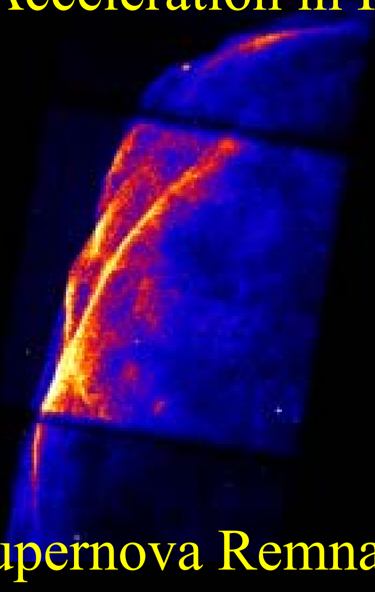
Particle Acceleration in Plerions

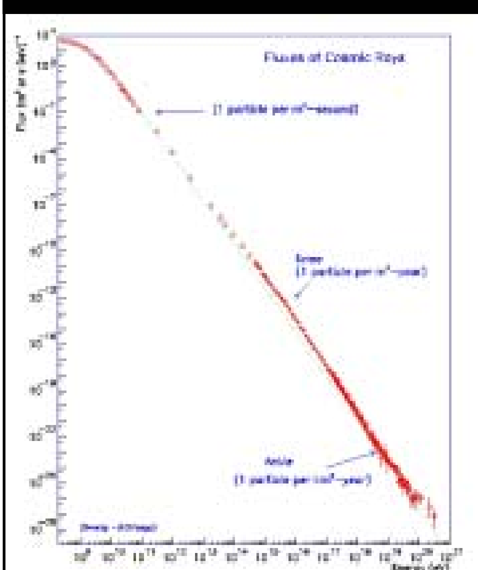


Collaborators:

Jack Hughes
Bryan Gaensler
Don Ellison
David Helfand
Steve Murray
Paul Plucinsky
Jasmina Lazendic
Steve Reynolds
and others…

and Supernova Remnants

Cosmic Rays and SNRs



- **Power law spectrum:**

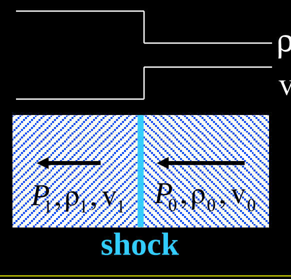
$$dN(E) \propto E^{-2.5} dE$$

  - **spectrum extends beyond** 10^{20} eV
  - **"knee" at** 10^{15} eV **- different origin?**
- **Energy density** $U_{cr} \approx 10^{-12}$ erg cm^{-3}
- **What is their origin?**
  - **gyroradius is small**

$$r_g = \frac{p}{eB} \approx 10^{-3} E_{TeV} B_{\mu G}^{-1} \text{ pc}$$

  - **direction "lost" for most particles**
  - **shocks observed in heliosphere give us a clue**

Shocks in SNRs



- Expanding blast wave moves supersonically through CSM/ISM; creates shock
  - mass, momentum, and energy conservation across shock give (with γ=5/3)

$$\rho_1 = \frac{\gamma+1}{\gamma-1}\rho_0 = 4\rho_0$$

$$v_1 = \frac{\gamma-1}{\gamma+1}v_0 = \frac{v_0}{4}$$

$$v_{ps} = \frac{3v_s}{4}$$

$$T_1 = \frac{2(\gamma-1)}{(\gamma+1)^2}\frac{\mu}{k}m_H v_0^2 = 1.3\times10^7 v_{1000}^2 \text{ K}$$

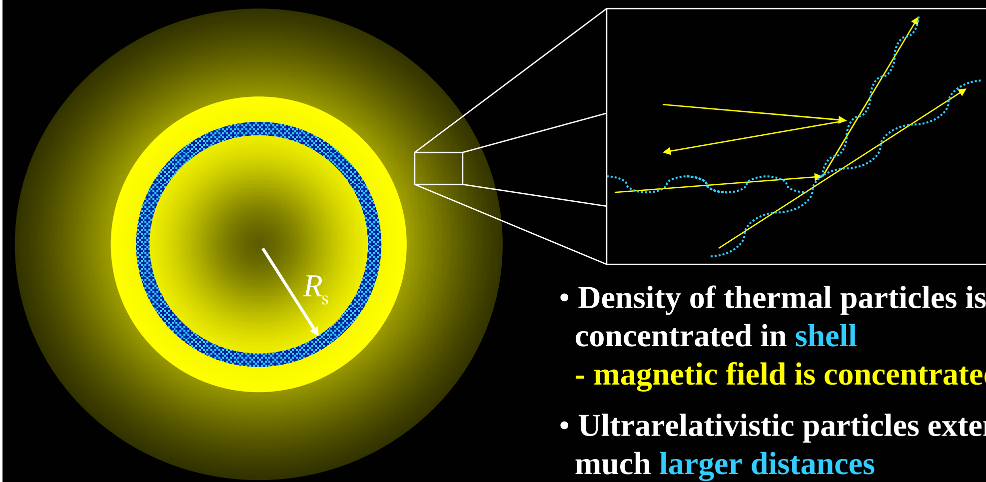
X-ray emitting temperatures

- Shock velocity gives temperature of gas
  - note effects of electron-ion equilibration timescales
- If another form of pressure support is present (e.g. cosmic rays), the temperature will be lower than this

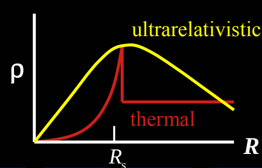
Diffusive Shock Acceleration

- Particles scatter from MHD waves in background plasma
  - pre-existing, or generated by streaming ions themselves
  - scattering mean-free-path $\lambda \propto r_g (\propto p)$
    (i.e., most energetic particles have very large λ and escape)
- Maximum energies determined by either:
  - age – finite age of SNR (and thus of acceleration)
  - escape – scattering efficiency decreases w/ energy, allowing escape
  - radiative losses – synchrotron or inverse-compton
- Produces power law particle spectrum with spectral index ~2
  - process highly nonlinear; if acceleration efficiency is high, impact on thermal gas is large, possibly enhancing acceleration
- SNRs have the energy to yield the cosmic rays in this way:

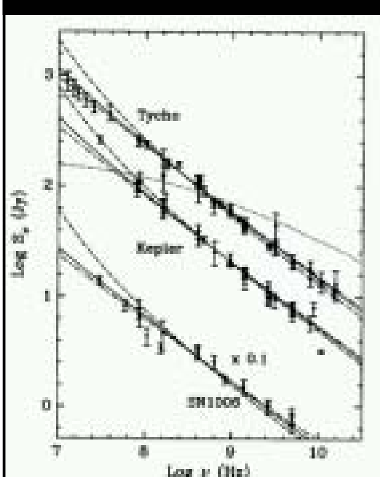
$$U = \frac{t_{esc}}{t_{SN}}\frac{fE_{SN}}{V} = \frac{30\text{yr}}{10^6\text{ yr}}\frac{f(10^{51}\text{erg})}{5\times10^{66}\text{cm}^3} = U_{CR} \text{ for } f = 0.1$$



