A Detailed Study of

the Pulsar Wind Nebula 3C 58

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Pulsar Wind Nebulae

- Young NS powers a particle/magnetic wind that expands into SNR ejecta
  - toroidal magnetic field results in axisymmetric equatorial wind

- Termination shock forms where pulsar wind meets slowly expanding nebula
  - radius determined by balance of ram pressure and pressure in nebula

- As PWN accelerates higher density ejecta, R-T instabilities form
  - optical/radio filaments result

- As SNR/PWN ages, reverse shock approaches/disrupts PWN
  - not of interest in context of 3C 58 as no blast-wave component is seen (low n)
About 3C 58

- **Wind nebula produced by PSR J0205+6449**
  - $D = 3.2$ kpc (HI absorption)
  - size: $9 \times 5$ arcmin $\Rightarrow 8.4 \times 4.7$ pc
  - $P = 62$ ms (Camilo et al. 2002)

- **Believed to be associated w/ SN 1181** based on historical records
  - pulsar has 3rd highest spin-down power of Galactic pulsars
    $\Rightarrow$ very young
  - however, PWN expansion velocity observed in optical filaments is too low to explain large size, making association troublesome

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How Does the Neutron Star Interior Cool?

- Charge neutrality requires:
  - NS matter is highly degenerate

- Momentum conservation requires

  We thus require
  - momentum can only be conserved for Urca reactions if proton fraction is >0.12
  - for lower values, need bystander particle to conserve momentum
PSR J0205+6449: Cooling Emission

- Point source spectrum is a power law; adding blackbody component leads to limit on surface cooling emission
  - since atmosphere effects harden spectrum, limit on surface temperature is conservative

- For NS w/ $R = 10$ km,
  - standard cooling models predict higher temperature for this age
  - may indicate direct Urca or pion cooling
PWN Jet/Torus Structure

- Poynting flux from outside pulsar light cylinder is concentrated in equatorial region due to wound-up B-field
  - termination shock radius decreases with increasing angle from equator

- For sufficiently high magnetization parameter ($\sigma \sim 0.01$), magnetic stresses can divert particle flow back inward
  - collimation into jets may occur
  - asymmetric brightness profile from Doppler beaming

- Collimation is subject to kink instabilities
  - magnetic loops can be torn off near TS and expand into PWN (Begelman 1998)
  - many pulsar jets are kinked or unstable, supporting this picture
Inner Structure in PWNe: Jets

- **Collimated features**
  - some curved at ends – why?

- **Wide range in brightness and size (0.01–6 pc)**
  - how much energy input?

- **Perpendicular to inner ring**
  - directed along spin axis?

- **Relativistic flows:**
  - motion, spectral analysis give $v/c \sim 0.3–0.6$

- **Primarily one-sided**
  - Doppler boosting?

- **Magnetic collimation / hoop stress?**

**Crab Nebula (Weisskopf et al 2000)**

**PSR B1509-58 (Gaensler et al 2002)**

**Vela PWN (Pavlov et al 2003)**

**Kommisarov & Lyubarsky (2003)**
3C 58: Structure of the Inner Nebula

- Central core is extended N/S
  - if termination shock, suggests ring-like structure tilted at about 70 degrees
  - agrees with spindown
  - profile shows bump from torus

- Suggests E-W axis for pulsar
  - consistent with E-W elongation of 3C 58 itself due to pressure from toroidal field (van der Swaluw 2003)
• Radial steepening of spectral index shows aging of synchrotron-emitting electrons
  - consistent with injection from central pulsar
• Modeling of spectral index in expected toroidal field is unable to reproduce the observed profiles
  - model profile has much more rapid softening of spectrum (Reynolds 2003)
  - diffusive particle transport and mixing may be occurring
3C 58: A Thermal Shell

- Outer region shows thermal emission (Bocchino et al. 2001)
  - Chandra confirms presence of a thermal shell
  - corresponds to ~0.06 solar masses
  - 3C 58 has evolved in a very low density region

- Thermal component requires enhanced neon
  - consistent with ejecta being swept up by PWN
• Current Con-X baseline gives \( \sim 16000 \) counts in Ne line in a 100 ks observation

• Can measure velocity shift of front/back shell to address discrepancy in expansion
  - variation in projected velocity with radius easily measured as well
Filaments in PWNe

- As PWN expands, it encounters and accelerates denser ejecta
  - Rayleigh-Taylor instabilities form a network of optical line-emitting filaments
  - Compressed magnetic field enhances synchrotron emission as well, creating radio filaments

- In Crab Nebula, velocities show that filaments form a shell
  - X-ray filaments not seen because B-field is too large for energetic particles to reach outskirts of nebula
3C 58: Radio vs X-ray Size

- The X-ray emission from 3C 58 extends virtually all the way to the radio boundary.
  - Magnetic is smaller than in Crab; synchrotron break must be just below X-ray band.
- In this case, we might expect to see X-ray filaments as well.
X-ray emission shows considerable filamentary structure
- particularly evident in higher energy X-rays
Radio structure is remarkably similar, both for filaments and overall size
• X-ray emission shows considerable filamentary structure
  - particularly evident in higher energy X-rays
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Reynolds & Aller 1988
Optical Filaments in 3C 58

- Considerable filamentary structure is seen in optical images of 3C 58 - these are presumably similar in nature to Crab optical filaments; evidence of ejecta encountered by expanding PWN

- These filaments do not seem to have X-ray counterparts (with a few possible exceptions) - indicative of a different origin?

- Loop-like structure and lack of thermal emission suggest magnetic structures - produced by kink instabilities in toroidal field (Begelman 1998)? - may also be responsible for curved jets seen in Crab, Vela, 3C 58, and others
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IRAC Observations of 3C 58

- PWN clearly detected
  - extent and morphology similar to radio
  - suggestions synchrotron emission in IR

- Torus region around pulsar detected as well
Summary

- **3C 58** is a typical PWN powered by a young, energetic pulsar.

- **Limits on blackbody emission from NS** indicate nonstandard cooling.
  - Interpretations with direct Urca processes or pion condensates are suggested.

- **Central X-ray source is extended in N-S direction**
  - Consistent with wind termination shock.
  - Indicates E-W pulsar axis with 70 degree tilt to line of sight.
  - Deep observation resolves jet/torus structure.

- **Outer nebula has thermal shell**
  - Overabundance of Ne indicates ejecta component.
  - Total mass of shocked gas is small; radius implies small ejecta mass.

- **Inner nebula shows numerous loop-like and extended structures**
  - Radio structure is remarkably similar.
  - Optical filaments do **not** show good coincidence w/ X-ray features.
  - Different origin? (kink instability structures?)
A Pulsar in G21.5-0.9

- Camilo et al. (2005 - submitted)

- 2nd highest spin-down power, next to Crab
- faint in radio: 70 μJy @1.4 GHz

- 350 ks HRC image shows compact object embedded in extended core
  - offset from center suggests tilted torus w/ spin axis in NE/SW direction

- No pulsations seen in 30 ks HRC timing data
  - pulsed fraction may not be extremely low; surrounding core is bright

- PWN is extended along same NE/SW direction, as with other such systems
  - "bay" in NW is along inferred equatorial plane - similar to Crab "bays"

Questions:
- Why is this young, energetic pulsar so faint?
- What is symmetric filamentary structure telling us about the geometry and evolution?