The Pulsar-Wind Nebula in SNR G11.2-0.3 and its Interaction with Interior Ejecta

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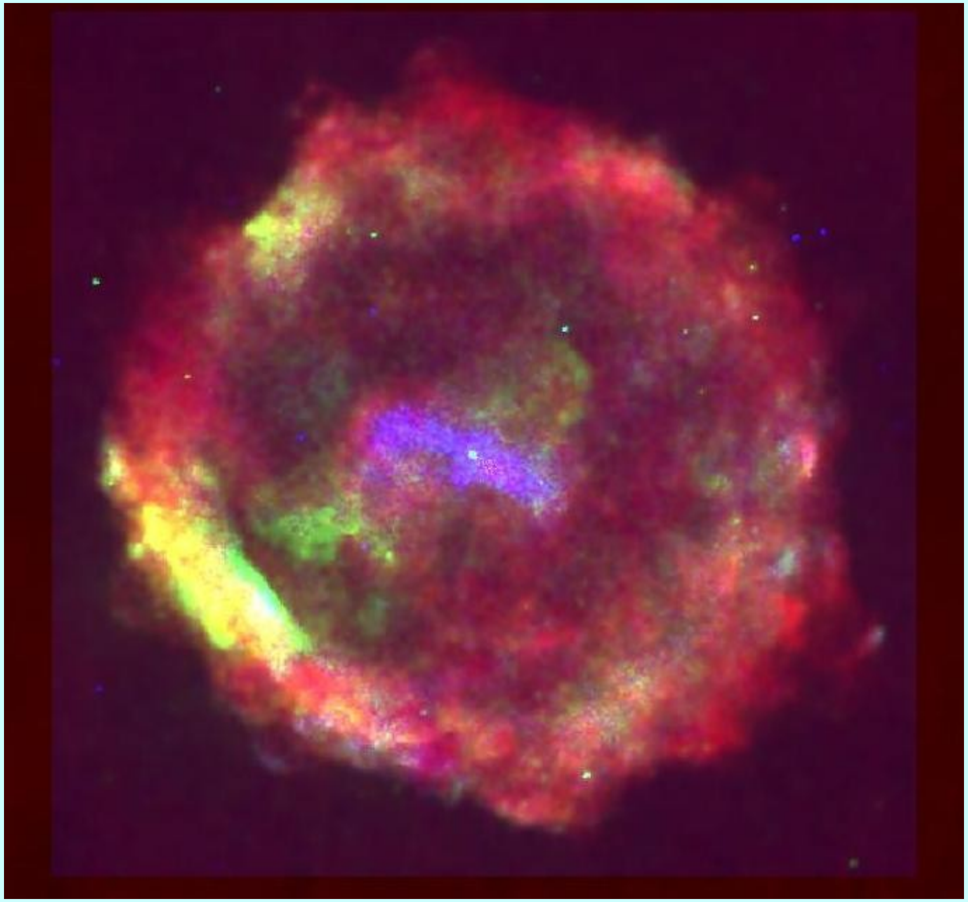


Red: VLA 8 GHz; green, Chandra 0.8 – 1.2 keV; blue, Chandra 3.3 – 8 keV (both smoothed)

1. The supernova event
2. The PWN
3. Draft scenario

Smoothing done with various experimental methods: platelets, spectro/spatial, nonlocal: Willett et al. 2007, Krishnamurthy et al. 2010, Salmon et al. 2013

Basic information

Ideal combination remnant: shell + pulsar-wind nebula (PWN) + pulsar (65 ms; $\dot{E}$ = 6.4 x 10^{36} erg s^{-1}). D ~ 4.4 kpc. τ ~ 24,000 yr ⇒ $P \sim P_0$ (Kaspi et al. 2001)

G11.2 is **not** the remnant of SN (?) 386 AD!

