

A pulsar wind nebula associated with PSR J2032+4127 as the powering source of TeV J2032+4130

Javier Moldón



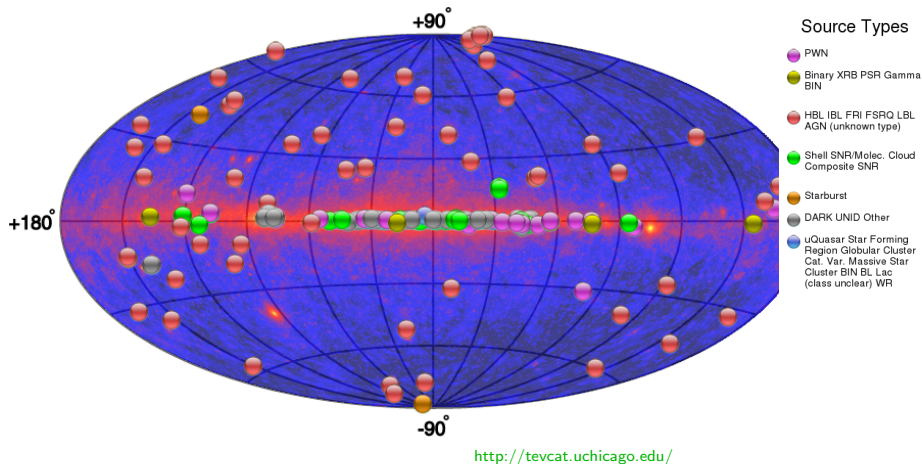
Netherlands Institute for Radio Astronomy

Extreme Astrophysics in an Ever-Changing Universe
Crete, June 16, 2014

Collaborators

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- V. Zabalza, The University of Leicester
- V. Bosch-Ramon, Universitat de Barcelona
- M. Ribó, Universitat de Barcelona
- J. Martí, Universidad de Jaén
- M. Kramer, Max-Planck-Institut für Radioastronomie
- A. G. Lyne, Jodrell Bank Centre for Astrophysics, The University of Manchester
- B. W. Stappers, Jodrell Bank Centre for Astrophysics, The University of Manchester

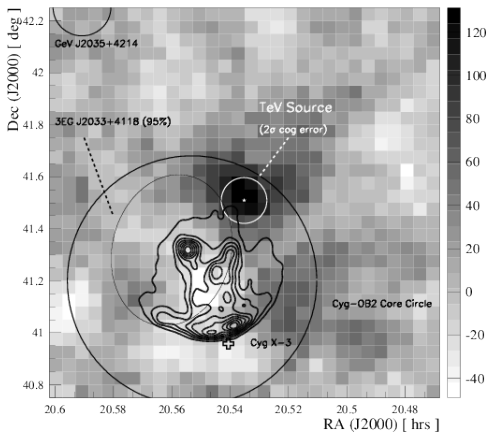
The gamma-ray sky



- VHE (> 100 GeV) sky as seen by Cherenkov telescopes. ~ 140 sources
- 46 extragalactic. 61 galactic. ~ 30 unidentified

First unidentified source: TeV J2032+4130

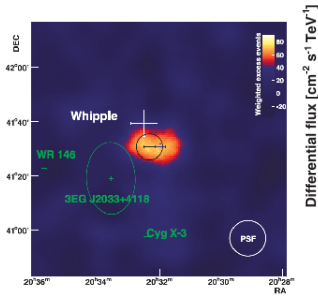
Cyg OB2 Field: HEGRA CT-System



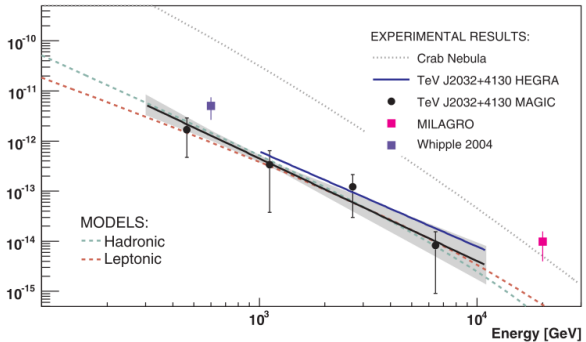
[Aharonian et al. 2002, A&A 293, L37]

