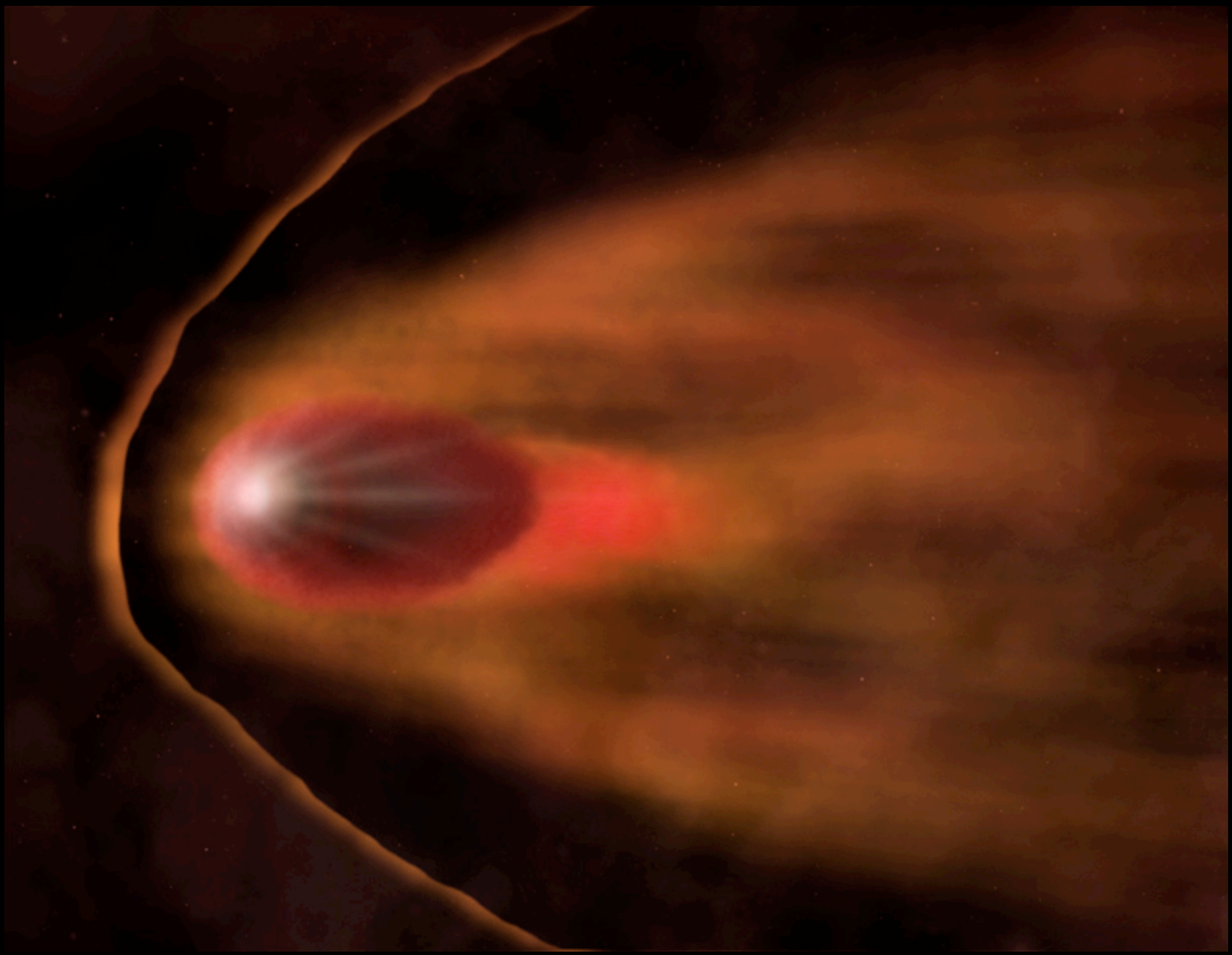
Observations of



Pulsar Bowshock Nebulae

Collaborators:
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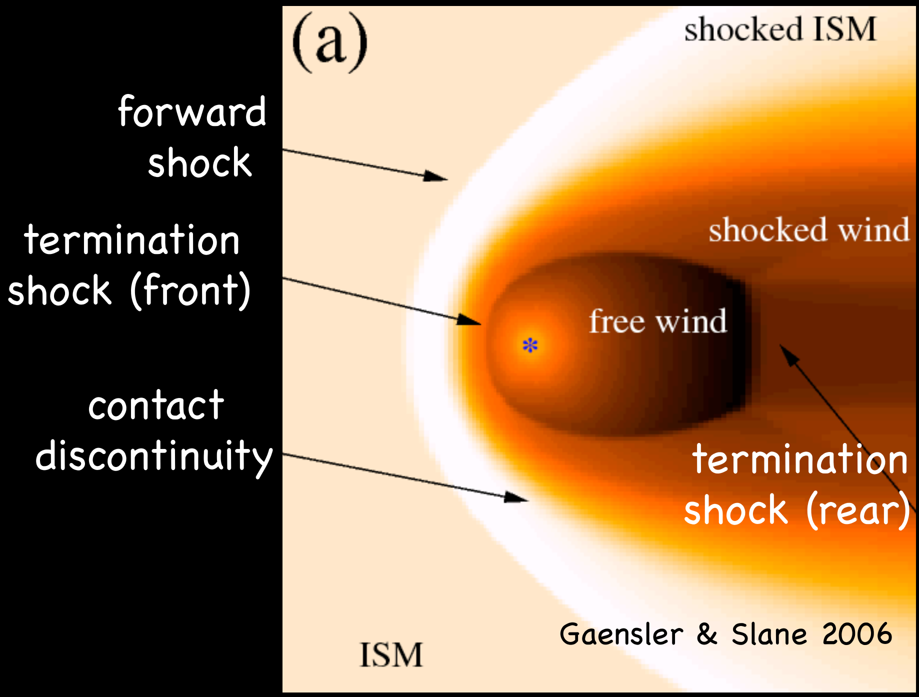
E. van der Swaluw
S. Chatterjee

Bow Shock PWNe: Introduction

- Formed by supersonic motion of pulsar through surrounding medium
  - can occur within host SNR or in ISM
  - different Mach numbers lead to different morphology
- Forward shock: stand-off distance defined by balance of wind with ambient pressure:

$$\frac{\dot{E}}{4\pi\omega R_0^2 c} = \rho_0 v_{PSR}^2 = \gamma \mathcal{M}^2 p_{amb}$$



- Termination shock – asymmetric

  for $\mathcal{M} \sim 1 - 3$, $R_{TS}^B/R_{TS}^F \sim \mathcal{M}$

  for $\mathcal{M} >> 1$, $R_{TS}^B/R_{TS}^F \sim 5 - 6$

- Shocked ambient material
  - Hα in partially-neutral material

- Shocked wind: radio/X-ray tail
  - broad tail from material shocked at $\phi \sim \pi/2$
  - narrow tail from flow along axis
  - tail region broader, TS region smaller for low-$\mathcal{M}$ shocks (such as within SNRs)
  - Note: for X-ray bow shocks, cometary shape is not described by classic Mach cone geometry

