

PULSAR WIND NEBULAE FROM RADIO TO X-RAYS

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1. Basic PWN physics: shock confinement, wave-like pulsar wind (unique)
2. Radio-to-X-ray diagnostics → composition, energy transport, magnetic field geometry

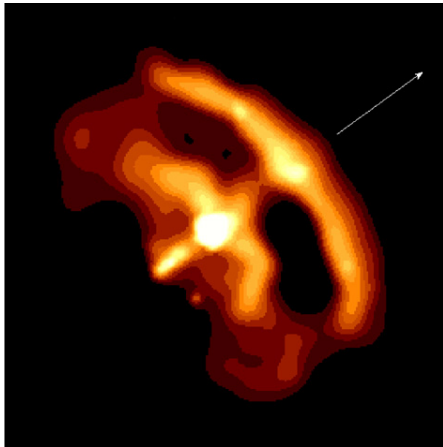
WHAT IS A PWN?

- “Bubble” of **magnetic field** and **relativistic e^\pm**
- Inflated by pulsar, confined by environment
- **Synchrotron** source: centre-filled, highly pol'd
- Wind **cools** adiabatically → invisible as far as **termination shock**



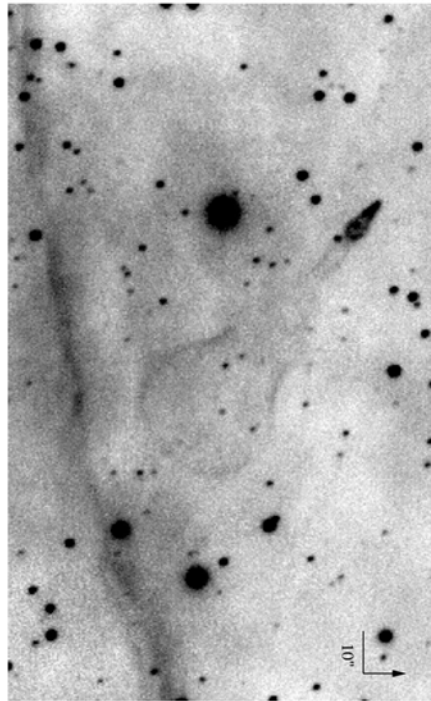
Crab nebula (optical)

ENVIRONMENTAL ZOO



Vela SNR

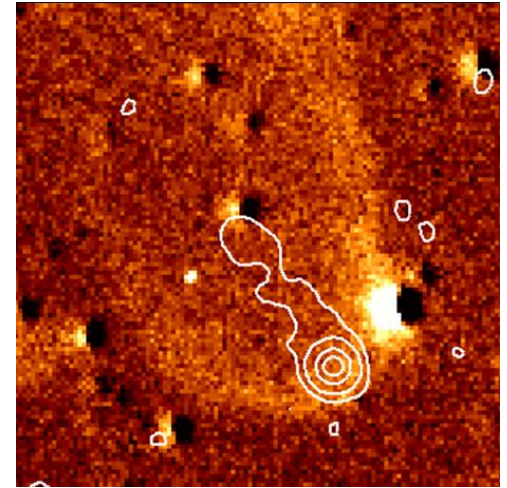
Like Crab, but older
(Helfand et al. 01)



Guitar nebula

H α bow shock

PSR speeding through ISM
(Chatterjee & Cordes 03)



