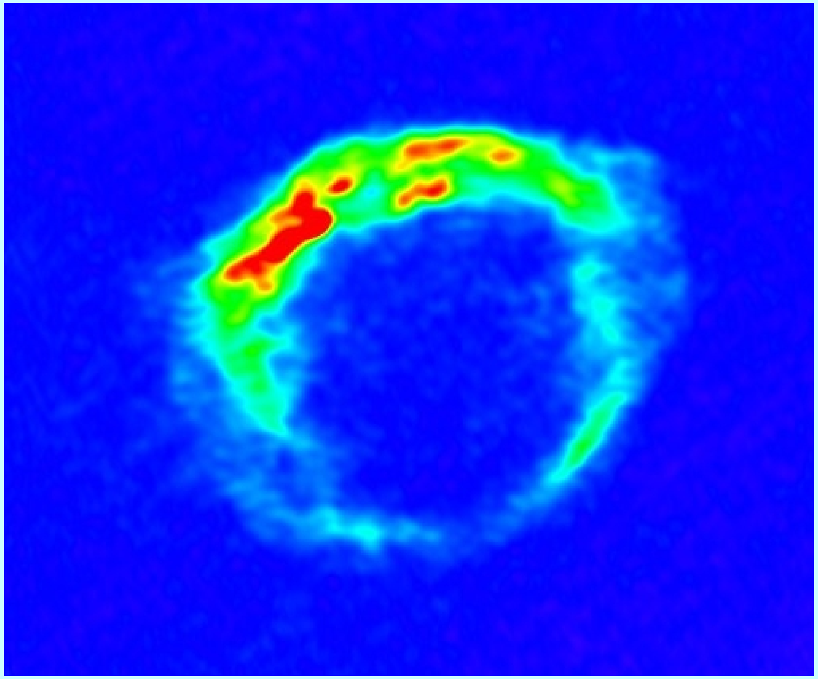
Conclusions

1. Spatial structure of synchrotron X-rays contains important information on the physics of shock acceleration and magnetic-field amplification.
2. “Thin rims” may require disappearance of *B* as well as of electrons (due to losses).
3. Bilateral symmetry of nonthermal X-rays in SN 1006 and G1.9+0.3 is most easily explained by obliquity variations as shock encounters roughly uniform *B*.
4. Observed azimuthal variations in rolloff cannot be explained by variations in *B* if electron acceleration is loss-limited. One source of possible dependence requires fairly ordered *B* upstream and gyrofactor somewhat > 1. This gives faster acceleration where shock is *perpendicular.*

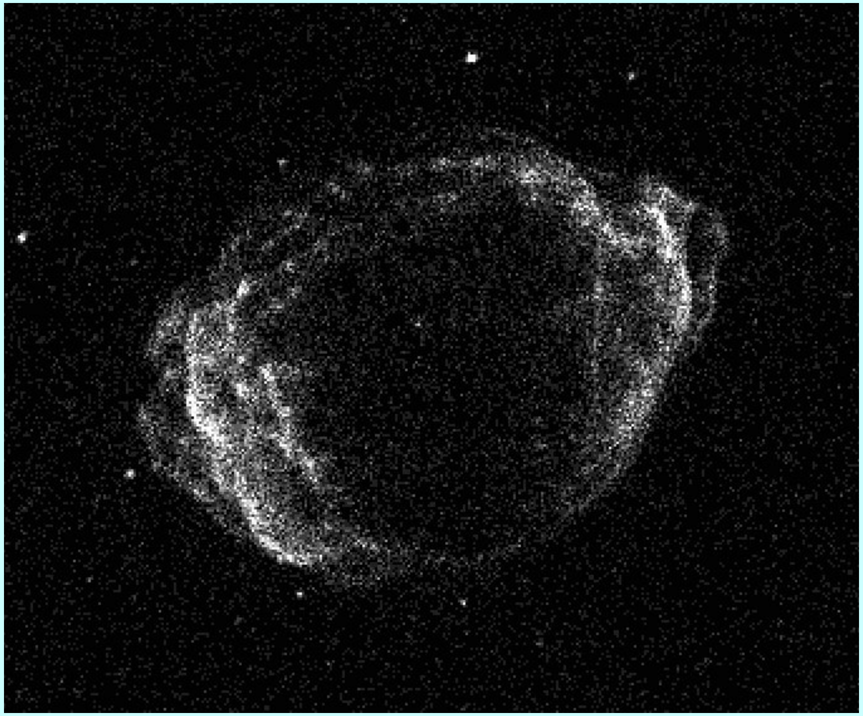
Conclusions

1. Spatial structure of synchrotron X-rays contains important information on the physics of shock acceleration and magnetic-field amplification.
2. "Thin rims" may require disappearance of *B* as well as of electrons (due to losses).
3. Bilateral symmetry of nonthermal X-rays in SN 1006 and G1.9+0.3 is most easily explained by obliquity variations as shock encounters roughly uniform *B*.
4. Observed azimuthal variations in rolloff cannot be explained by variations in *B* if electron acceleration is loss-limited. One source of possible dependence requires fairly ordered *B* upstream and gyrofactor somewhat > 1. This gives faster acceleration where shock is *perpendicular.*
5. Comparison of radio and X-ray imaging data can allow separation of *injection* effects from *rate* effects.