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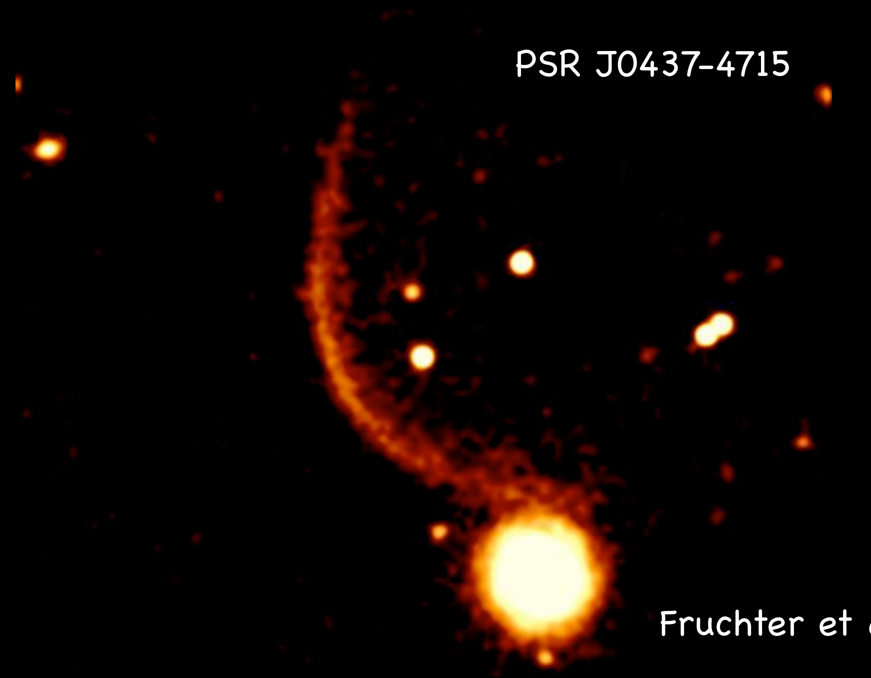

Fruchter et al.

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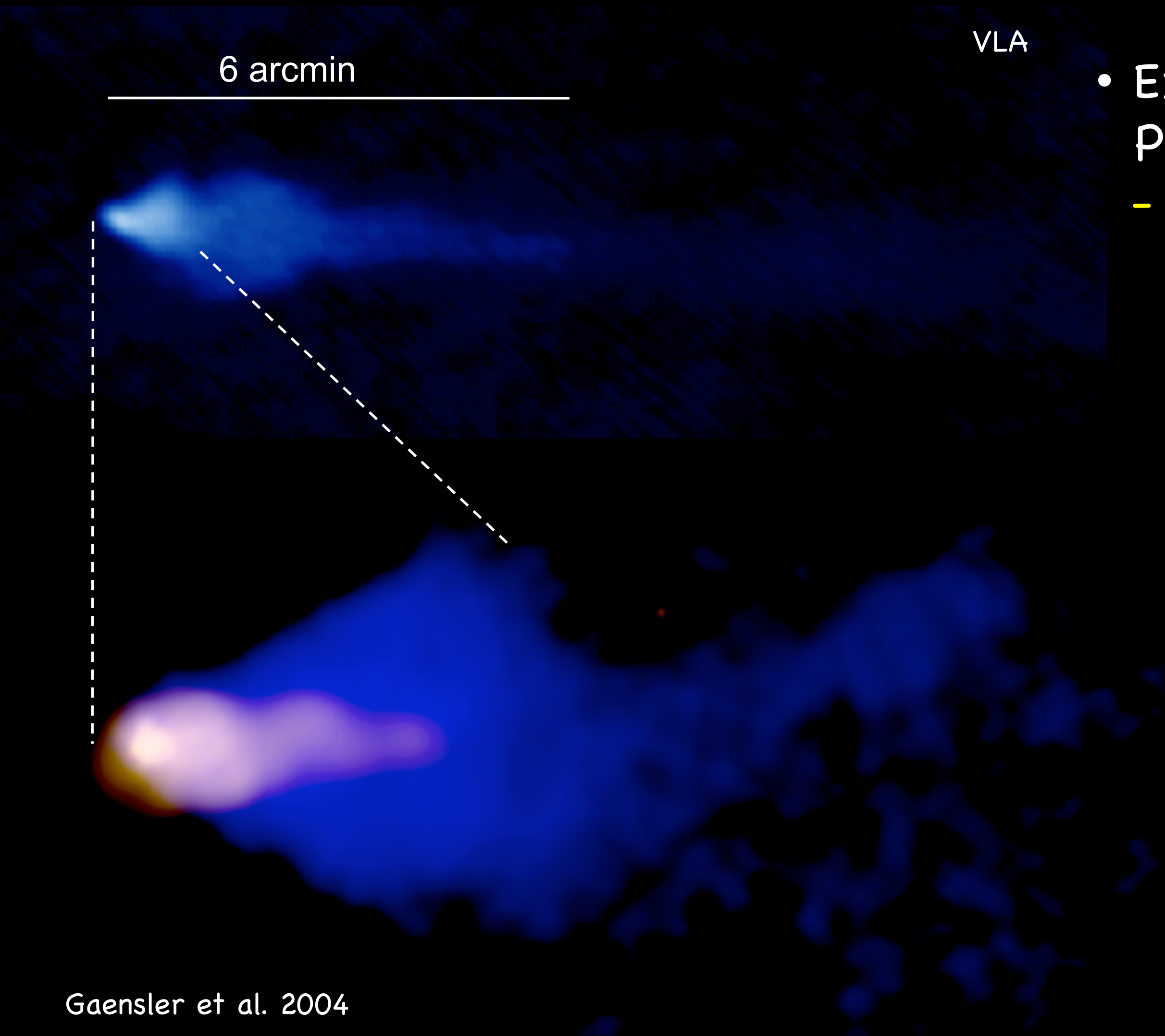
Bow Shock PWNe in the ISM: The Mouse