“Black Widow” binary

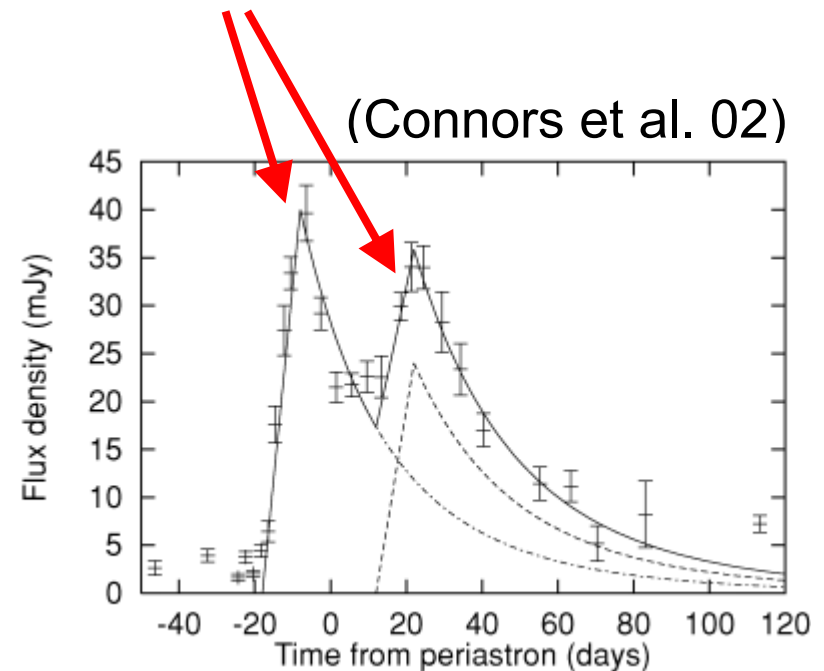
H α + X-ray shocks

Wind ablates companion
(Gaensler et al. 03)

FLARES FROM PSR B1259-63

- Eccentric binary PSR
- Splashes into Be star's disk → **eclipse**
- **Pulsed** radio → DM, RM → density, B field
- **Unpulsed** radio & X-ray → shock physics

transient “mini-PWN”