X-ray absorption toward PWN: $N_H \sim 3 \times 10^{22}$ cm^{-2} ⇒ $A_V \sim 14^m$

(Optical/NIR: $A_V \sim 16^m - 20^m$; Lee et al. 2013)

Bright core-collapse SNIIL: $M_V \sim -19$ ⇒ $V \sim 8.5^m$

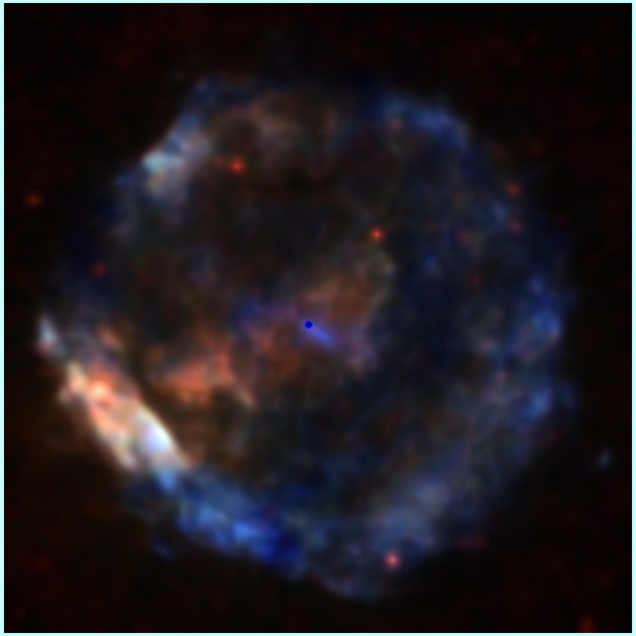
Far too faint for naked-eye discovery. (CE 386 may not have been a SN)

However: 2003 – 2013 expansion proper motions in X-rays give rate of 0.30 (0.27, 0.32)% ⇒ age upper limit (no deceleration) of 3300 (3100, 3600) yr. **Expect $R \propto t^m$ with m = 2/3** (expansion into stellar wind; Chevalier 2005) so **age ~ 2200 (2100, 2400) yr.** Consistent with spectroscopic vels. ~ 900 km/s and with radio expansion (Tam & Roberts 2003).

PWN: length ~ 30" (~ 0.7 pc); L_X = 1.0 x 10^{34} erg s^{-1} (0.5 – 8 keV).

Spectrum: radio, α = 0.27 ($S_\nu \propto \nu^{-\alpha}$); X-ray, Γ = 1.73 (Roberts et al. 2003)