Gaensler et al. 2004

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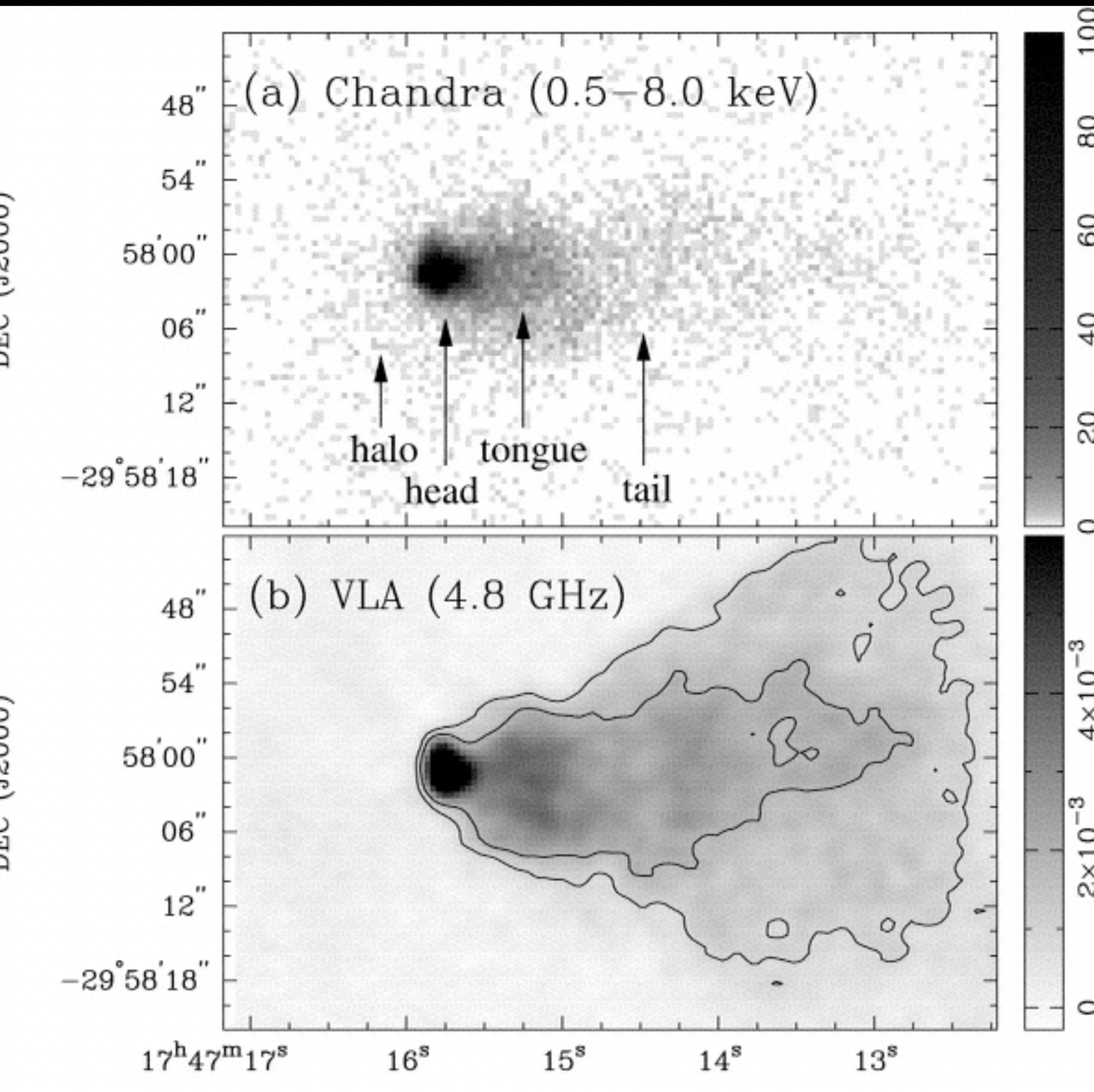

Gaensler et al. 2004

- Extremely long PWN produced by PSR J1747-2958 ($l \sim 17 d_5$ pc)
  - observe X-ray/radio emission from innermost regions, and long radio tail
- X-ray image shows compact emission around pulsar, "tongue" region behind pulsar, and extended tail
  - $L_x/\dot{E} = 0.02$
  - tongue corresponds to TS region
  - standoff distance implies $\mathcal{M} \geq 60$
    $\therefore v \approx 600$ km s^{-1}
    assuming motion through warm ISM
  - consistent w/ $R_{TS}^B/R_{TS}^F > 5$
- X-ray tail is shocked wind from back TS region
  - outer tail shows steeper spectrum
  - long, broad radio tail is combination of swept-back wind w/ that from behind TS

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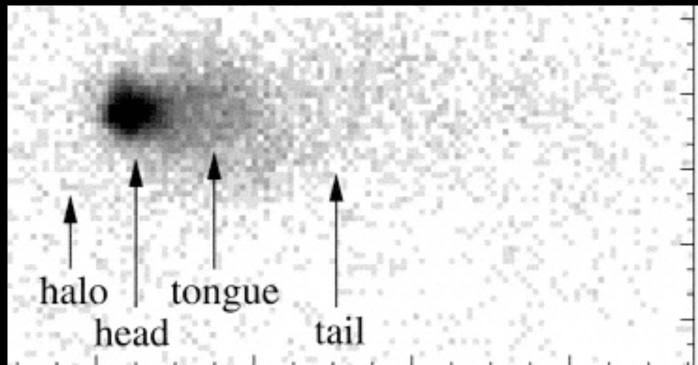
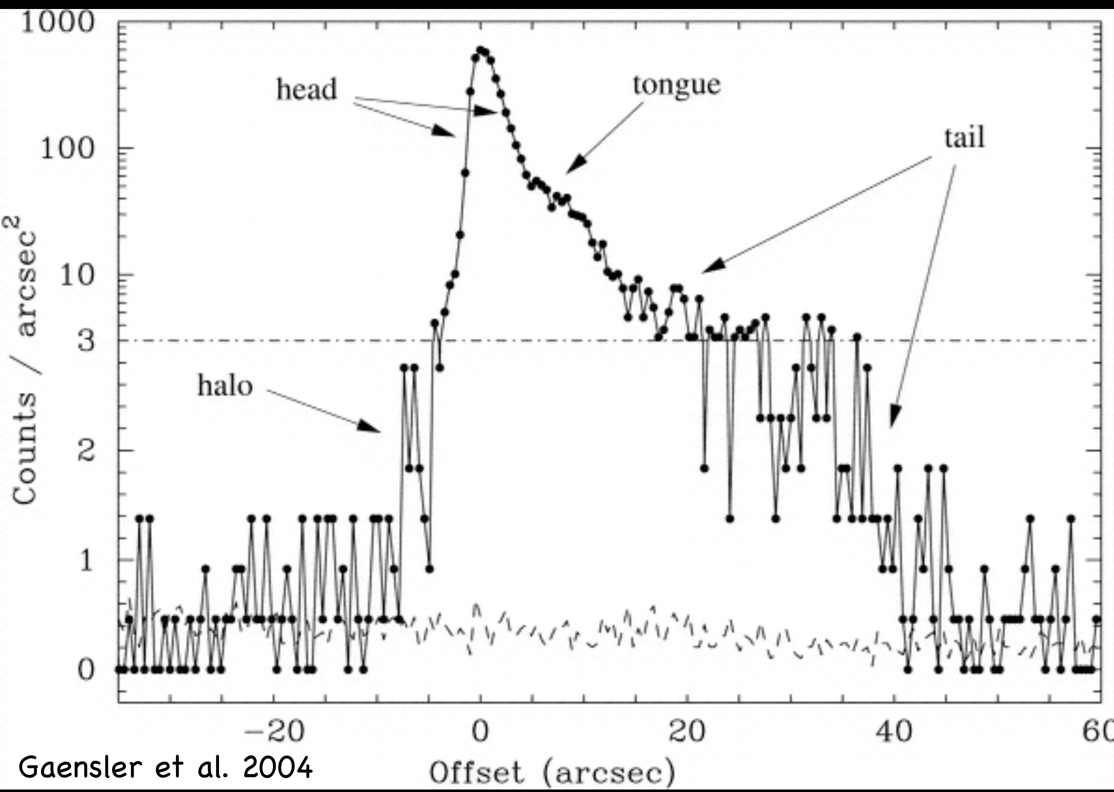