radio eclipse
1.4 GHz

TERMINATION SHOCK

PSR wind
ram pressure

$$P \approx L/4\pi r^2 c$$

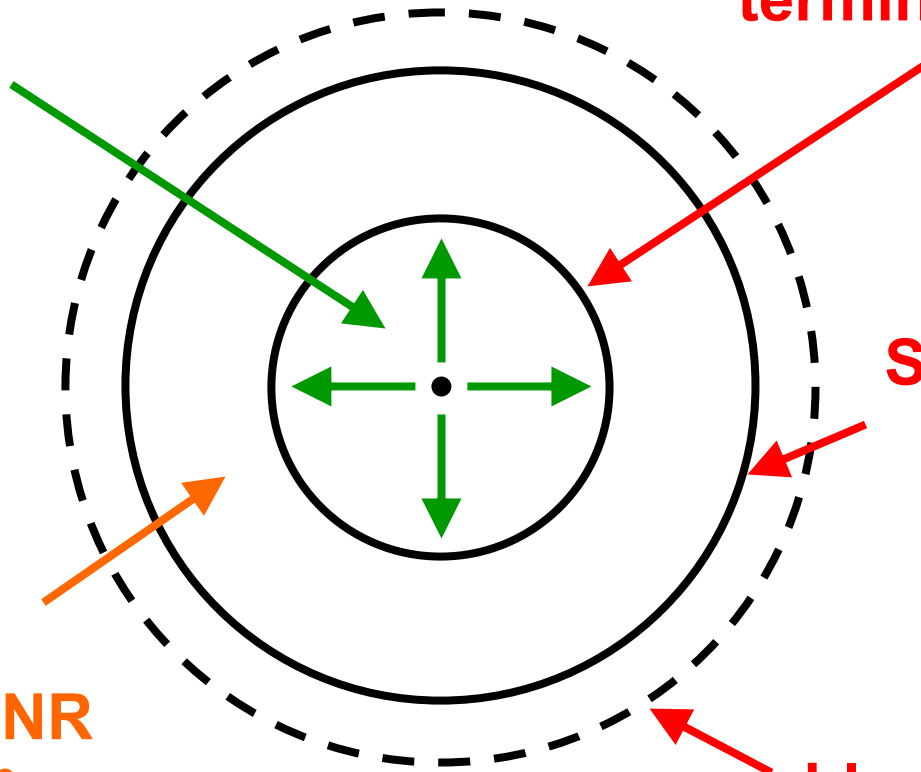
termination shock

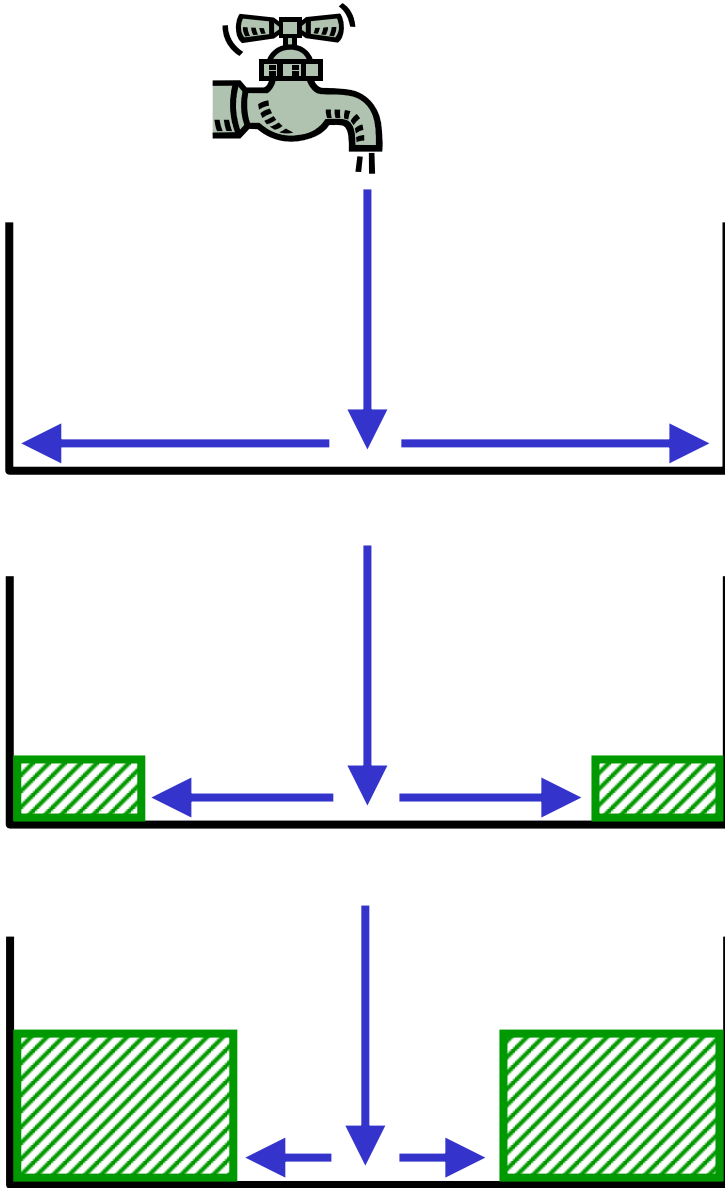
SN remnant +
filaments

backwash
confined by SNR

$$P \approx L \times \text{age} / (4\pi r^3 / 3)$$

blast wave





Reverse shock: contracts as backwash accumulates

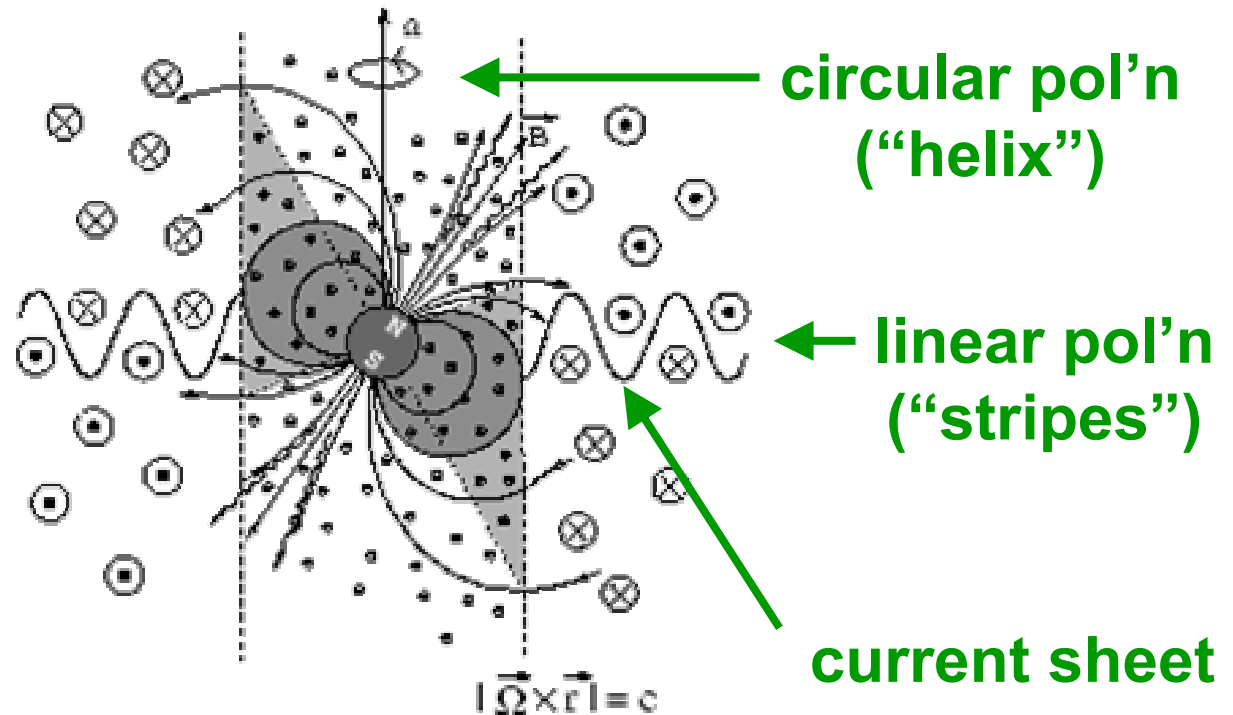
WAVE-LIKE WIND