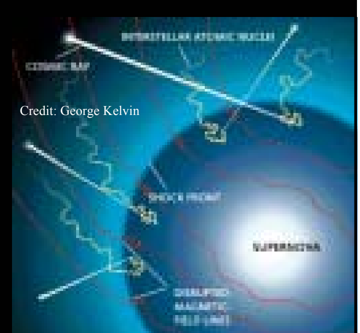
- **Density of thermal particles is concentrated in shell**
  - **magnetic field is concentrated here**
- **Ultrarelativistic particles extend to much larger distances**
  - **upstream scattering is from self-generated waves**
- **Synchrotron emission is confined to magnetic field region**



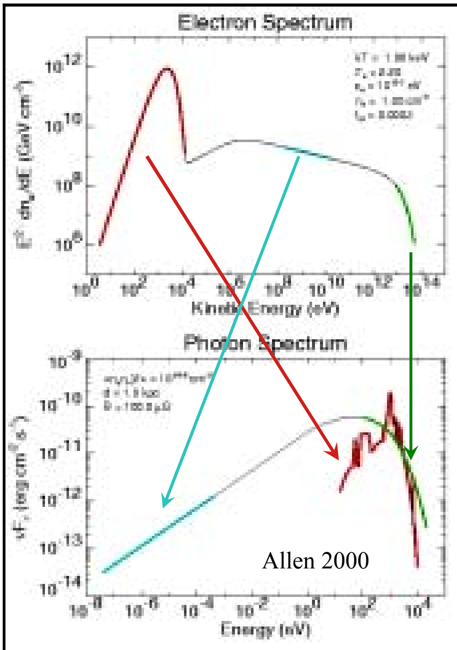
Radio Emission from SNRs



- **Synchrotron Radiation:** $E_{GeV} = \left[\frac{\nu}{16\text{MHz}} B_{\mu G}^{-1} \right]^{1/2}$
  - **for typical fields, radio emission is from GeV electrons**
    >>Hint: for X-rays, $\nu \geq 10^{18} \longrightarrow$ **>TeV electrons**
  - **PL spectra imply PL particle spectrum**
    $dN = KE^{-\gamma} dE$
    gives
    $f_\nu \propto \nu^{\left(-\frac{\gamma-1}{2}\right)}$
  - **shell-type SNRs have**
    $f_\nu \propto \nu^{(-0.6)}$

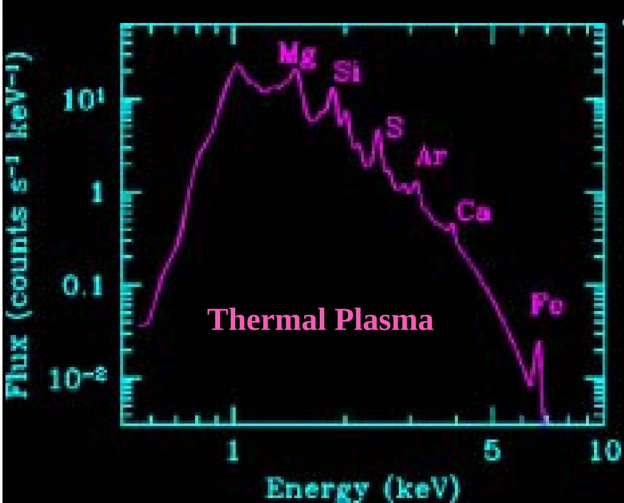


$\therefore \gamma = 2.2$ **similar to CR spectrum**



- Thermal electrons produce line-dominated x-ray spectrum with bremsstrahlung continuum
  - yields kT, ionization state, abundances
- nonthermal electrons produce synchrotron radiation over broad energy range
  - responsible for radio emission
- high energy tail of nonthermal electrons yields x-ray synchrotron radiation
  - rollover between radio and x-ray spectra gives exponential cutoff of electron spectrum, and a limit to the energy of the associated cosmic rays
  - large contribution from this component modifies dynamics of thermal electrons

X-Ray Spectra:Thermal and Nonthermal Emission



- thermal X-ray spectra reveal ejecta material and composition of swept-up ISM
  - composition and relative abundances constrain supernova models

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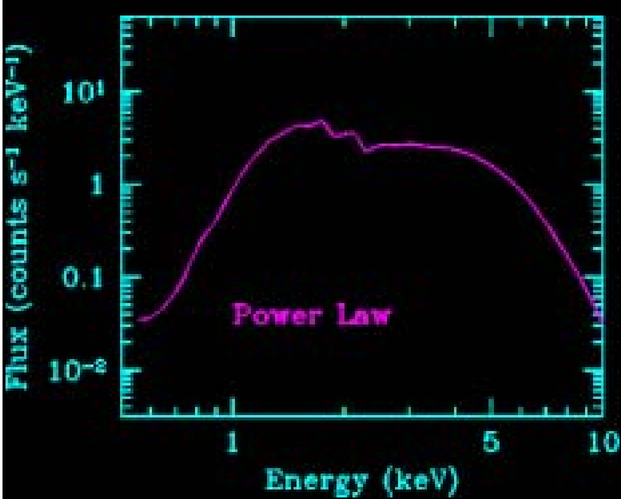

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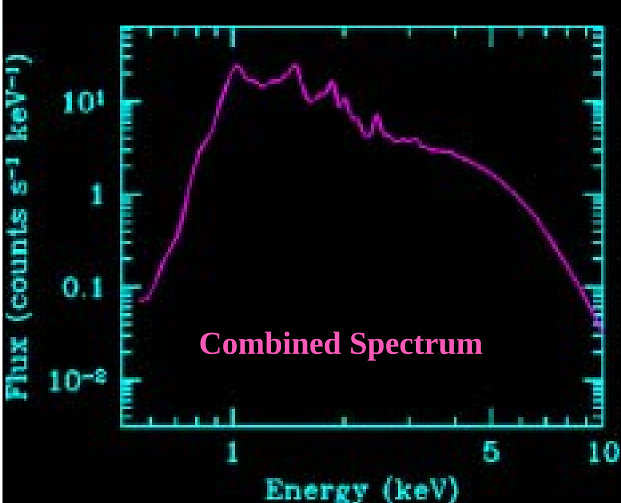

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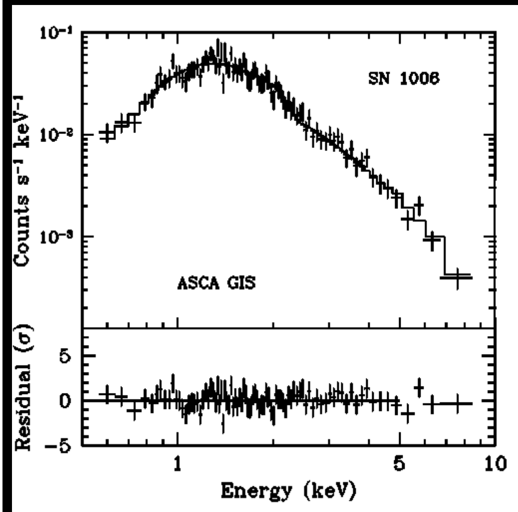
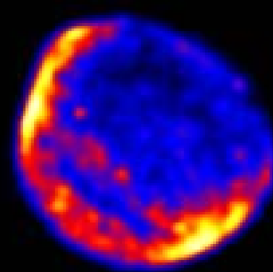
Particle Acceleration in SN 1006