Gaensler et al. 2004

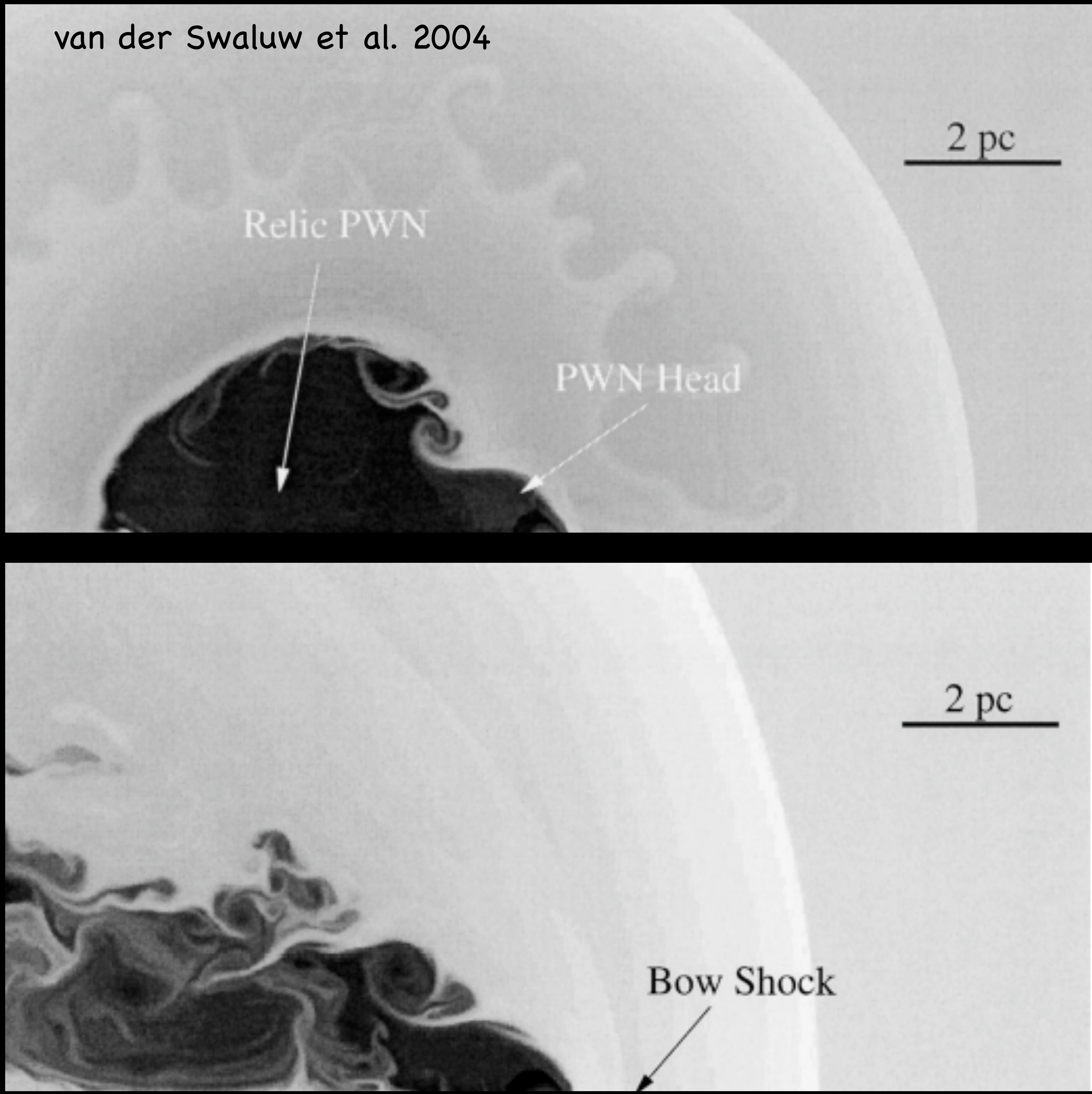
Issues:

- Compact "head" of X-ray emission appears extended
  - should just be the pulsar
  - possibly a pileup effect, or is this something similar to clumps seen "inside" TS region in Crab and other PWNe?
- Faint halo observed ahead of bow shock
  - unlikely to be shocked ISM
  - probably dust scattering halo
- X-ray emission in "tongue" region has a "filled" morphology
  - associated with finite thickness due to ion gyration, along with Doppler beaming

Going Supersonic

- If pulsar is moving through SNR, it will encounter reverse shock first in direction of motion
  - relic PWN is pushed back from pulsar
  - nebula around pulsar begins being swept into a cometary shape

- SNR temperature drops toward outer shell, reducing sound speed
  - for Sedov-phase SNR, pulsar motion becomes supersonic at $R \approx 2R_s/3$
  - beyond this a true bow shock forms