$$J_{\text{disp}} \propto E \propto r^{-1}$$

$$J_{\text{cond}} \propto n \propto r^{-2}$$

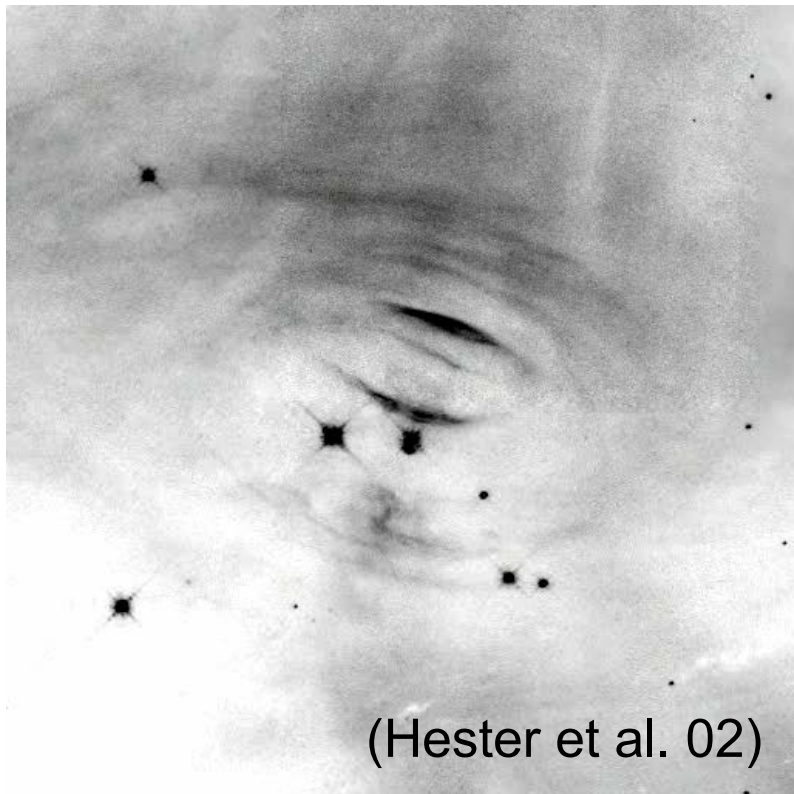
$$J_{\text{disp}} > J_{\text{cond}}$$

for $r > 10^5 r_{\text{LC}}$

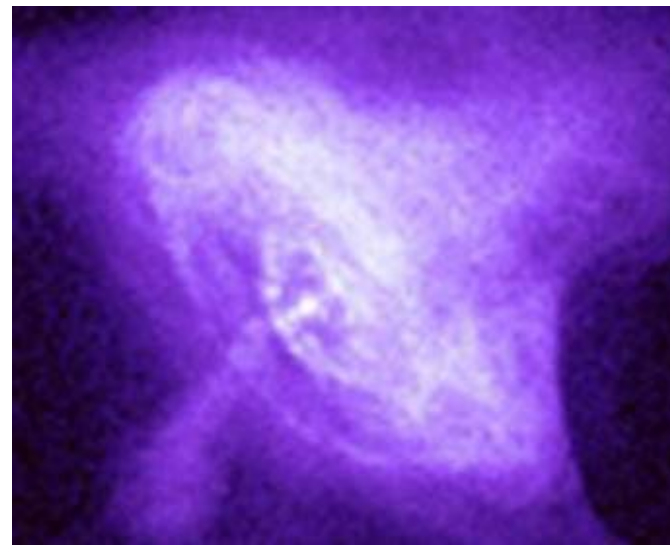


Global plasma wave oscillating at Ω_*

“CROSSBOW” MORPHOLOGY

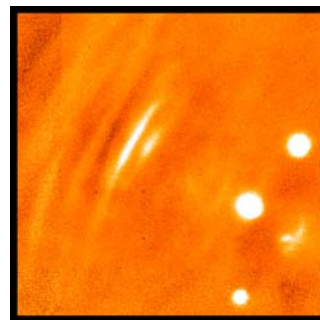


(Hester et al. 02)



Chandra
(X-ray)

HST
(optical)