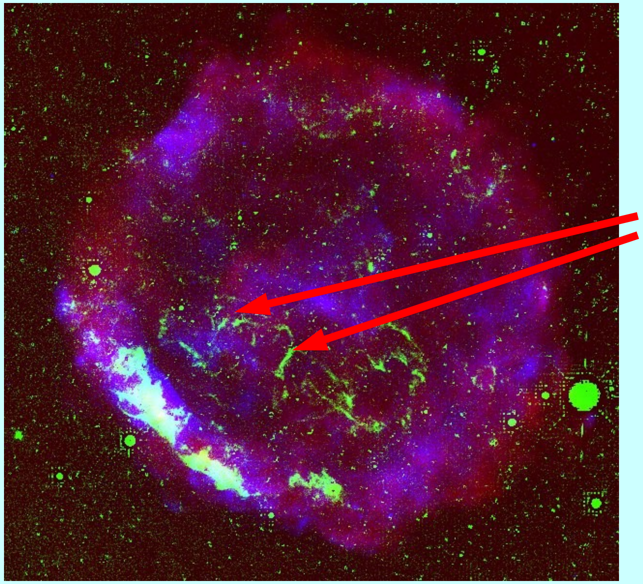
Shell remnant properties



Red: 0.86 keV; green, 1.2; blue 2.2

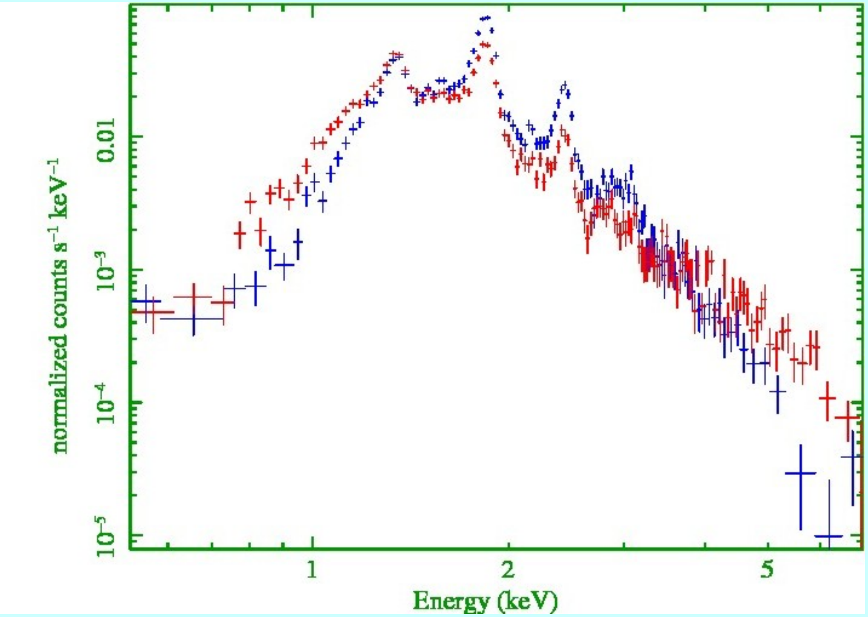
Highly variable absorption: A_V varies between 14^m and 18^m around shell. (SE: low absorption; sim. in PWN.)

Near-IR [Fe II] emission seen in wisps and filaments (Koo et al. 2007; Moon et al. 2009; Lee et al. 2013) – some interior features have v ~ 1000 km/s. Unshocked interior ejecta? Projections from front of shell? Shocked and cooled dense clumps?



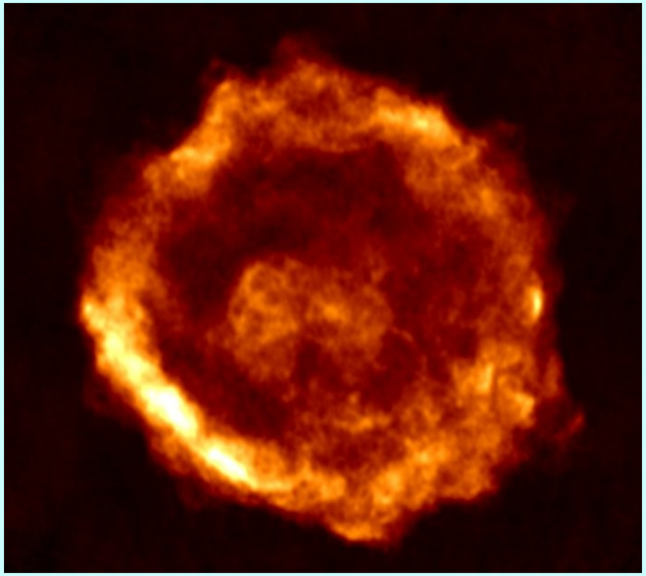
filaments blueshifted by ~1000 km/s

Red: 8 GHz; green: [Fe II] 1.644 μm (Koo et al. 2007); blue, 1 – 8 keV

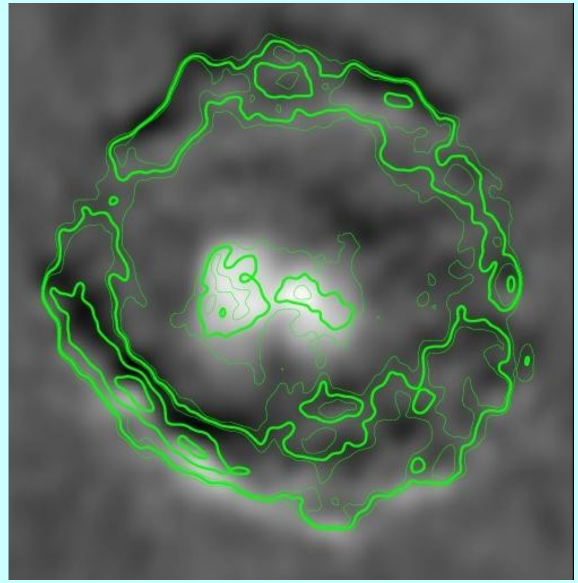


Blue: NW shell region. Red: interior, away from PWN. Interior is *thermal, softer, with hard excess*