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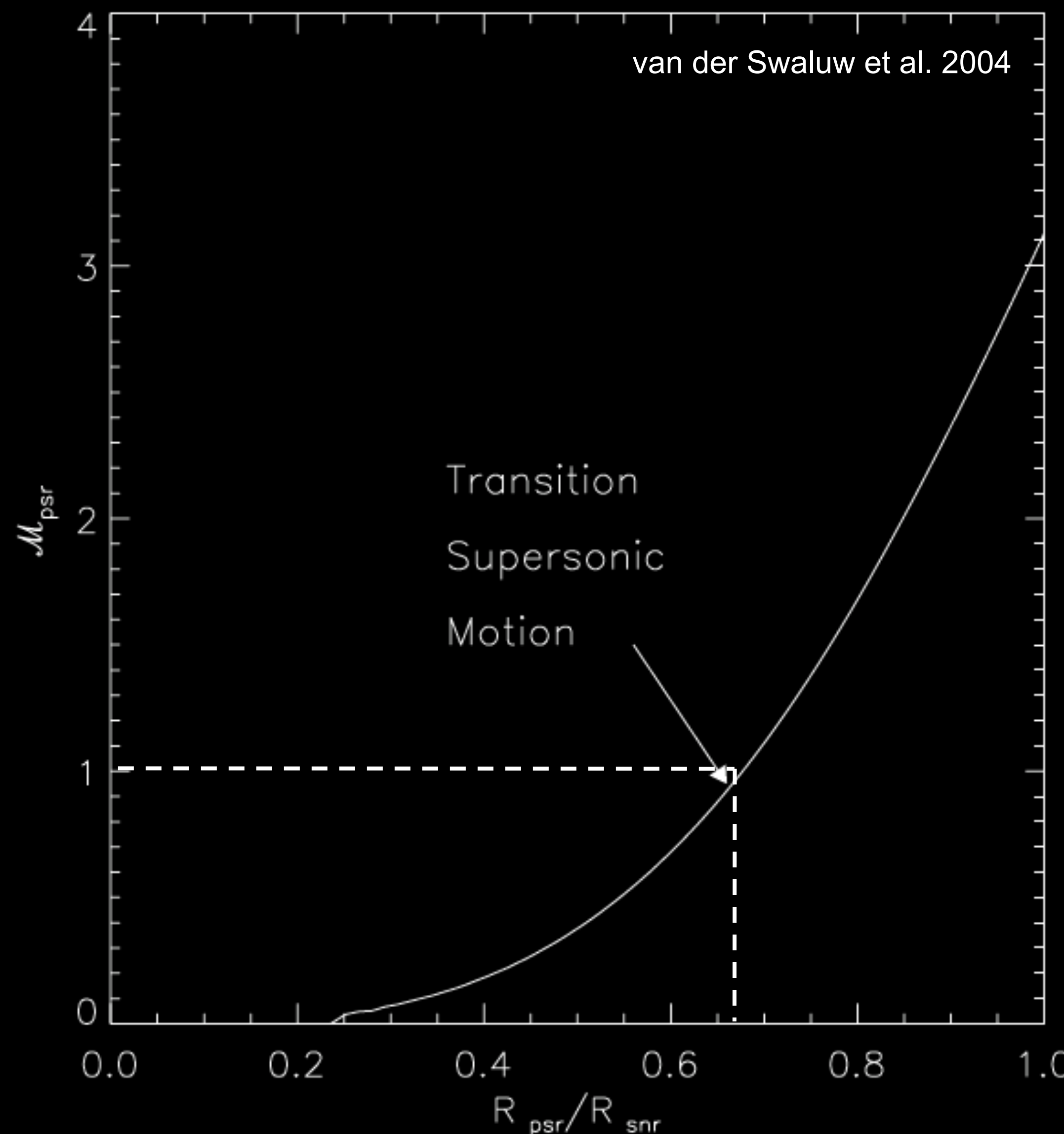
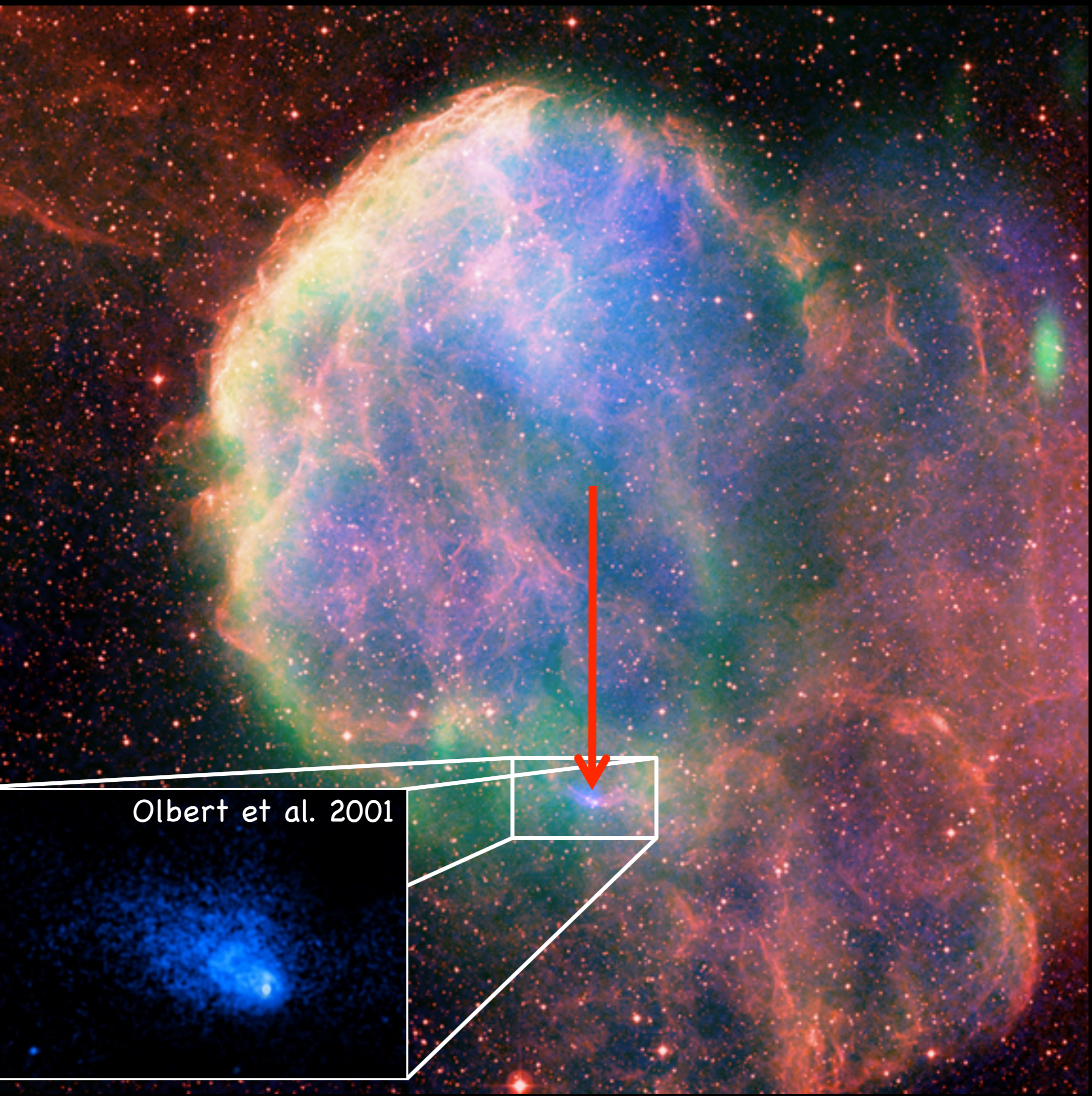