- **Spectrum of limb dominated by <u>nonthermal emission</u>**
  - **keV photons imply** $E_e \approx 100$ TeV



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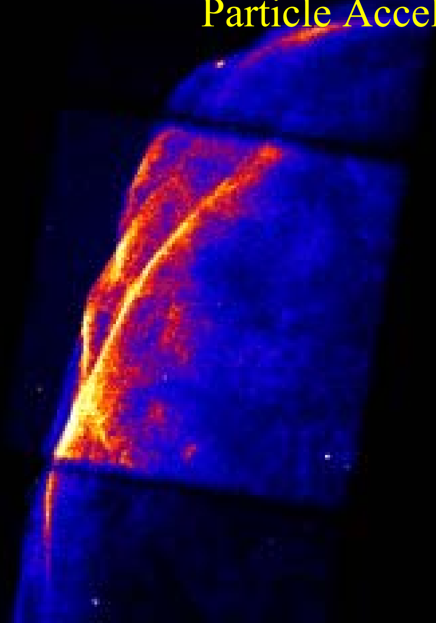

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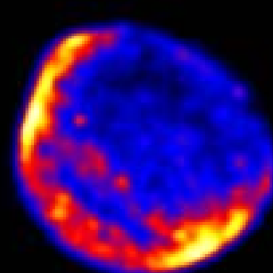
- ***Chandra* observations show distinct shock structure in shell**



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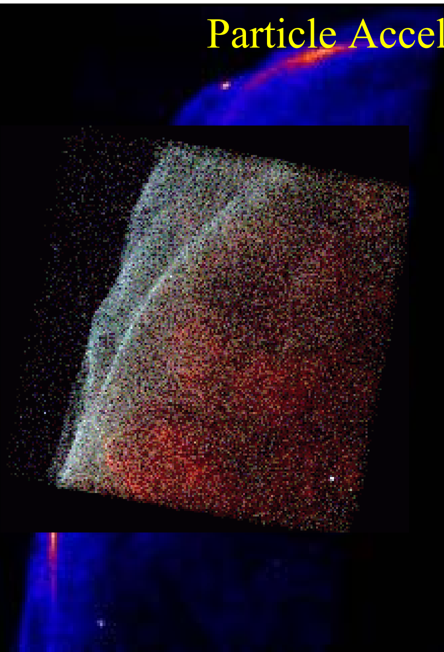
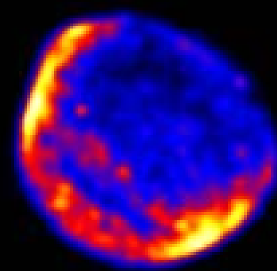
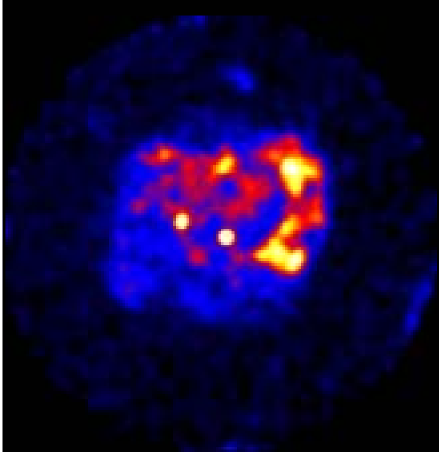
Particle Acceleration in SN 1006



- Spectrum of limb dominated by <u>nonthermal emission</u>
  - keV photons imply $E_e \approx 100$ TeV
- *Chandra* observations show distinct shock structure in shell
- Interior of SNR shows thermal gas



G347.3-0.5 (RX J1713.7-3946)



- Discovered in ROSAT All-Sky Survey (Pfeffermann & Aschenbach 1996)
  - large (D = 1 deg) Galactic SNR

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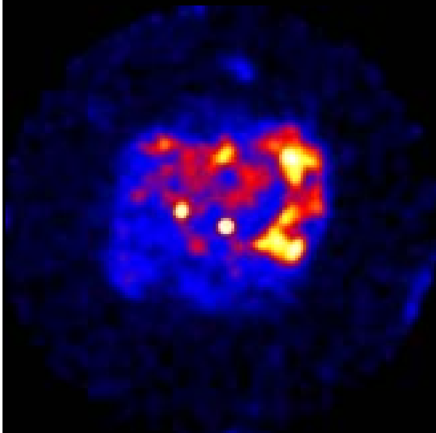

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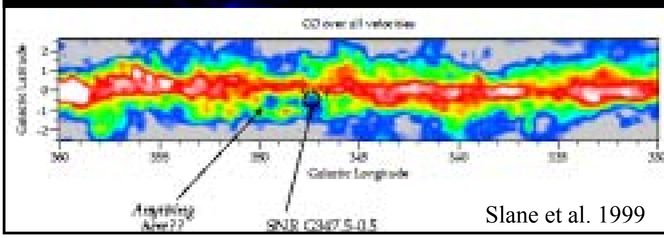
  - large (D = 1 deg) Galactic SNR
- Located in "cavity-like" region of Galactic Plane (Slane et al. 1999)
  - CO data show adjacent clouds and HII region
  - molecular line velocities give distance of ~6 kpc based on Galactic rotation curve



Slane et al. 1999

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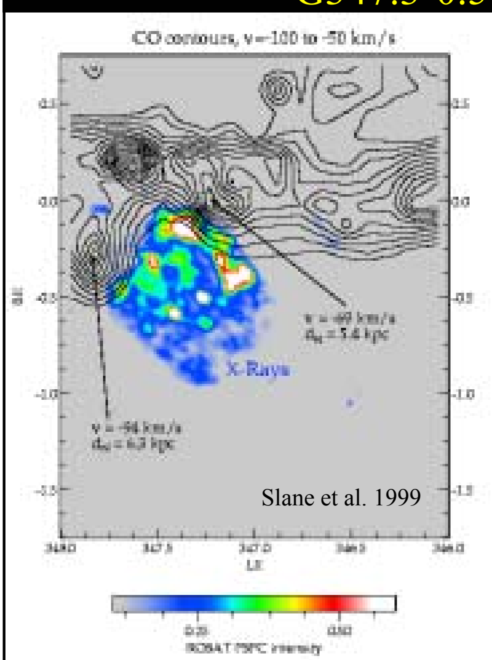