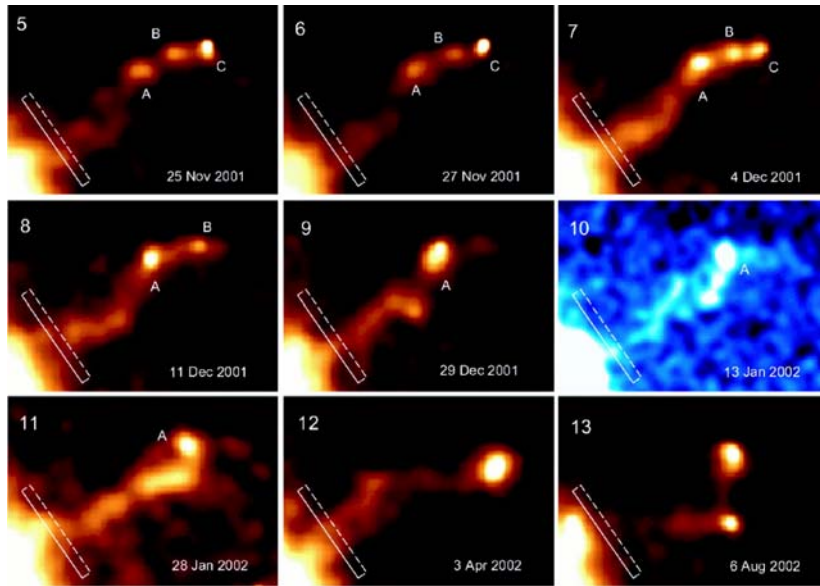
Gemini
(near-IR)

Torus (wisps) + **jet** (knots) **vary** daily

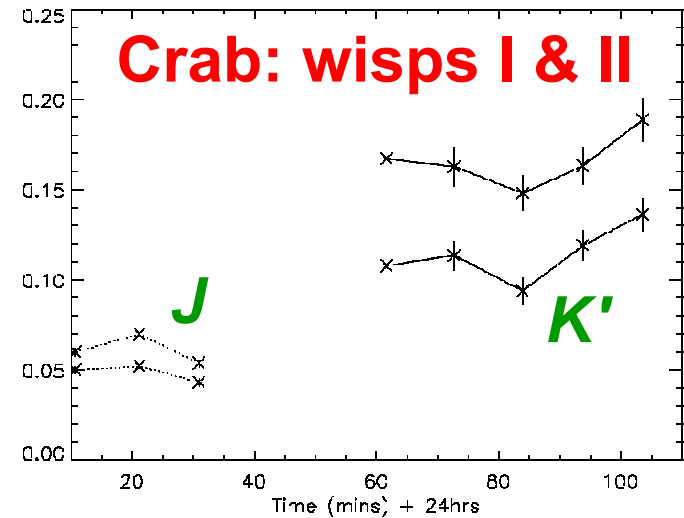
mHz variability in near IR:

Hokupa'a adaptive optics –
beware PSF & background
(Melatos et al. 04)

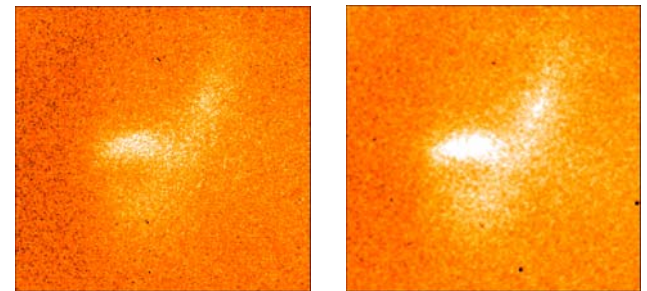
Vela: X-ray jet = “fire hose”



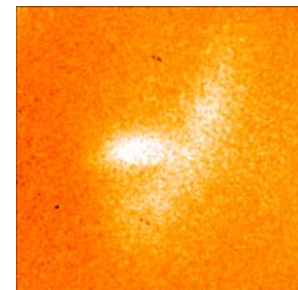
(Pavlov et al. 03)