Bow Shock PWNe in SNRs: G189.22+2.90



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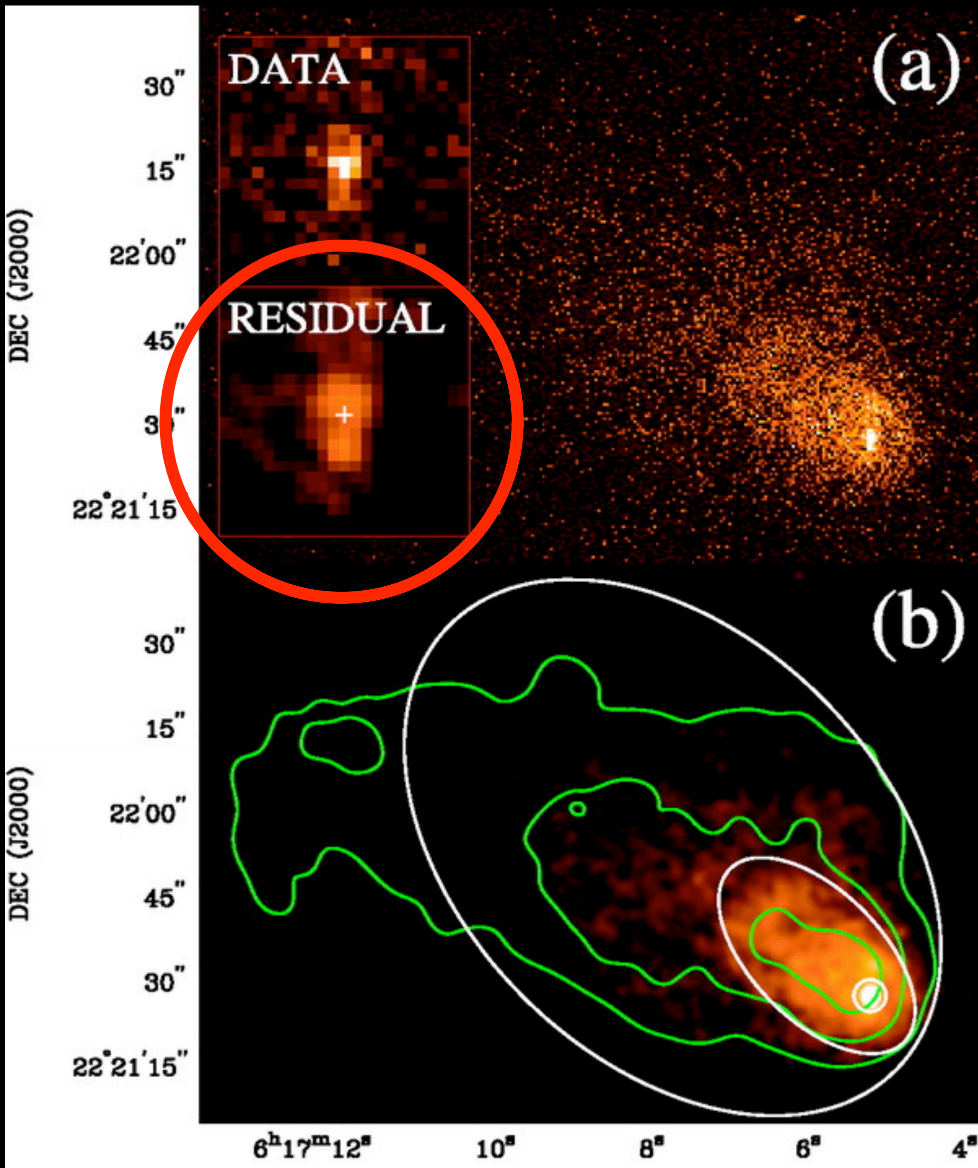
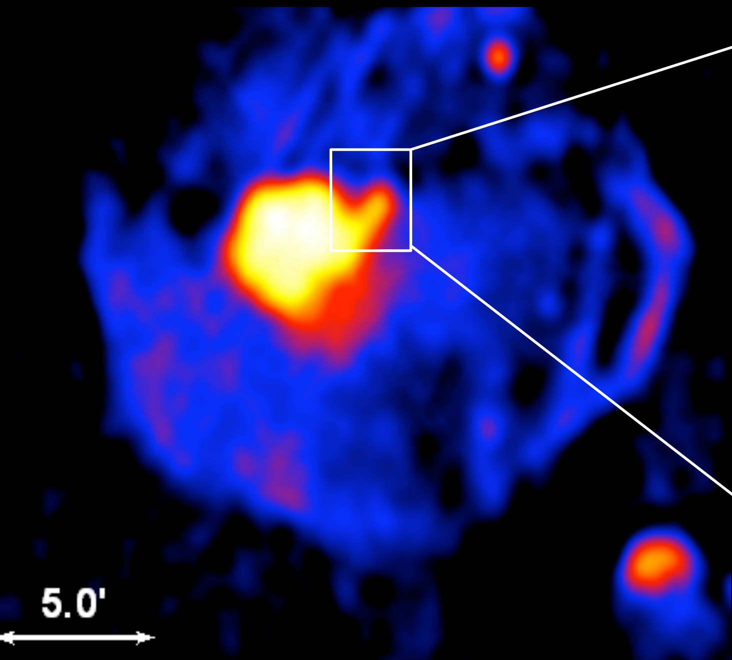
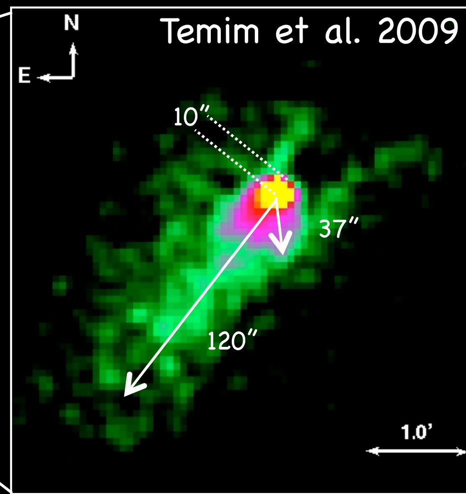


Gaensler et al. 2006

- G189.22+2.90 is a bow shock PWN in IC 443 (t_{SNR} ~30,000 yr)
  - orientation suggests non-uniform medium for SNR (plus "crosswinds" for PWN)
- The standoff distance is resolved
  - indicates v ≈230 km s^{-1}
- "Tongue" feature traces TS region
  $\mathcal{M} = \gamma^{-1/2} R_{TS}{}^{B}/R_{TS}{}^{F} \approx 1.2$
  - low Mach number consistent w/ high sound speed in SNR interior
  - "tongue" is filled, like in Mouse
  - tail is less elongated and broader than that for Mouse, consistent with small $\mathcal{M}$
- Pressure balance w/ SNR (kT ~0.2 keV) suggests $\dot{E} \approx 5 \times 10^{37}$ erg s^{-1}