- Observed by HEGRA in 1999-2001
- Significance of 6.1σ
- **Steady** flux on yr timescales
- **Extended** with radius $6.2 \pm 1.2 \pm 0.9$ arcmin
- **Hard spectrum** with index $-1.9 \pm 0.1_{\text{stat}} \pm 0.3_{\text{rmsys}}$
- **Integral flux** > 1 TeV at the level of $\sim 5\%$ Crab

TeV counterpart (MAGIC)

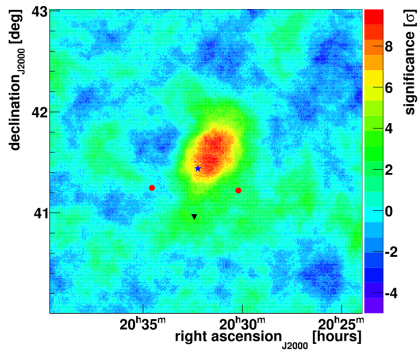


[Albert et al. 2008, ApJ, 675, L25]



- Extension of the energy spectrum down to 400 GeV. No spectral break
- Extension of the source: ~ 5 arcmin (assuming Gaussian shape)
- No flux variability over several yr, compatible with HEGRA (not Whipple)

TeV counterpart (VERITAS)

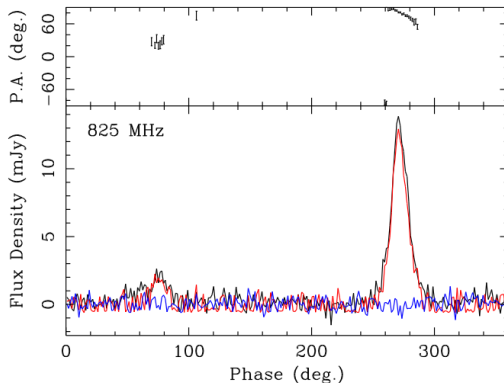


Summary of VHE Detections, Measured Positions, and Extensions for Each Experiment Prior to VERITAS Observations

Experiment	R.A.	Error in R.A. <i>Stat(Sys)</i> (arcmin)	Decl.	Error in Decl. <i>Stat(Sys)</i> (arcmin)	Reported Extension $\pm Stat(Sys)$ (arcmin)
HEGRA	20 ^h 31 ^m 57 ^s	6.2(13.7)	+41°29′57″	1.1(1.0)	6.2 ± 1.2(0.9)
Whipple	20 ^h 32 ^m 27 ^s	21(23)	+41°39′17″	5(6)	<6.0
MAGIC	20 ^h 32 ^m 20 ^s	11(11)	+41°30′36″	1.2(1.8)	5.0 ± 1.7(0.6)
Milagro	20 ^h 28 ^m 43 ^s .2	25	+41°07′48″	16	66
ARGO	20 ^h 32 ^m 24 ^s .0	...	+41°45′00″	...	12 ⁺²⁴ ₋₁₂

[Aliu et al. 2014, ApJ 783, 16]

PSR J2032+4127

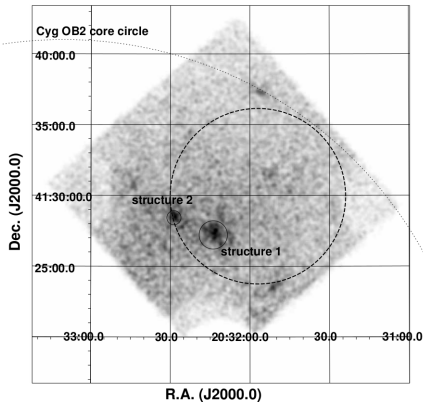


[Camilo et al. 2009, ApJ 705,1]