Radio pulsar-wind nebula

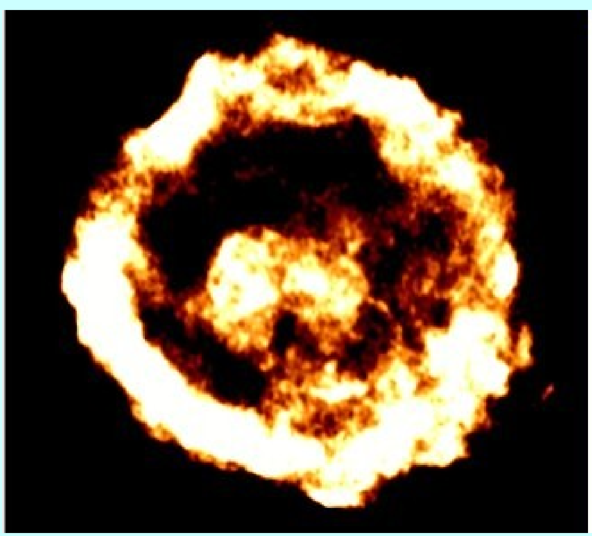


8 GHz (VLA)

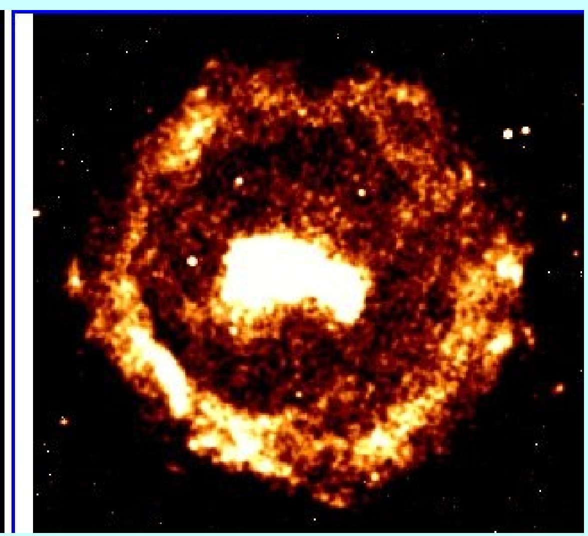


5 GHz – scaled 1.4 GHz

Residual image (1.4 – 5 GHz): Scale 1.4 GHz image to 5 GHz using mean spectral index –0.56, subtract. Central PWN is far brighter (flatter spectrum): α = –0.27. No strong spectral-index variations within PWN