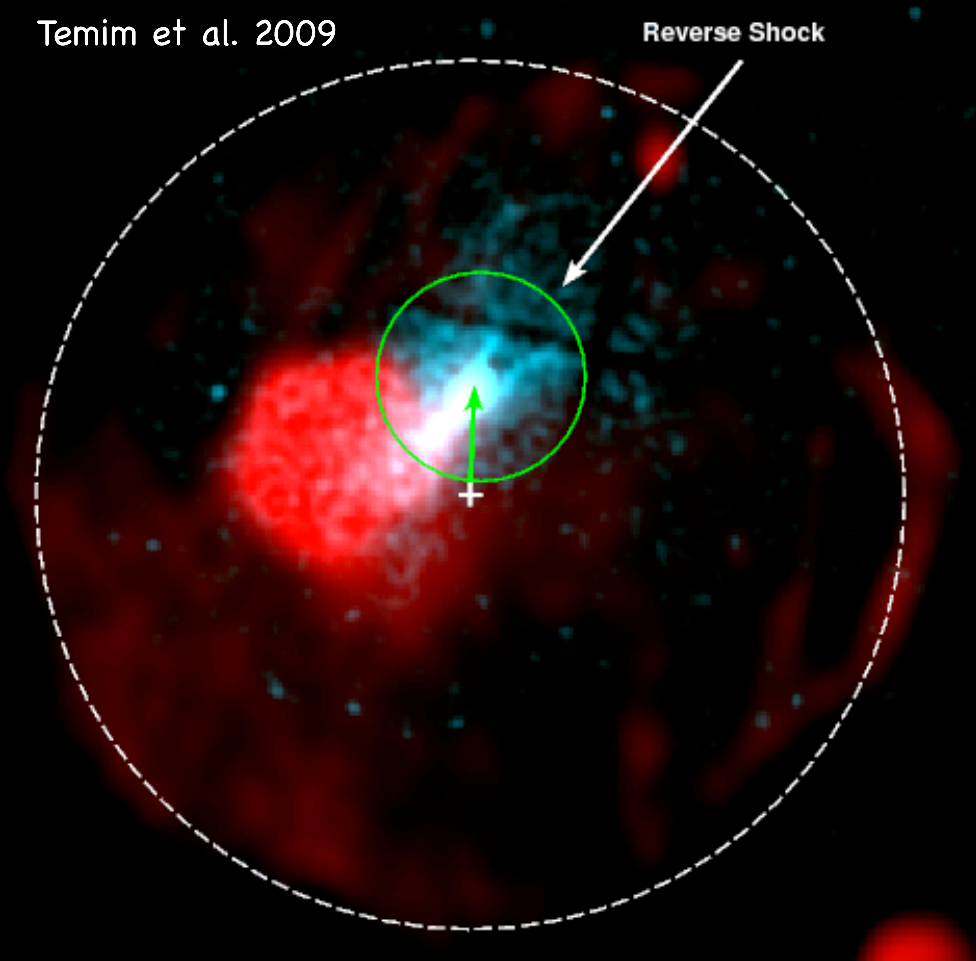
PWNe in Transition? G327.1-1.1





- X-ray observations reveal compact core at tip of radio finger
  - trail of emission extends into nebula
  - L_x suggests $\dot{E} \sim 10^{37.3}$ erg s^{-1}
- Compact core is extended, and surrounded by cometary structure
  - tail extends back toward radio PWN
- Estimates of pressure, velocity, and $\dot{E}$ suggest entire TS shock region extent of ~3.5 arcsec
  - similar to extent of inner core, but this doesn't explain cometary shape
- If cometary segment is TS, then $R_{TS}^B/R_{TS}^F > 3.7$, suggestive of high-Mach number
  - inconsistent w/ being inside SNR…
- Curious prong-like structures extend in direction opposite the relic PWN
  - nothing seems consistent with a standard bow shock PWN…
  - **perhaps in transition to this stage?**