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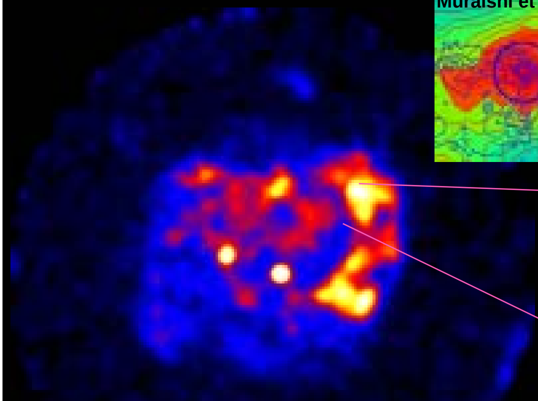
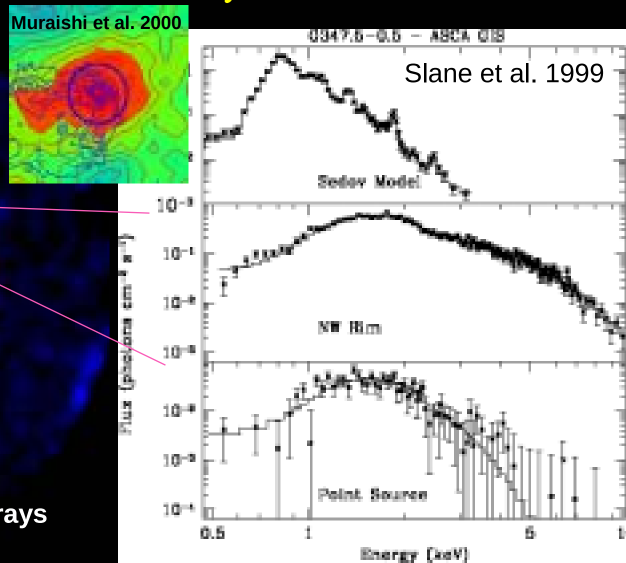
- Located in "cavity-like" region of Galactic Plane (Slane et al. 1999)
  - CO data show adjacent clouds and HII region
  - molecular line velocities give distance of ~6 kpc based on Galactic rotation curve
- Unidentified **EGRET** source located outside of SNR boundary, possibly in molecular cloud region (Butt et al. 2001)

G347.3-0.5: A Cosmic Ray Accelerator





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  - suggests multi-TeV electrons
- SNR limb is detected in TeV γ-rays

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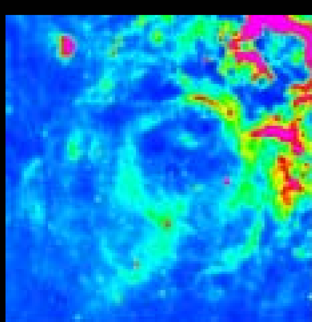
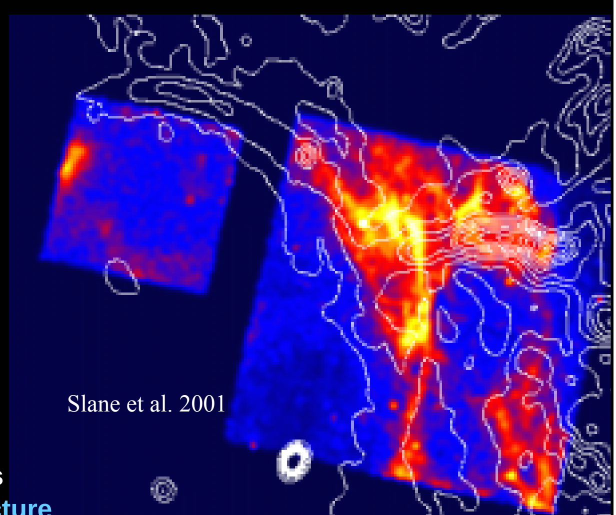
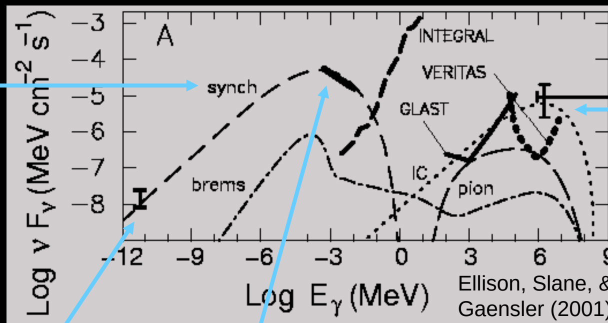




- X-ray emission is nonthermal
  - suggests multi-TeV electrons
- SNR limb is detected in TeV γ-rays
- ATCA reveals complex radio structure
- Chandra shows X-ray/radio structure similar; combined spectra constrain models

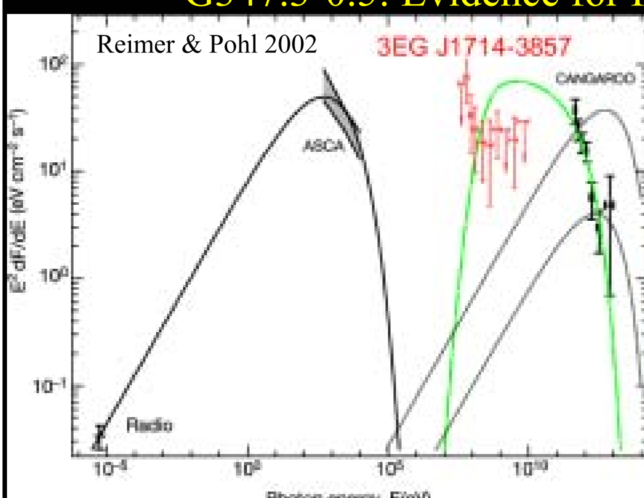
G347.3-0.5: 17 Decades of Photons

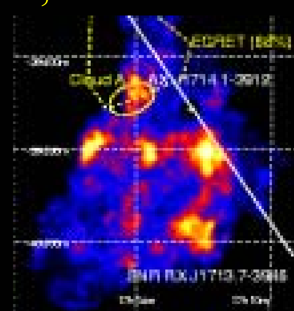


- **synchrotron emission dominates spectrum from radio to x-rays**
  - shock acceleration of electrons and protons to > 10^{13} eV
  - >25% of shock energy is in energetic ions E_{max} is below "knee" in CR spectrum
  - SNRs with larger B fields may fill in up to knee

- **γ-ray emission is from inverse-Compton scattering off 2.7K background**
  - pion production falls below EGRET sensitivities; still no direct evidence of energetic ions in SNR shocks
  - upcoming experiments may be able to detect this in G347.3-0.5 and other SNRs

G347.3-0.5: Evidence for Hadrons, or Not?