8 GHz

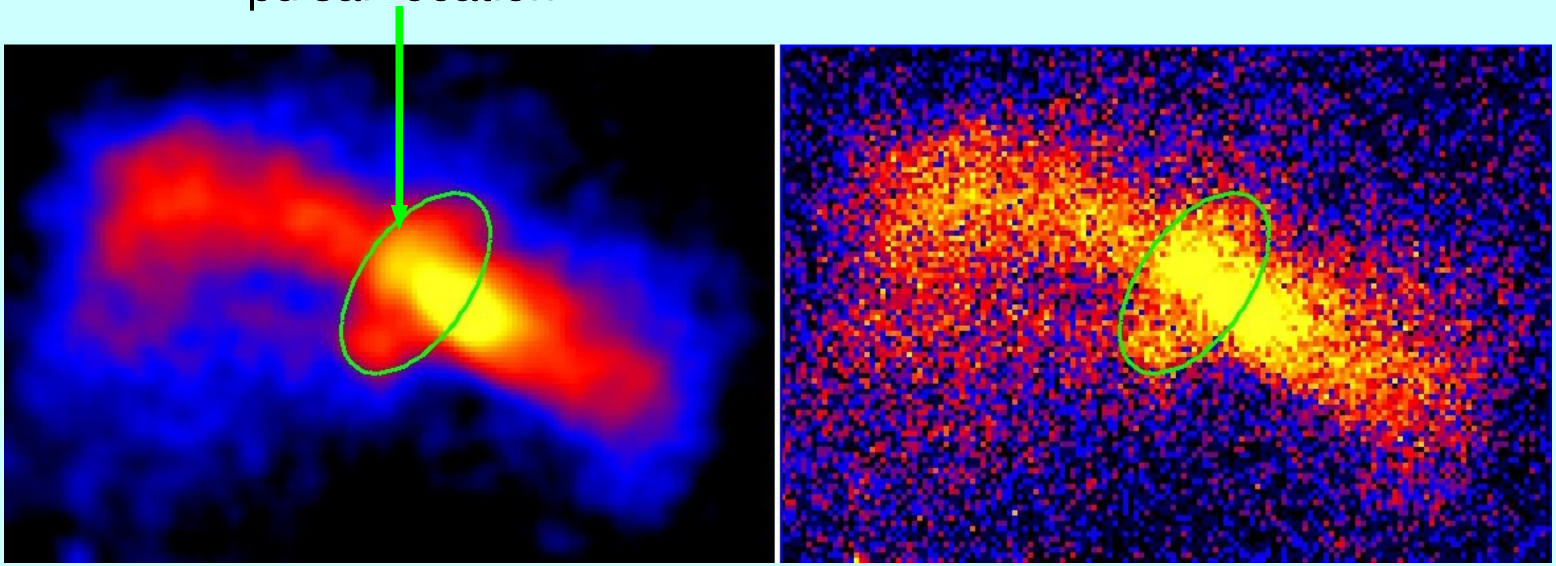


3.3 – 8.1 keV

Maximum extent of PWN is similar at radio, hard X-ray energies: prominent jets are surrounded by faint halo (still some thermal emission present above 3.3 keV)

PWN Closeup

pulsar location

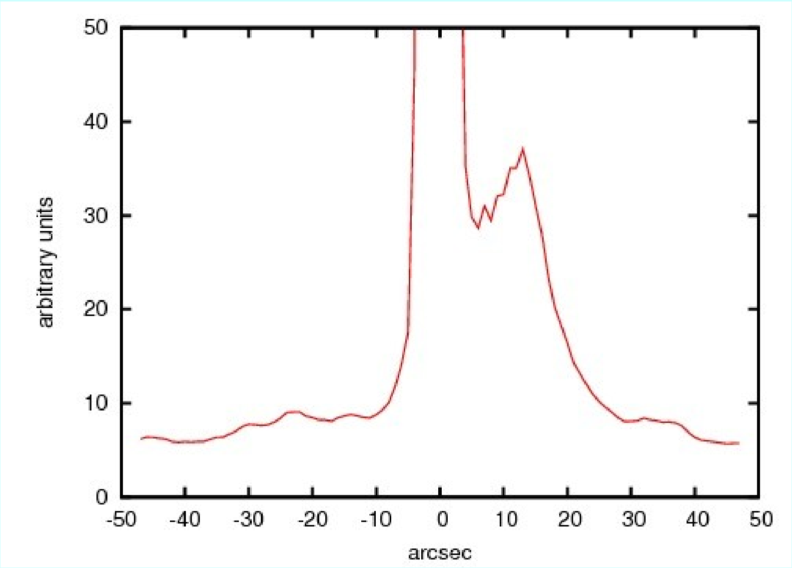


3.3 – 8 keV. Left: smoothed with spatio/ spectral method (pulsar removed). Right: same raw image. Log transfer function.