- Fermi: GeV pulsar LAT PSR J2032+4127 [Abdo et al. 2009, Sci 325, 840]
- $P = 143$ ms, $\tau_c = 0.11$ Myr, $\dot{E}_{\text{sp}} = 2.7 \times 10^{35}$ erg s $^{-1}$
- GBT: radio pulsar same position and period GeV pulsar, and a Be star

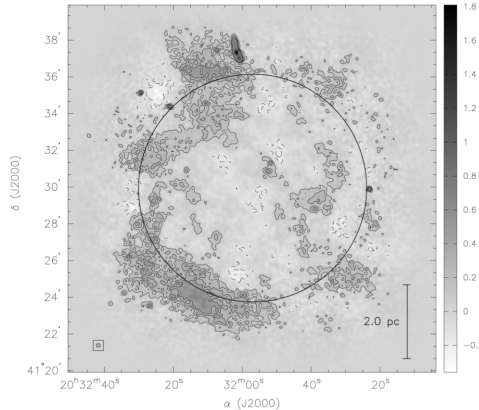
Field around PSR J2032+4127

Suzaku



[Murakami et al. 2011, PASJ, 63, 873]

VLA 6 cm



[Butt et al. 2008, MNRAS 385, 1764]

Observations

- VLA
 - June 28, 2010
 - Two frequency bands centered at 4.4 and 7.8 GHz
 - D configuration
- EVN
 - Observations on 2010, 2011, and 2014
 - 1.6 GHz
 - Pulsar gating
- *Chandra*
 - Archival data, 0.5-10 keV band, 48.7 ks observation on 2004 July 12 with the Advanced CCD Imaging Spectrometer (ACIS) detector.



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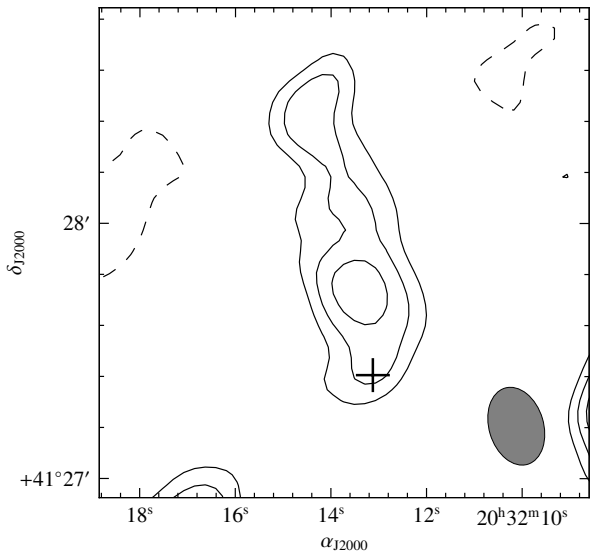
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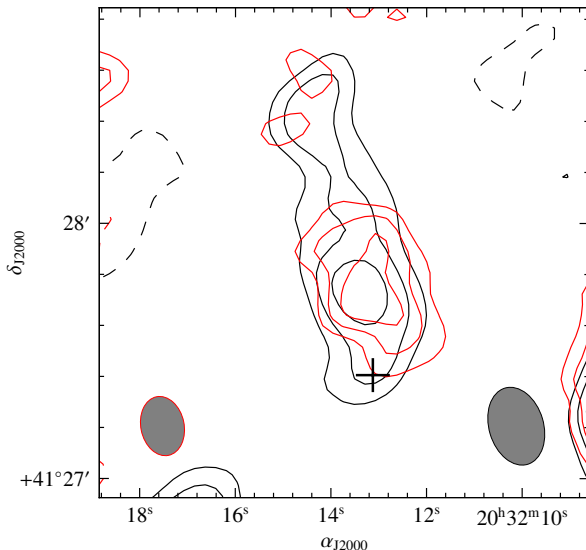
VLA: Extended radio emission