Crab: sprite + rod



+ 20 min



+ 2 d

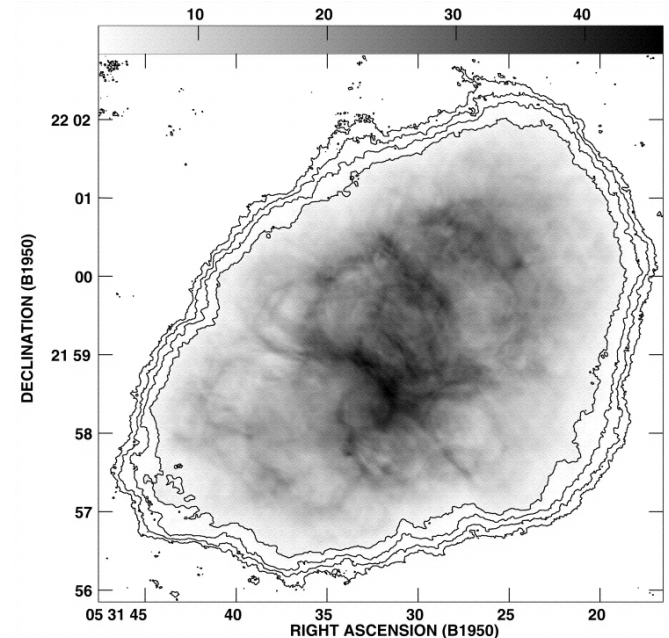
RADIO ELECTRONS

- Radio, X-ray wisps **coincide**
- **Move** in concert ($\approx 0.24c$)
- Uniform radio spectrum

→ radio and X-ray e^\pm
accelerated together!

- Near-IR spectrum varies:
sprite $\nu^{-0.2} \neq$ wisps $\nu^{-0.7 \pm 0.1}$

VLA, 5 GHz



(Bietenholz et al. 01)

MULTI- λ DIAGNOSTICS

Wisp structure \rightarrow wind **composition**

- Ion cyclotron acceleration \rightarrow ν and γ -rays

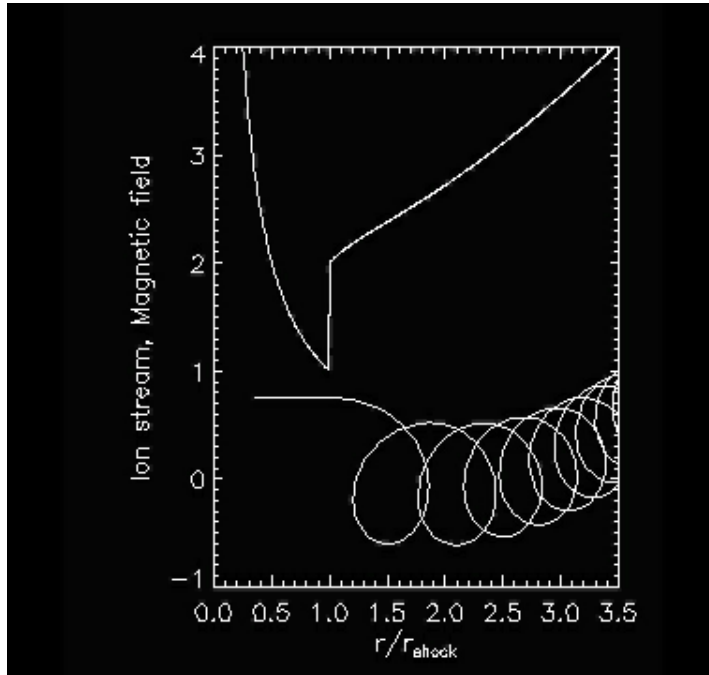
Confinement geometry \rightarrow **energy transport**

- Energy flux versus latitude
- Electromagnetic or kinetic?

Polarization \rightarrow **magnetic field** geometry

- Collimation and stability

I. WISPS = ION SHOCK?

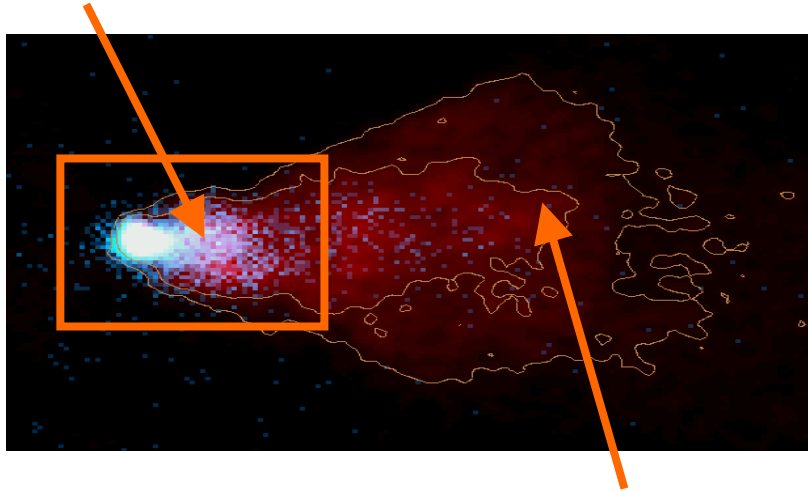


- **ions gyrate** → B field compressed → ion bunches → variability (Spitkovsky & Arons 02; cf. Komissarov & Lyubarsky 03)
- Internal structure of shock **resolved** – unique!