Uchiyama et al. 2002

- **Hard X-ray source in NE region may be from protons driven into cloud from SNR**
  - **but energy budget requires huge fraction of total SNR energy**

- **Subsequent CANGAROO data argue for evidence of pion decay as source of TeV gamma-rays**
  - **EGRET limits in conflict with this interpretation**

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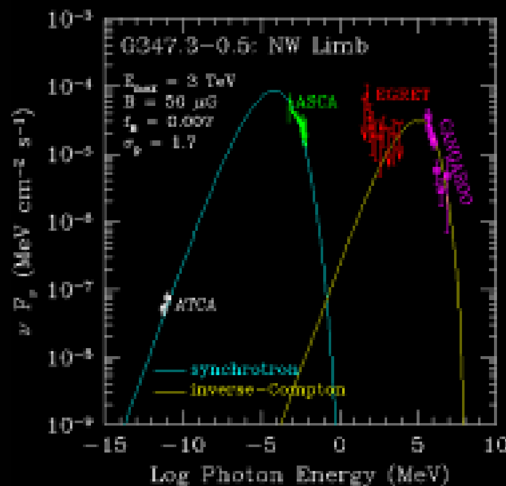
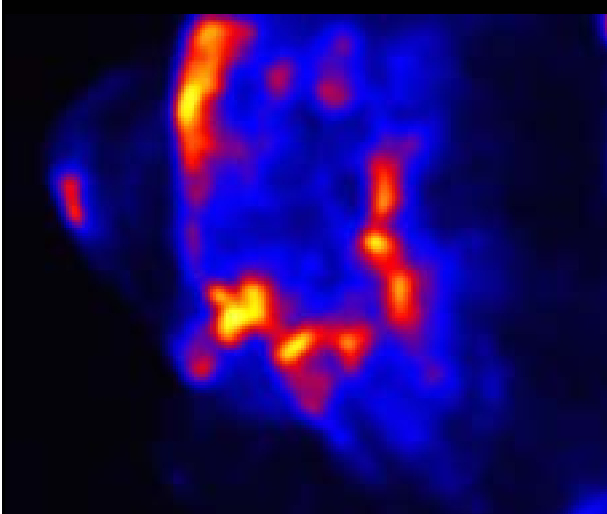
Most Recently…

- **Joint analysis of ATCA and Chandra data allow us to investigate the broad band spectrum (Lazendic et al. 2002)**
  - **radio, X-ray, and γ-ray data can be accommodated along with EGRET limits, with no contributions from pion decay**
  - **<u>large magnetic field</u> is required, with relatively small filling factor**
  - **this is a reasonable picture for an SNR evolving toward a molecular cloud**



G266.2-1.2 (RX J0852-46): A Ghost Lurking in Vela



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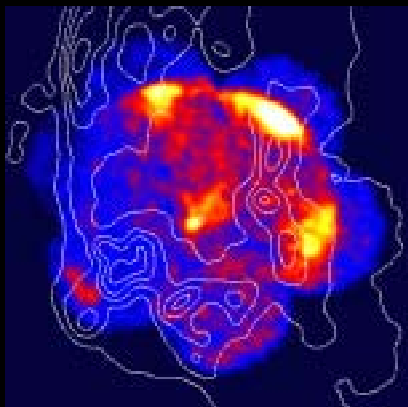
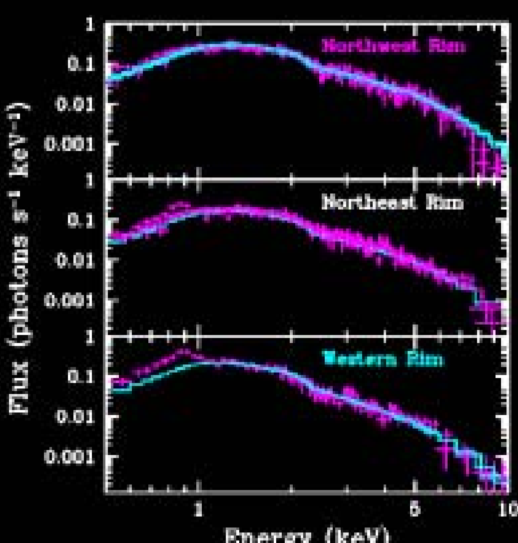
Aschenbach 1998 Iyundin et al. 1998



- **Large (2 degree diameter) SNR in direction of Vela SNR**
  - **observed only above ~1 keV, below which soft flux from Vela dominates**
- **Claims of ^{44}Ti emission yield extremely young age**
  - **large size then implies very small distance**
  - **however, significance of ^{44}Ti results not high**
- **X-ray limits on distance still low (d < 1-2 kpc)**
  - **remnant is young**

G266.2-1.2: Another Nonthermal Shell-type SNR



- **Shell x-ray spectrum is nonthermal**
  - soft emission from Vela limits sensitivity to thermal emission
- **Column density indicates SNR may lie near edge of Vela Molecular Ridge – well beyond Vela SNR**
  - strong candidate for γ-ray studies
- **Central source unidentified**
  - surrounded by diffuse emission; plerion?
  - Chandra observations (Pavlov et al. 2001) show spectrum similar to other radio-quiet neutron stars, with N_H similar to SNR

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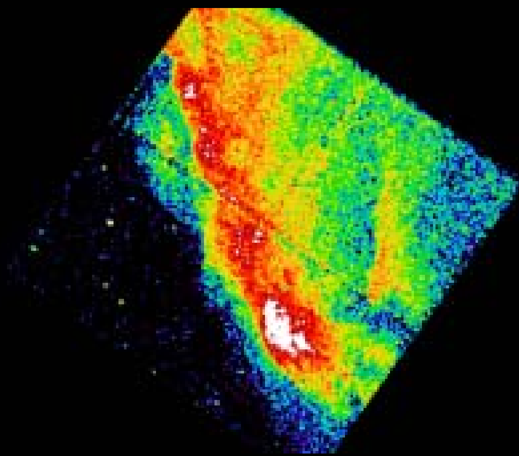

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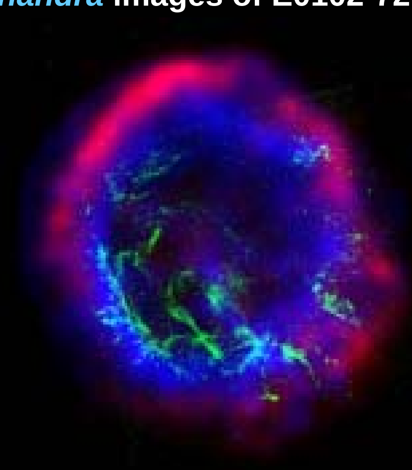
  - Chandra observations (Pavlov et al. 2001) show spectrum similar to other radio-quiet neutron stars, with N_H similar to SNR
- **Redmond et al (2002) argue Vela Bullet D is part of G266.2-0.2**
  - Chandra study (Plucinsky et al. 2001) shows spectrum is thermal – unlike G266.2-0.2
  - N_H also implies larger distance

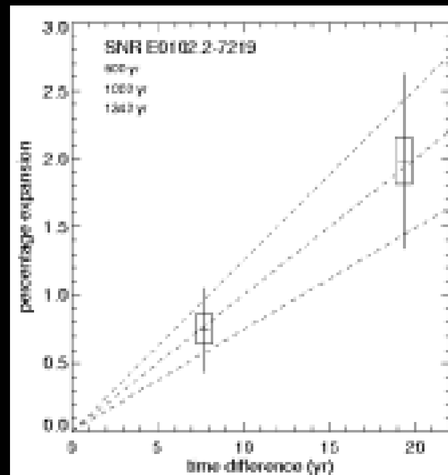
Shock Dynamics and SNR Expansion

- **Comparison of *Einstein*, ROSAT, and *Chandra* images of E0102-72 give expansion velocity of ~6000 km/s**
  - $kT_s = 45^{+25}_{-20}$ keV