Extended radio emission: a PWN



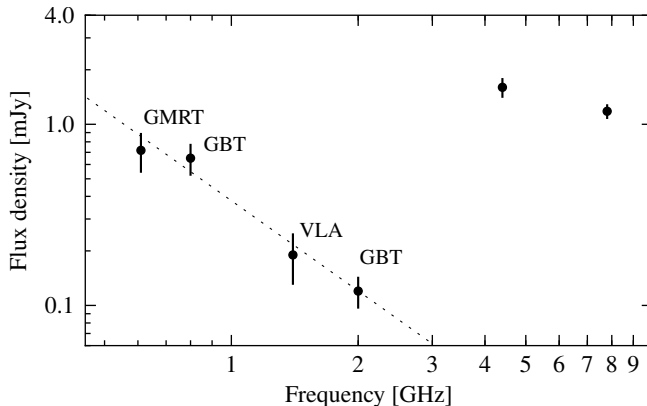
+ PSR J2032+4127
VLA 4.4 GHz

Extended radio emission: a PWN



+ PSR J2032+4127
VLA 4.4 GHz
VLA 7.9 GHz

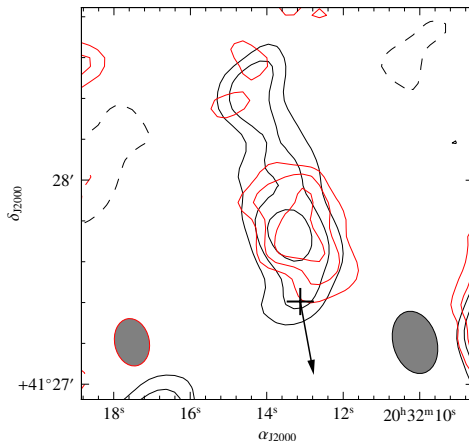
Radio spectrum



- Pulsar spectrum: $S_\nu = (0.36 \pm 0.02)(\nu/\text{GHz})^{-1.6 \pm 0.1}$ mJy
- Insignificant contribution from the pulsar: $\alpha = -0.4 \pm 0.4$

EVN: Pulsar proper motion

PSR J2032+4127 proper motion



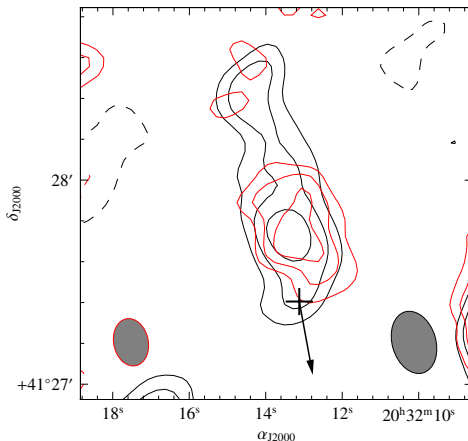
$$\mu_{\alpha} \cos \delta = -2.0 \pm 2.0 \text{ mas yr}^{-1}$$

$$\mu_{\delta} = -10.8 \pm 2.0 \text{ mas yr}^{-1}$$

$$\alpha_{\text{J2000.0}} = 20^{\text{h}}32^{\text{m}}13.125 \pm .002^{\text{s}}$$