- **Ion current** = **Goldreich-Julian** ($dN_i/dt \approx 10^{34} \text{ s}^{-1}$)
- **Neutrinos!** $p p \rightarrow \pi \rightarrow \gamma \nu$ (in known ratio $L_\gamma : L_\nu$)

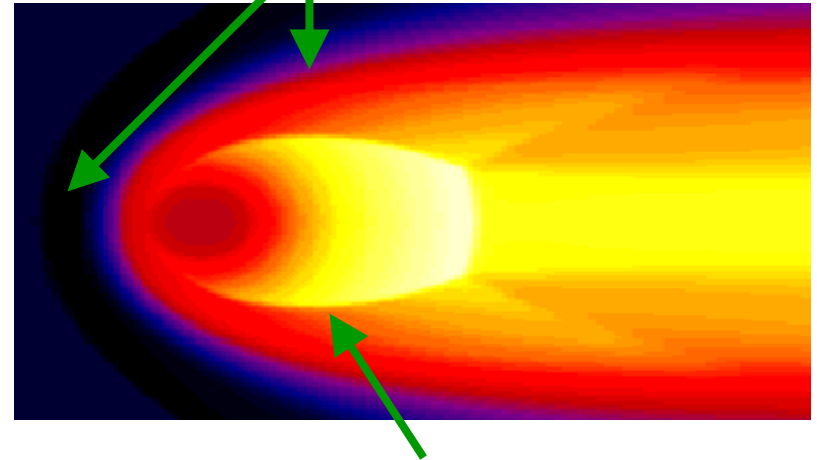
II. CONFINEMENT GEOMETRY

X-ray backflow from aft shock



radio backflow from fore shock

bow shock + CD

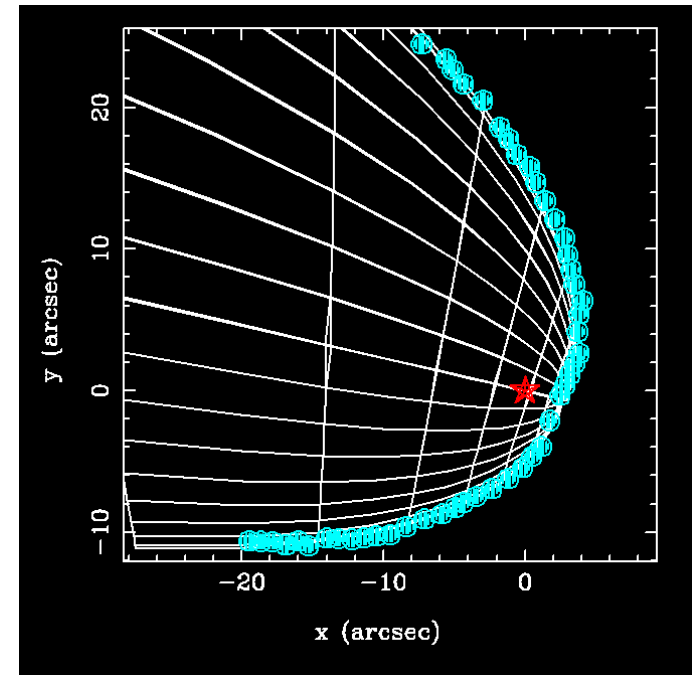


termination shock

- Example: The Mouse (Gaensler et al. 03)
- Radio + X-ray synchrotron tails
- Mach number from stand-off distance

ENERGY FLUX VS LATITUDE

- Shape: **ram pressure**
- Brightness: **Doppler**
- Anisotropic wind **or**
ISM density gradient
(Chatterjee & Cordes 04)
- Monopole flux $\propto \sin^2\theta$
(Komissarov & Lyubarsky 03)