Shock Dynamics and SNR Expansion

- Comparison of *Einstein*, ROSAT, and *Chandra* images of E0102-72 give expansion velocity of ~6000 km/s
  - $kT_s = 45^{+25}_{-20}$ keV
- Spectrum of outer shell provides electron temperature
  - $kT_e = 0.4 - 1.0$ keV
  - 25 times smaller than kT_s estimate!
- Electron temperature lags behind ions
  - assuming Coulomb equilibration, expect $kT_e = 4.5 - 8$ keV; too high!
- Strong cosmic ray component can decrease kT_s for given shock velocity
  - conclude efficient and copious cosmic ray acceleration in E0102-72



Hughes, Rakowski, & Decourchelle 2000

Particle Acceleration in Plerions

- **Typical value for pulsar wind is** $\gamma \approx 10^6$
  - **but** $\nu_c \approx 4.2\gamma^2 B_{\mu G}^2$ **for synchrotron radiation**

$\therefore \gamma \approx 8\times10^8 B_{\mu G}^{-1/2}$ **for 10 keV X-rays in plerion**

  - **particles from wind are accelerated somewhere**

- **Wind carries a fraction ε of the pulsar spin-down power**

$$P_{wind} = \frac{\varepsilon \dot{E}}{4\pi c r_s^2}$$ **ram pressure of wind**

  - **shock forms where ram pressure balances internal pressure in nebula**

$$r_s = \left[\frac{\varepsilon \dot{E}}{4\pi c P_{neb}}\right]^{1/2}$$ **wind termination shock**

Basic Structure of Pulsar Wind Nebula

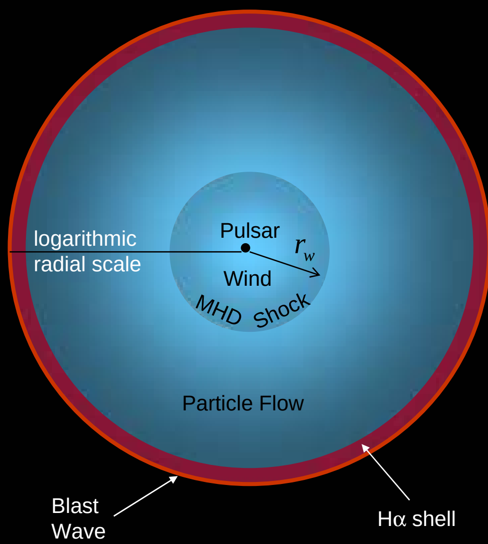
- Pulsar accelerates particle wind

$$\dot{E} = \dot{E}_0 \left[1 + \frac{t}{\tau_0} \right]^{-\frac{n+1}{n-1}}$$

- wind inflates bubble of particles and magnetic flux

$$\sigma = \frac{F_{E\times B}}{F_{particle}}$$

- Outer boundary of nebula **confined** by material swept up by blast wave, or pressure from surrounding SNR



- Shock forms at r_w as particles decelerate to match outer boundary condition
  - wind termination shock
- Particle flow in magnetic field creates **synchrotron nebula**
  - spectral break at

$$\nu_{br} \approx 10^{24} B^{-3} \tau^{-3} \text{ Hz}$$

where synchrotron lifetime of particles equals SNR age
  - radial spectral variation from burn-off of high energy particles

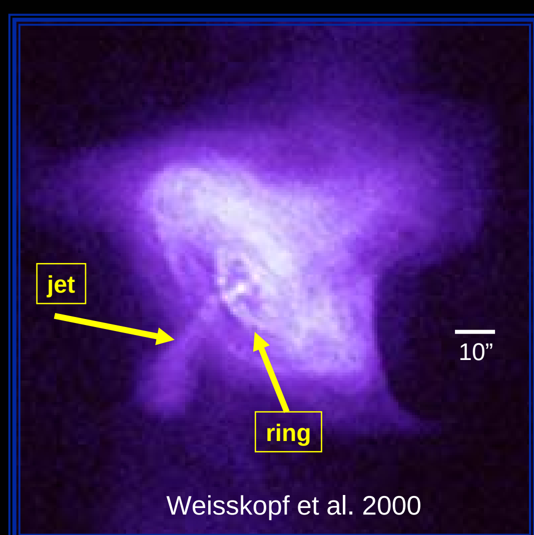
Chandra Probes the Crab

How does pulsar energize synchrotron nebula?

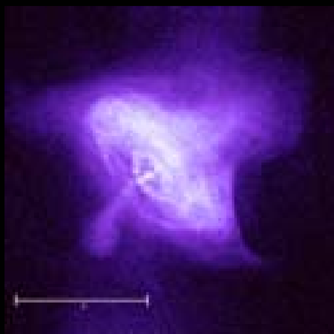
Pulsar: P = 33 ms
dE/dt = 4.5 x 10^{38} erg/s

Nebula: L_X = 2.5 x 10^{37} erg/s

- X-ray **jet-like structure** appears to extend all the way to the neutron star
- **inner ring** of emission may be associated with shock wave produced by matter rushing away from neutron star
  - corresponds well with optical wisps thought to delineate shock boundary



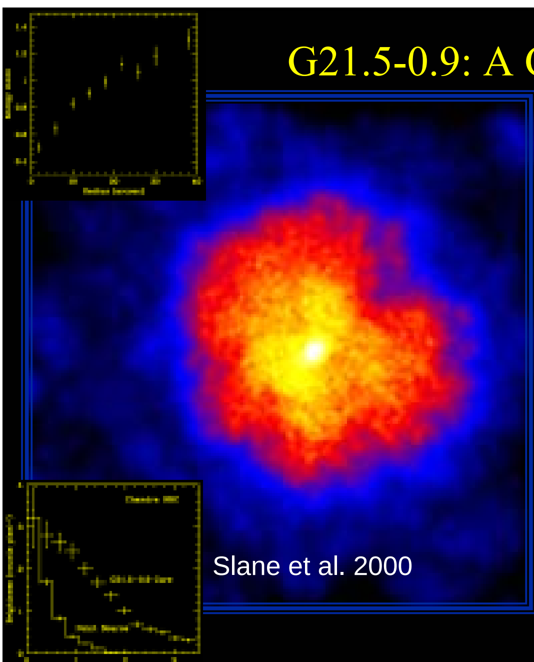
Crab: The Movie (courtesy J. Hester)



- **Dynamic structures in wisp region**
  - **suggest that synchrotron cooling instability (Hester) or ion cyclotron wave compression (Arons)**
  - **latter requires (and is self-consistent with) ion acceleration at wind termination shock**

[Movie not available in on-line presentation]

G21.5-0.9: A Crab with a Shell



- ***Chandra*** **image reveals central compact emission region**
- **Synchrotron spectrum varies with distance from center**
  - **consistent with burn-off of high energy electrons injected at center**
- **Central emission is extended**
  - **may be indicative of stand-off shock from confined pulsar wind**