$$\delta_{\text{J2000.0}} = +41^{\circ}27'24.44 \pm 0.02''$$

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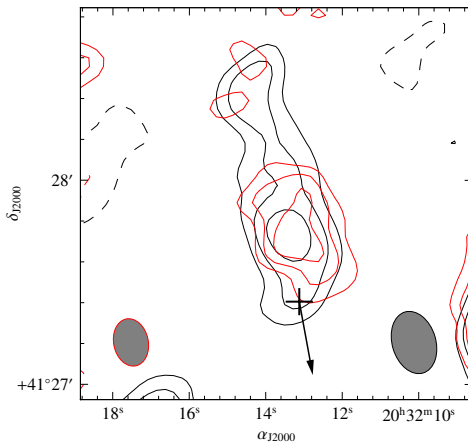
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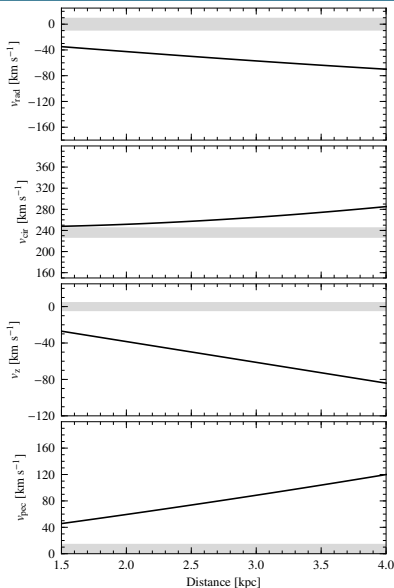


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2D velocity: $90\text{--}190 \text{ km s}^{-1}$
at $1.7\text{--}3.6 \text{ kpc}$

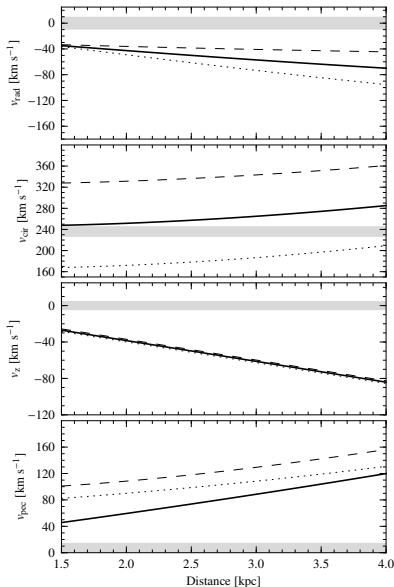
Galactic velocity



- Components of the Galactic and peculiar velocity of PSR J2032+4127.
- The grey areas indicate the expected Galactic velocity for young stars.
- (II) Assuming radial velocity of:
 - +100 km/s (dashed line)
 - 100 km/s (dotted line)

The velocities are not compatible with the expected ones from Galactic rotation

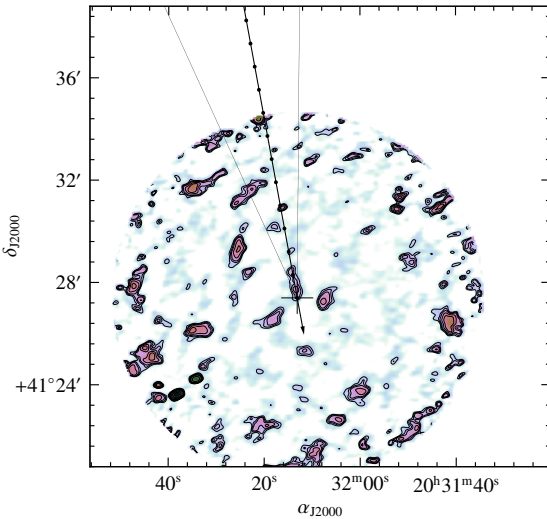
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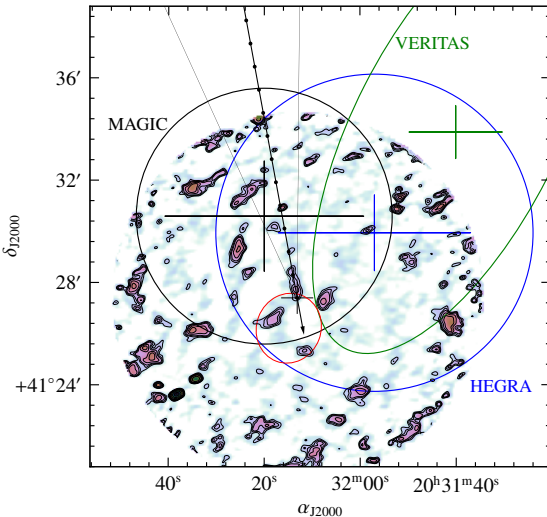
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Widefield