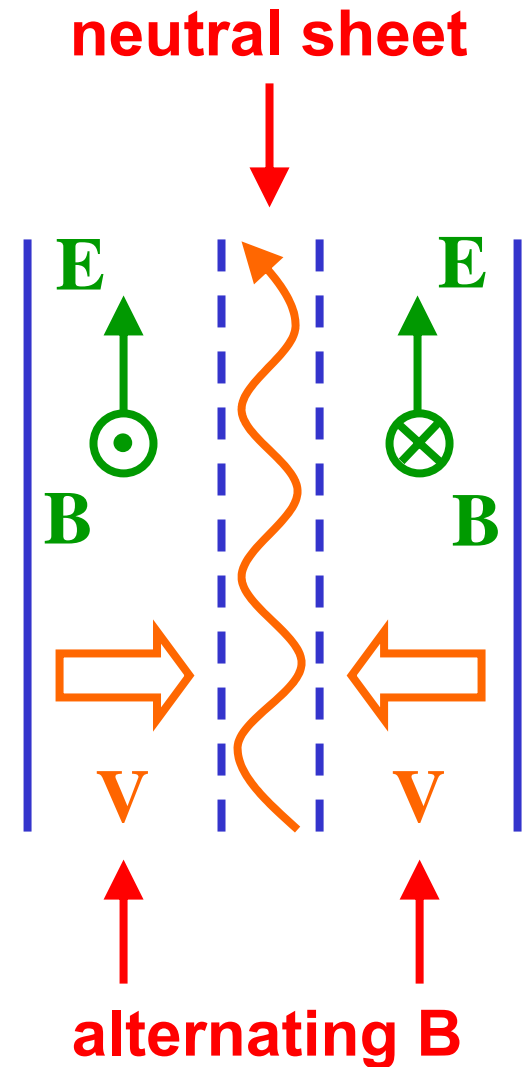
(Gaensler et al. 02)

EM \rightarrow KE CONVERSION

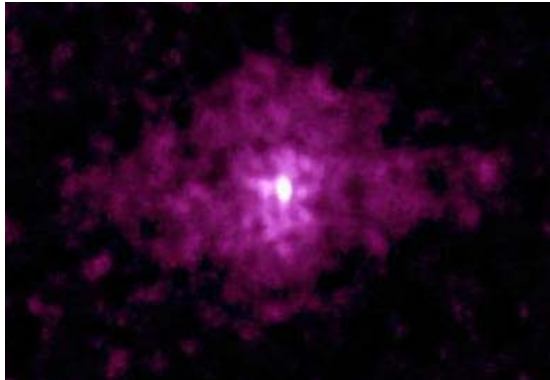
$$\sigma = \text{EM flux} : \text{KE flux}$$

- **Shock:** $\sigma \approx 10^{-3}$ so MHD flow can decelerate from shock ($c/3$) to edge of PWN (1500 km s^{-1})
- **Pulsar:** $\sigma \approx 10^6$ (e^\pm cascades)
- Force-free **linear accelerator** (Contopoulos et al. 02)
- **Reconnection** in striped wind (Lyubarsky & Kirk 01)
- **Wave conversion** via instability (Melatos 98)

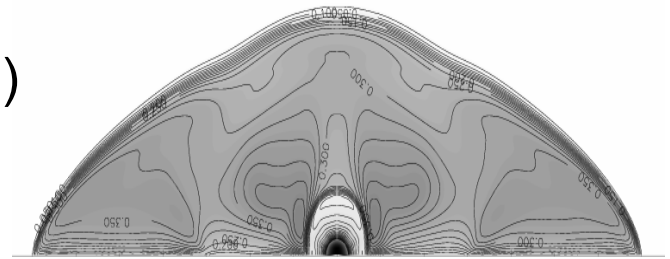
- **Striped wind:** $V_{\text{phase}} = V_{\text{wind}}$
- Reconnection and heating (Lyubarksy & Kirk 01)
- **Electromagnetic wave:** large amplitude ($\omega < \omega_p$)
- Unstable (Melatos & Melrose 96)
- Puzzles... How launched?
Synchro-Compton rad'n?
Energy transport?



III. POLARIZATION = B FIELD



3C58 in X-rays
(Murray et al. 02)



MHD simulations
(van der Swaluw 03)

- **Collimation:** postshock hoop stress ($\rho\mathbf{E} + \mathbf{J} \times \mathbf{B} \approx \mathbf{0}$ before the shock) & anisotropic energy flux
- **Disruption of B_ϕ :** MHD kink instability (Begelman 98)
BUT pol'n regular – regenerated by α dynamo?

SUMMARY

Radio-to-X-ray PWN:

- SN remnant, ISM, eclipsing binary
- Shock = “**crossbow**” which **varies** daily
- PSR wind = two-zone large-amplitude **wave**

- Radio & X-ray wisps → **ions** → **$v + \gamma$**
- ISM bow shock → anisotropic energy flux
- SNR → calorimeter → **EM : KE**
- Radio & X-ray pol'n → **B field** & collimation