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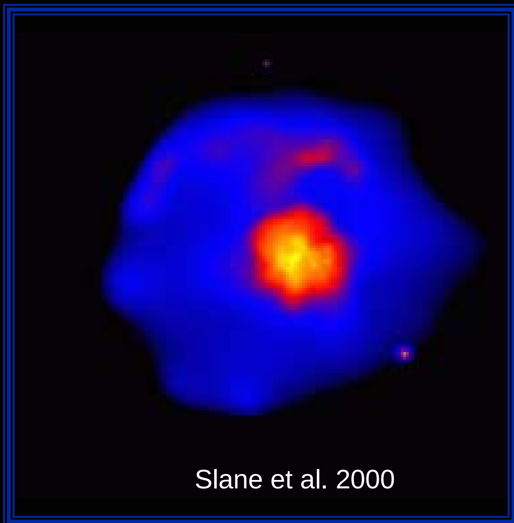
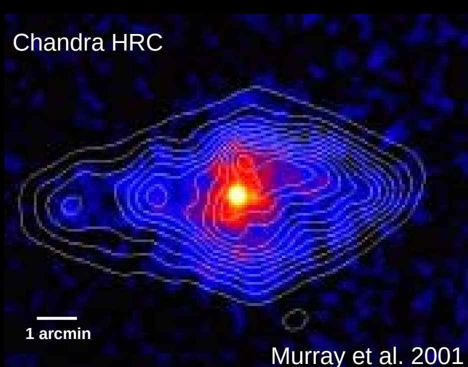
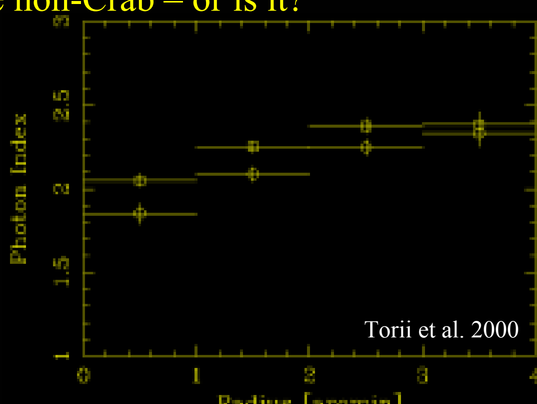


- *Chandra* image reveals central compact emission region
- Synchrotron spectrum varies with distance from center
  - consistent with burn-off of high energy electrons injected at center
- Central emission is extended
  - may be indicative of stand-off shock from confined pulsar wind
- Faint extended shell may be associated with blast wave
  - featureless spectrum; NEI effects? Non-thermal emission?
  - confirmed by XMM (Warwick et al '01)

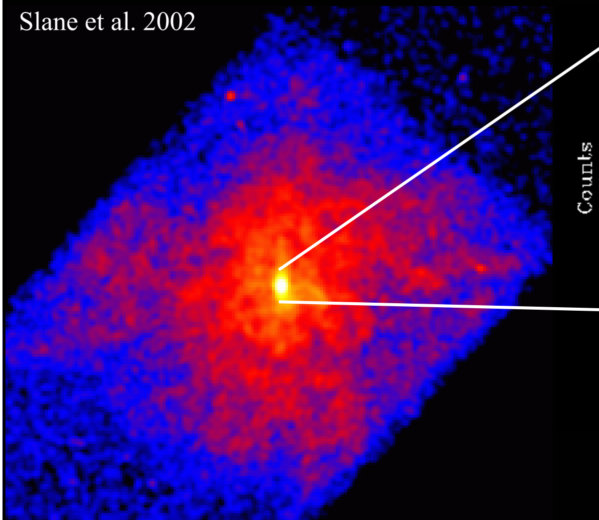
3C 58: The non-Crab – or is it?

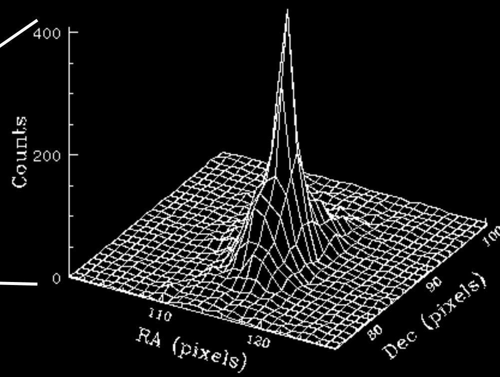




- Thought to be counterpart of SN 1181; younger than Crab
  - radio flux is 10 times weaker than Crab; X-ray flux 2000 times weaker
  - clearly, 3C 58 has had a different evolutionary path than the Crab
- X-ray spectral variations show synchrotron burn-off in nebula, as expected for nebula powered by central pulsar
  - low break frequency suggests pulsar output has undergone rapid decline

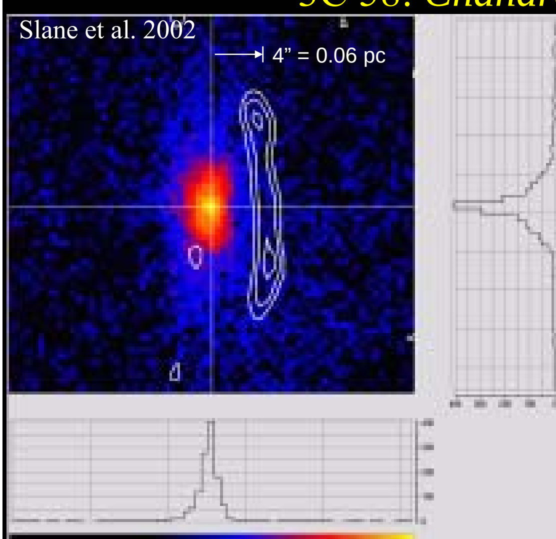
3C 58: *Chandra* Observations



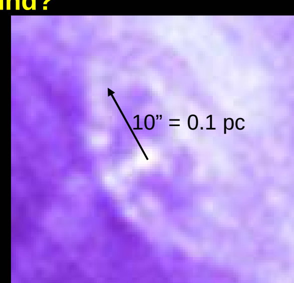


- Compact center appears to be a point source with a surrounding nebula
  - pulsar with wind nebula
- Central source is extended in N/S direction, similar to radio wisp

3C 58: *Chandra* Observations



- Radio wisp seen along western limb (Frail & Moffett 1993)
  - termination shock of pulsar wind?