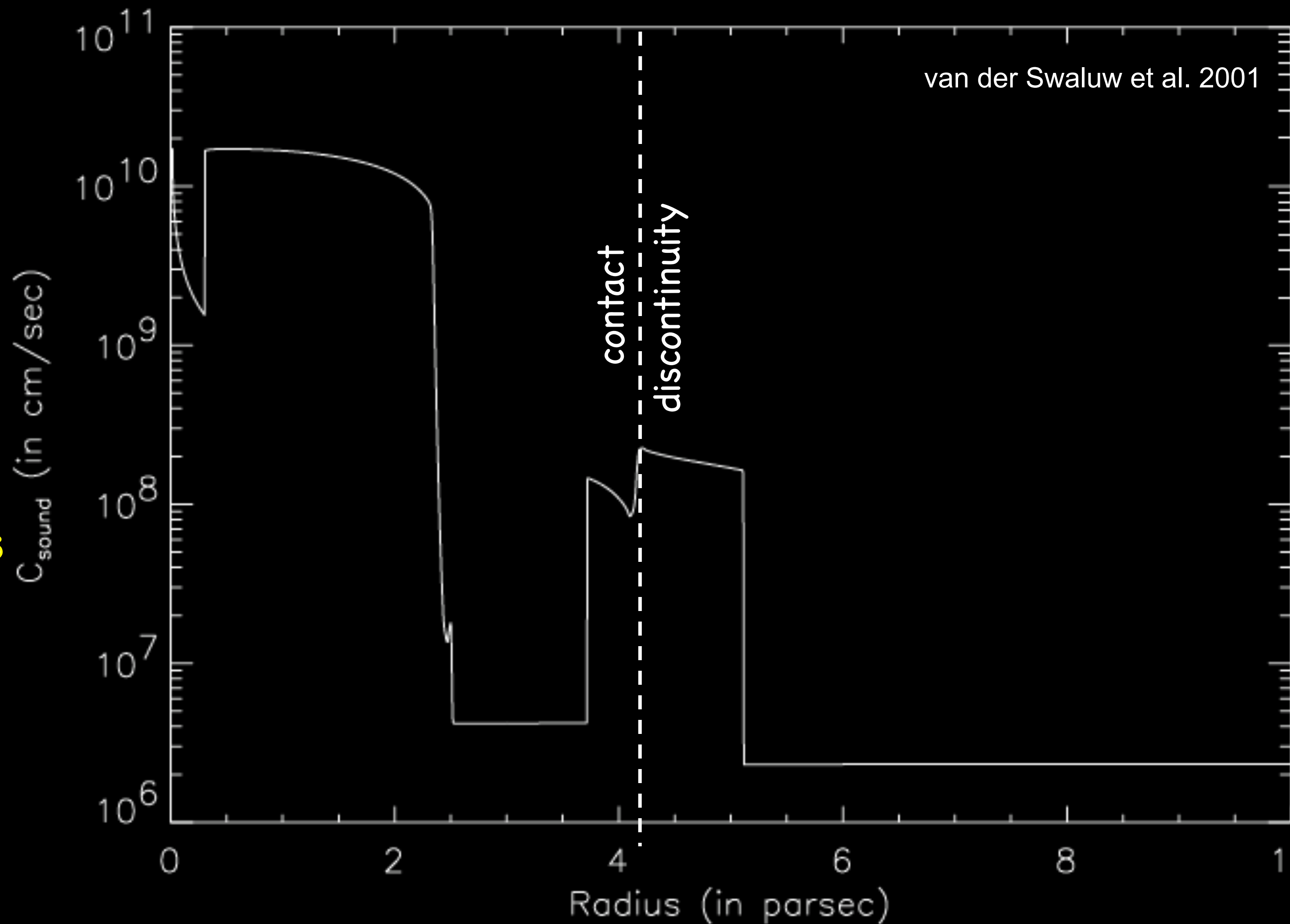
PWNe in Transition? G327.1-1.1



- Overall morphology of SNR and PWN suggests that an asymmetric reverse shock has played a role
  - PWN has apparently been disturbed by RS, and is now re-forming around pulsar
- RS appears to have approached more rapidly from the northwest
  - pulsar appears to be traveling northward
  - combination produces offset between NS and SNR center, as well as displacement of PWN
- Prong-like structures connect to a bubble
  - appears to be blown by the pulsar into the SNR interior, apparently in the region recently crossed by the reverse shock

Cruising at the Reverse Shock

- Note that in pre-Sedov phase, sound speed is lower in reverse shock region than in outer SNR
  - bow shocks can start to form soon after pulsar encounters reverse shock
  - this can have implications for inferences about pulsar velocities based on presence of bow shock structure



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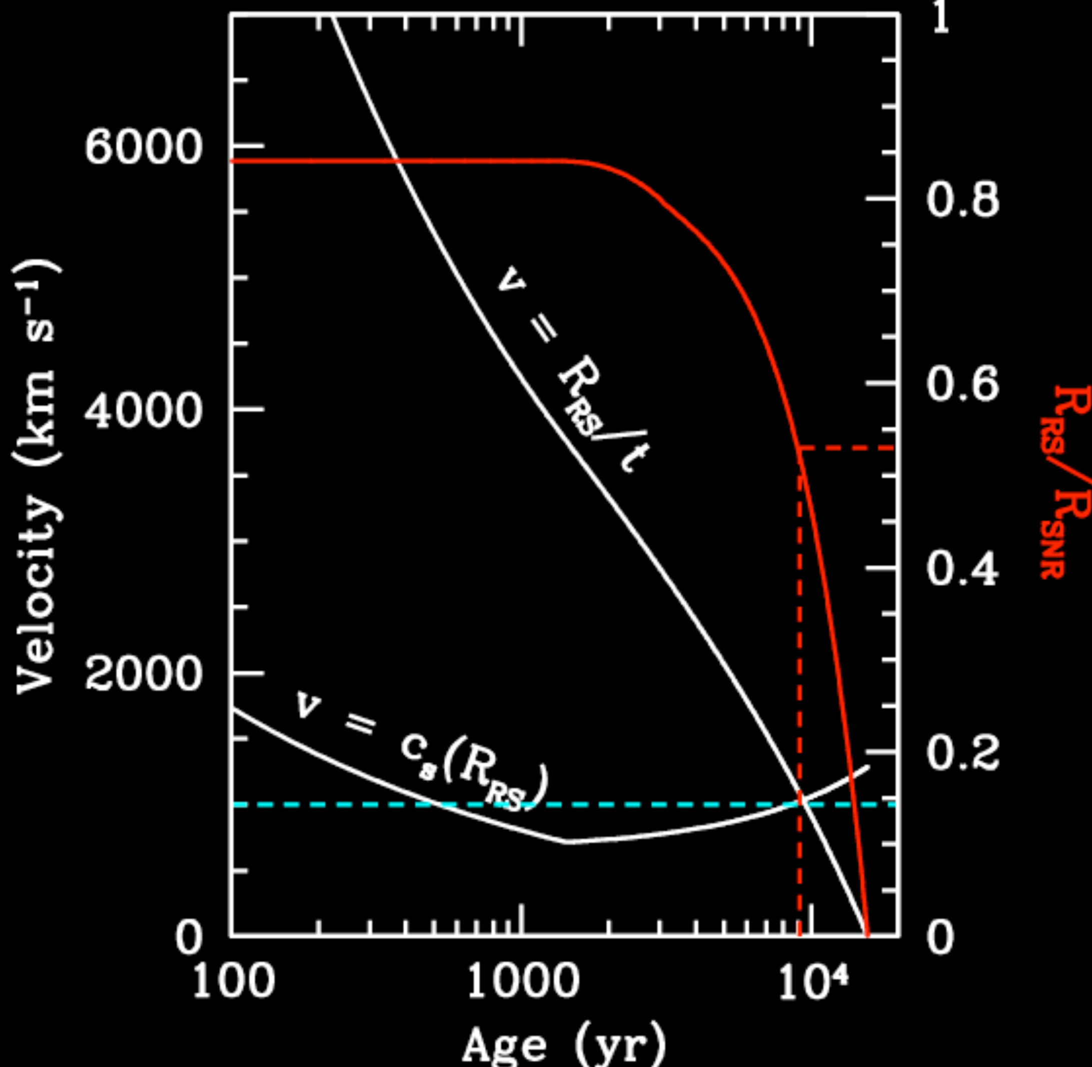
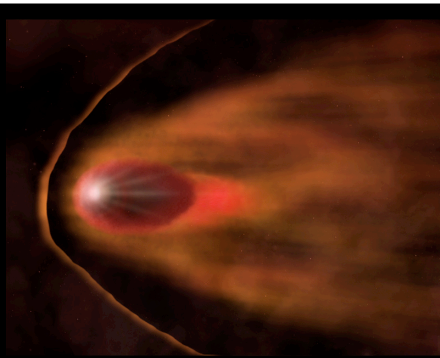


Summary



I. Observations of Bow Shock PWNe

- High-resolution studies reveal similar underlying structure to static PWNe
- Morphology provides measure of Mach number
- Knowledge of surroundings provides $\dot{E}$, pulsar velocity
- Questions remain on detailed structure of innermost regions

II. Transition Objects

- As pulsars approach supersonic speeds, PWN morphology is distorted toward bow shock geometry
- More modeling required to study the structure in this stage

III. Bow Shocks Near the Reverse Shock

- At least some fast pulsars should form bow-shock-like structures well inside SNRs, as they pass through the reverse shock
- This has impact for interpretation of pulsar velocities, and possibly as a probe of ejecta