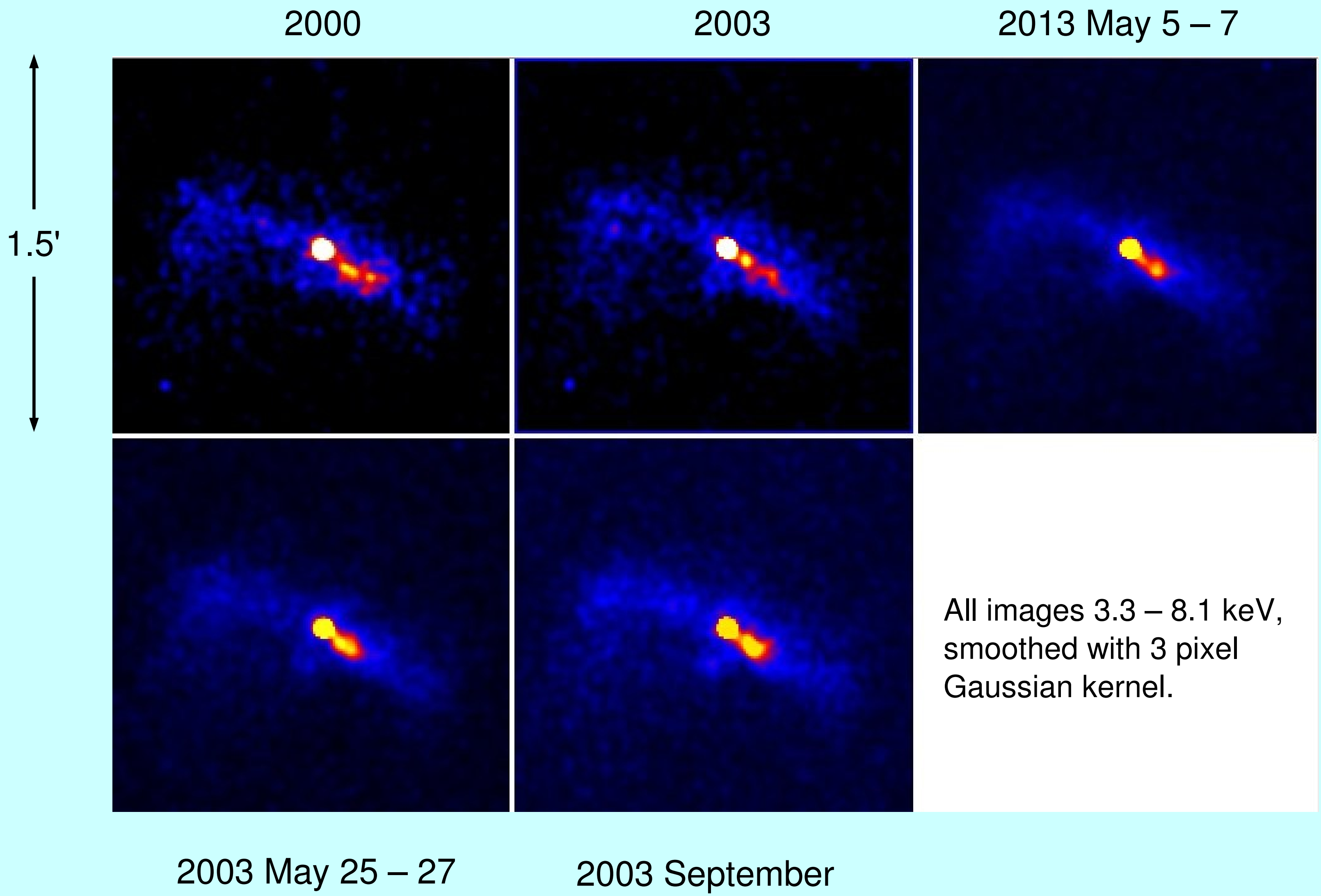
Torus is clearly present, but jets dominate. Torus axial ratio ~ 1.8 ⇒ axis inclined to line of sight by ~ 56˚ Pulsar does not appear to be at torus center. Bright jets are surrounded by fainter nonthermal X-rays.

Jet profile: ~ factor 4 brightness contrast between SW, NE. If Doppler boosted with θ ~ 56˚, infer β ~ 0.44. (Beyond bright knots, jet intensities are comparable.)

Bright knots have harder spectra:
Γ = 1.36 (1.20, 1.46) (overall: Γ = 1.73 ± 0.07)



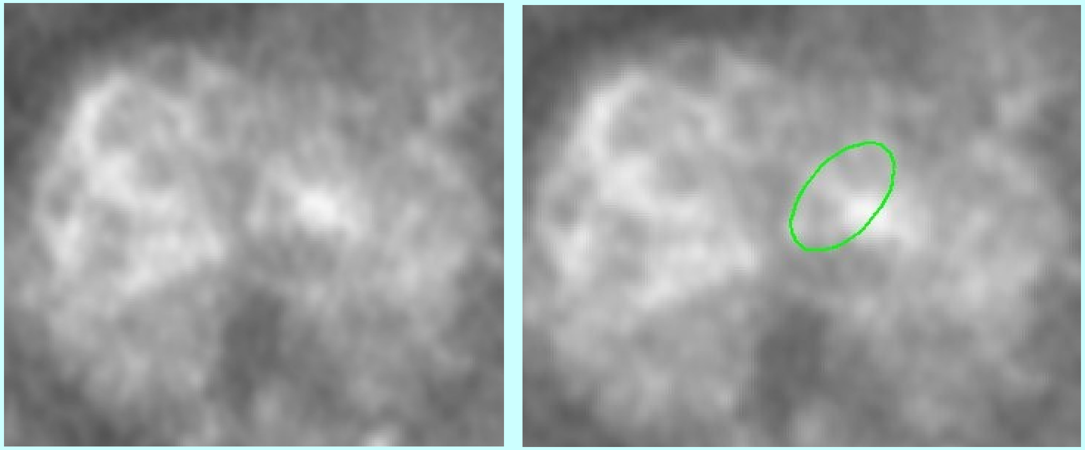
The PWN varies on timescales from weeks to years