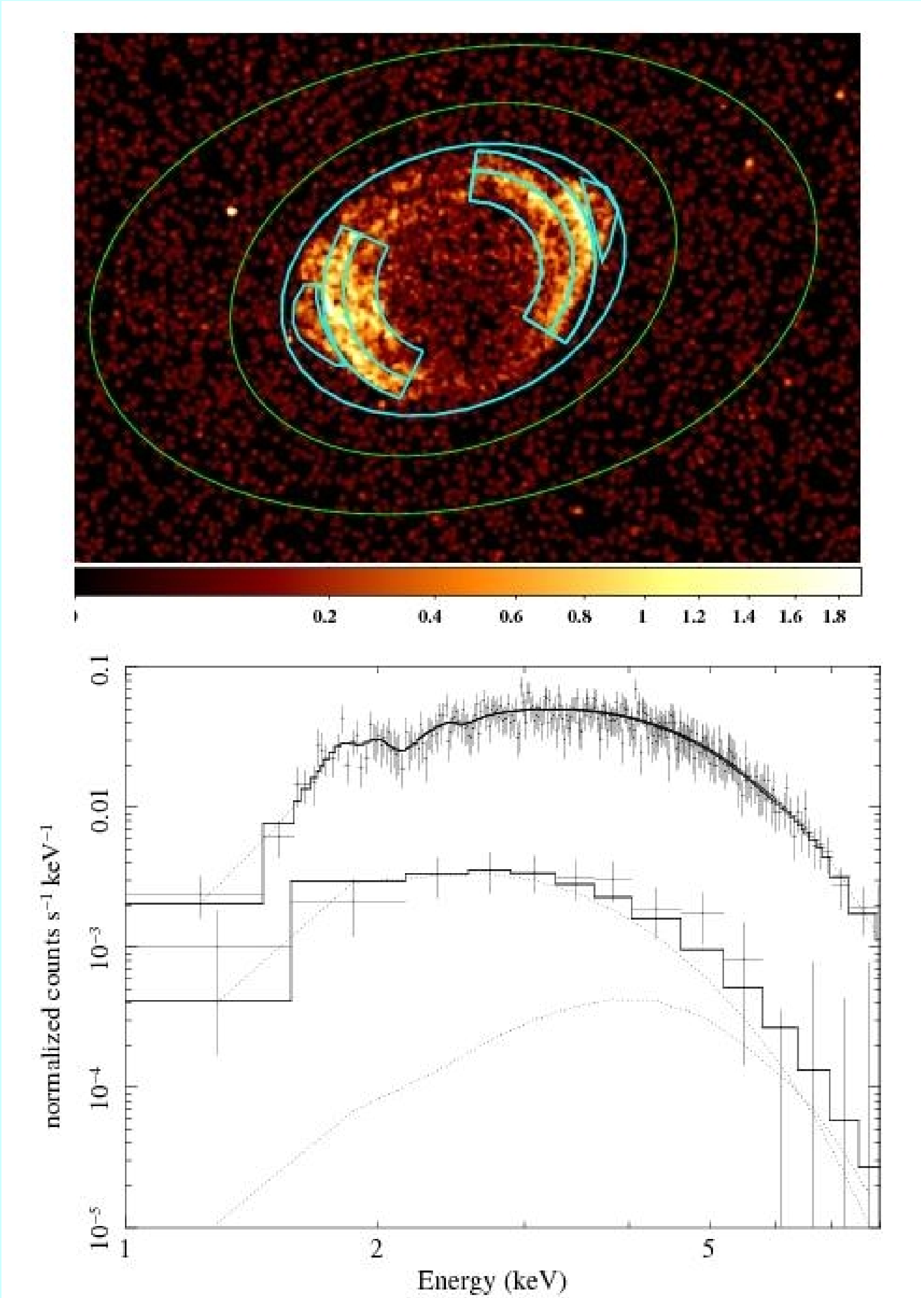
New observations of G1.9+0.3



VLA (1.4 GHz, resolution 2”)



Chandra (250 ks observation; 1 – 7 keV)



Integrated spectrum as seen by Chandra

Spatially resolved spectral analysis of G1.9+0.3:

Bright shell has higher rolloff (as in SN 1006). Rolloff drops both around shell and toward interior.

Power-law fits $F \propto E^{-\Gamma}$ show same effect: (low $\Gamma \leftrightarrow$ high rolloff)

E(out)	E(in)	center, faint rims	W(in)	W(out)
2.2	2.6	2.8	2.4	2.1

Highest rolloffs in “ears”, $\Gamma \sim 2.0$.

Original observation limited in statistics; much longer observation currently being analyzed