$$\dot{E} = 4\pi c R_s^2 P_{neb}$$

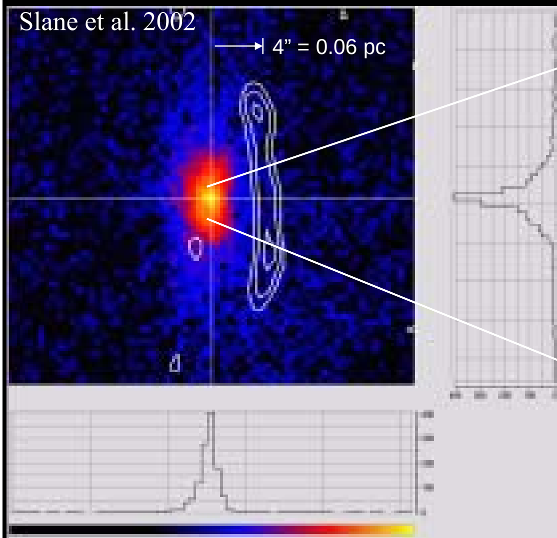
- agrees w/ that from spindown

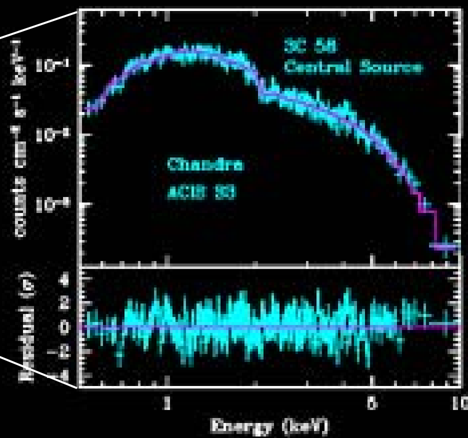
$$\sigma \approx (3-5)\times 10^{-3}$$

- particle-dominated wind

- Central source is extended in N/S direction, similar to radio wisp

3C 58: *Chandra* Observations



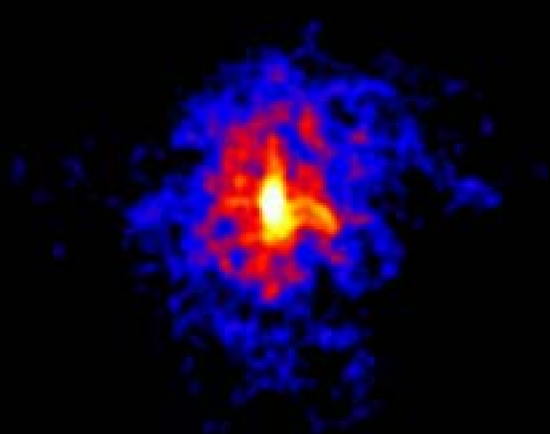


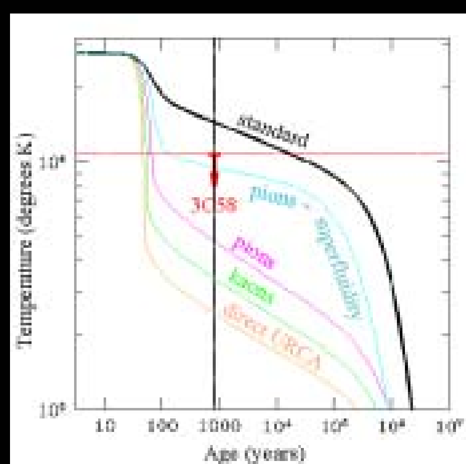
- Central spectrum is a power law

$\Gamma = 1.6 \pm 0.1,\quad L_x = 9.0\times10^{32}\, d_{3.2}^2\, \text{erg s}^{-1}$

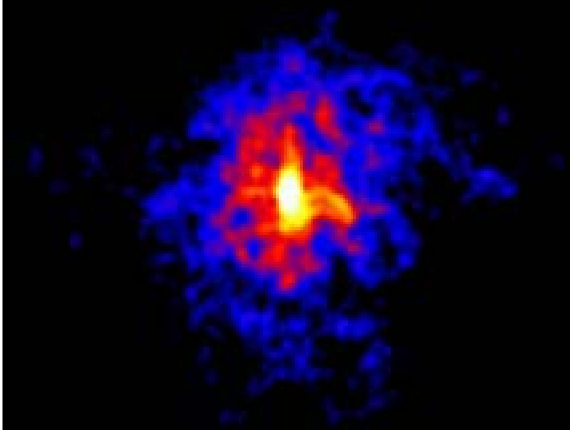
- no evidence of blackbody component

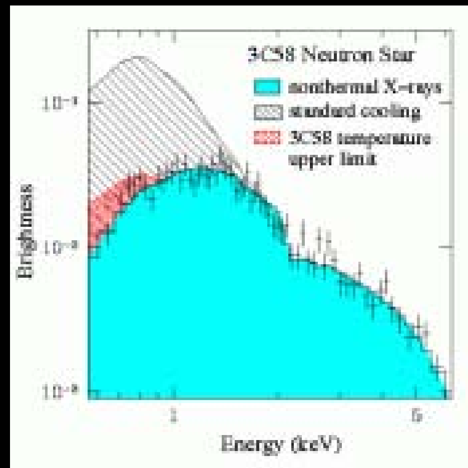
PSR J0205+6449: A Rapidly Cooling Neutron Star



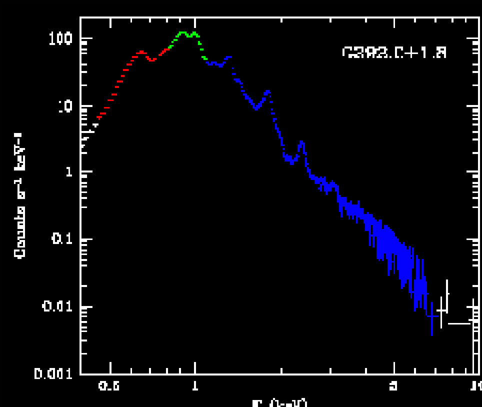


PSR J0205+6449: A Rapidly Cooling Neutron Star





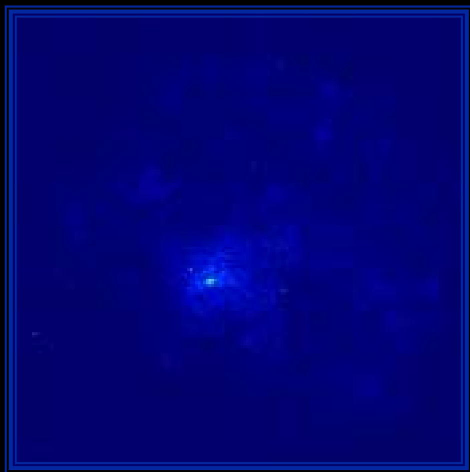
G292.0+1.8: O-Rich and Composite?



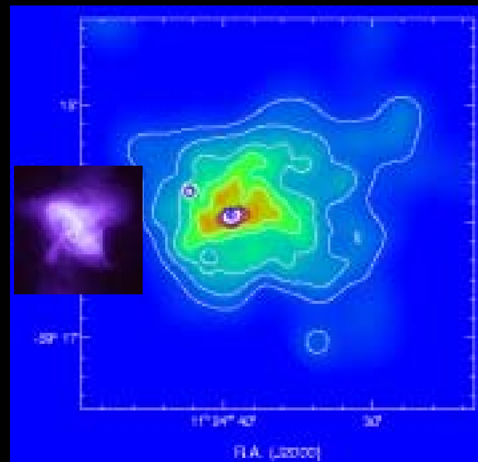
- **Compact source observed**

Hughes et al. 2001

G292.0+1.8: O-Rich and Composite?



Hughes et al. 2001



- synchrotron nebula in hard x-ray band; core extended
- young radio pulsar detected (Camilo et al. 2002)

Summary

- **Direct evidence of particle acceleration in SNRs to E > 1 TeV is observed in multiple sources**

- **Indirect evidence for ion acceleration is also observed, both from broad-band spectral/dynamical modeling and from direct comparison between shock velocities and temperatures**

  - **SNR expansion studies in X-rays offer great promise for further advances**

- **X-ray observations show pulsar wind termination shocks, where particle acceleration is ongoing**

  - **ion content of wind still under debate**

  - **high resolution X-ray studies of inner structure in PWNe holds promise for settling this issue**