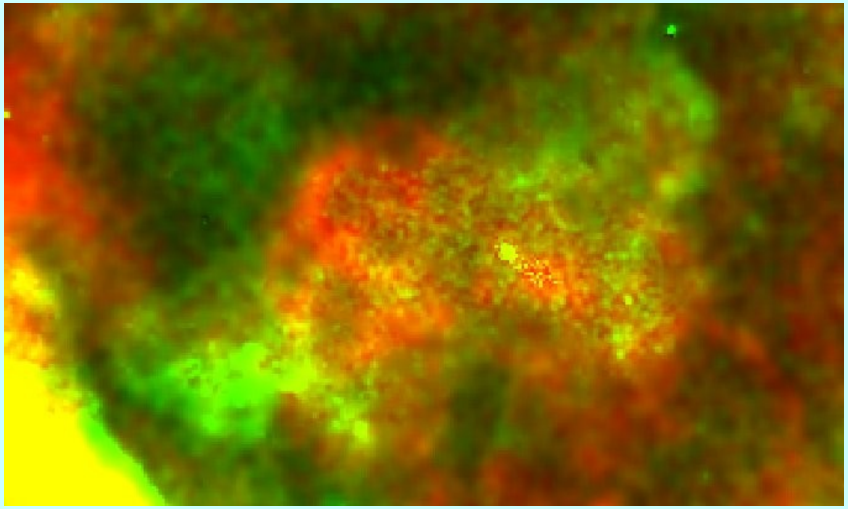
No systematic motion is evident. At 4.4 kpc, c = 14"/yr in plane of sky; in 3 weeks, maximum displacement = 0.8". Not simple outflow.

-- But: No apparent motion of *ends* of jets in 13 yr (v < 1000 km/s)

PWN confinement?

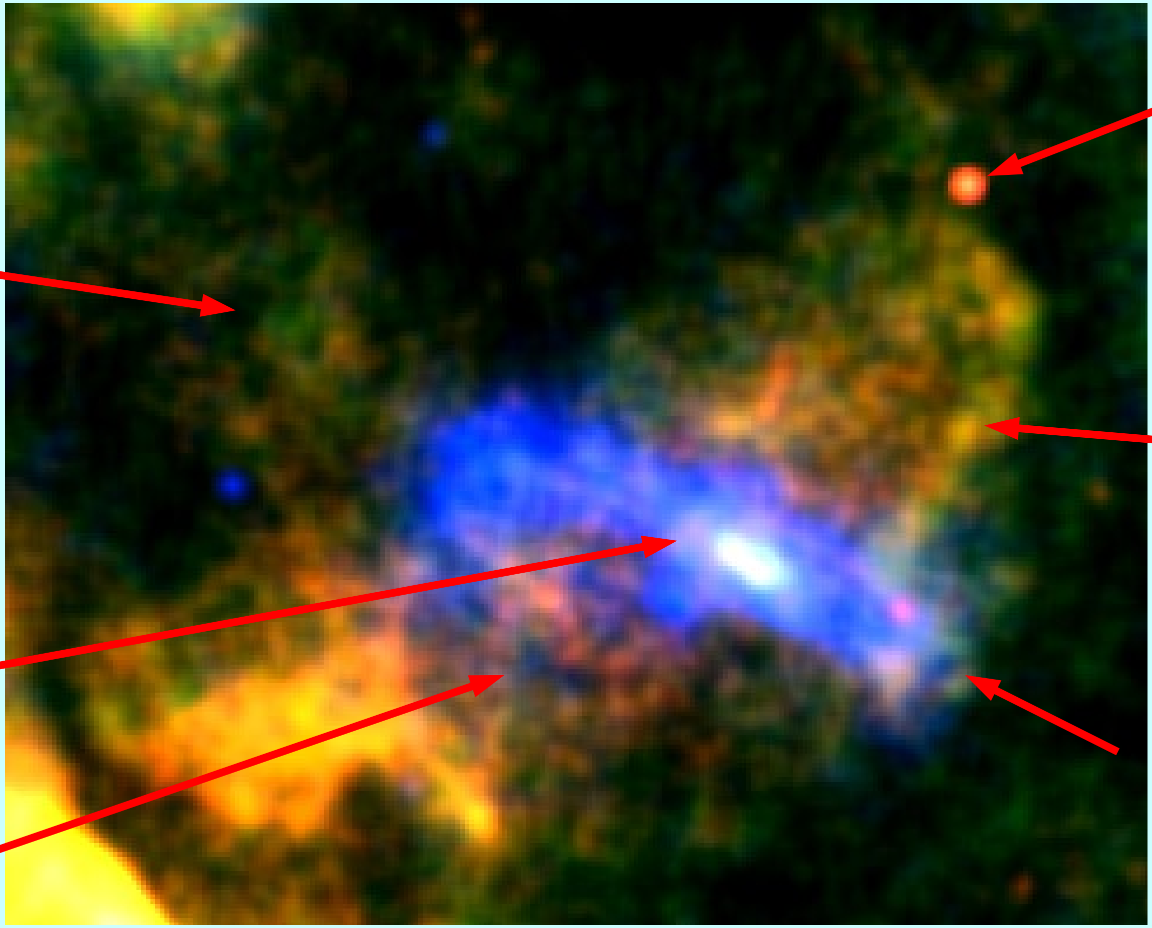


VLA X-band (8 GHz); torus is evident. Bright spot is not pulsar but location of jet-torus intersection; coincident with bright X-ray knot.



Radio PWN (red) fills cavity in soft X-ray image (green)

Evidence for PWN interaction with hot (X-ray-emitting) thermal gas



material beyond NE jet

star

rim of thermal feature

Pulsar removed for smoothing. Pulsar position

extension of rim feature at location of jet intersection

Cavity in soft X-rays is filled by radio PWN

Red: 0.58 – 1.17 keV; green, 1.17 – 1.66 keV; blue, 3.3 – 8.1 keV.
Smoothed with nonlocal spectro-spatial method of Salmon et al. (2013)

These morphological associations require thermal gas to be in remnant interior, not just projected against center

Nonthermal PWN analysis

Chevalier 2005: Model PWN as sphere; radio spectrum meets extrapolated X-ray spectrum at “break frequency” ν_b ~ 8 GHz; minimum nonthermal energy gives pressure $\mathbf{p_{min} \sim 10^{-10}}$ **dyn cm^{-2}**. Nearby thermal gas could possibly provide this.

Except for bright spots, jets show no spectral variation along their length. If 0.44c is jet velocity, move projected 5.3"/yr on sky; reach jet end in ~6 yr. For emission at 8 keV, t(loss) > 6 yr requires **B < 200 μG** or so. (But equipartition *B* ~ 50 μG only which would allow 36 yr transit time: β ~ 0.07.)

If external pressure is ~ 10^{-10} dyn cm^{-2}, can estimate **termination shock radius** (torus scale):

$r_s = (\dot{E}/4\pi c\, P_{ext})^{1/2}$ ~ 0.13 pc ~ 6" – comparable to torus semi-major axis.

Tentative scenario for G11.2–0.3

1. After Chevalier (2005): SN IIL/IIb: mostly stripped core.
   Asymmetric CSM: disk wind? (Binary progenitor??)
   Sweep up large mass early, enter wind Sedov stage (expansion into r^{-2} medium).

2. Reverse shock has moved back in, reheated interior material.
   Ejecta are in dense clumps; cooled to produce [Fe II] emission.

3. Pulsar was born with low velocity; remained near SNR center.
   Early PWN compressed symmetrically around it by return of reverse shock.

4. Continuing pulsar input blows a cavity in interior thermal emission.
   (Sedov model: interior thermal pressure can be comparable to PWN pressure
   if PWN pressure is larger than the minimum equipartition value.)

Prediction: If faint interior emission (away from jets) can be separated into thermal and nonthermal, expect steeper nonthermal emission

Need: **Hydrodynamic modeling**
Further X-ray spectro/spatial analysis