Contours: JVLA 4.4 GHz
Black Cross: EVN, pulsar
Black dots every 5000 yr

Widefield

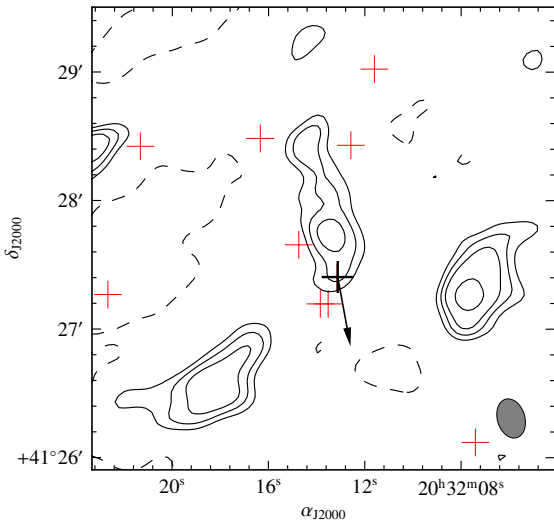


Contours: J2000 4.4 GHz
Black Cross: EVN, pulsar
Black dots every 5000 yr
Red ellipse: *Fermi*

The past trajectory of PSR J2032+4127 coincides with the measurement of the CoG of the TeV emission measured with MAGIC, which is compatible with the measured positions from HEGRA and VERITAS

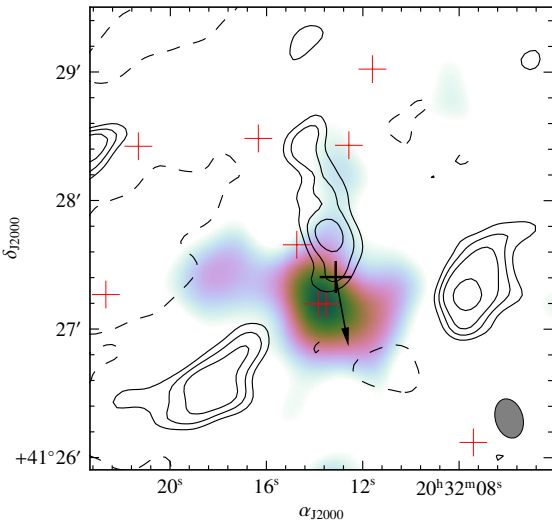
Chandra: diffuse X-ray emission

Diffuse X-ray emission



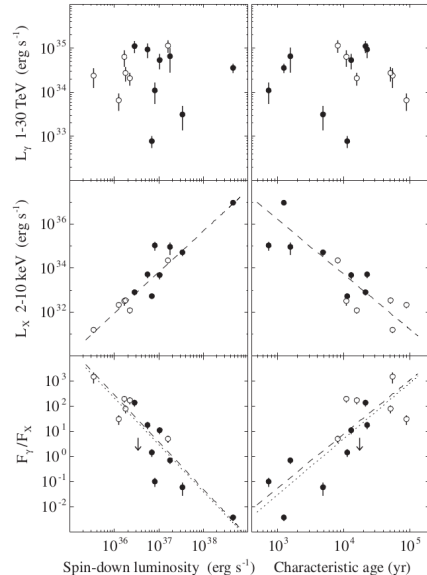
Contours: JVL4 4.4 GHz
Cross: EVN, pulsar
Red Crosses: *Chandra*

Diffuse X-ray emission



Contours: JVLA 4.4 GHz
Cross: EVN, pulsar
Red Crosses: *Chandra*
Color scale: diffuse *Chandra*

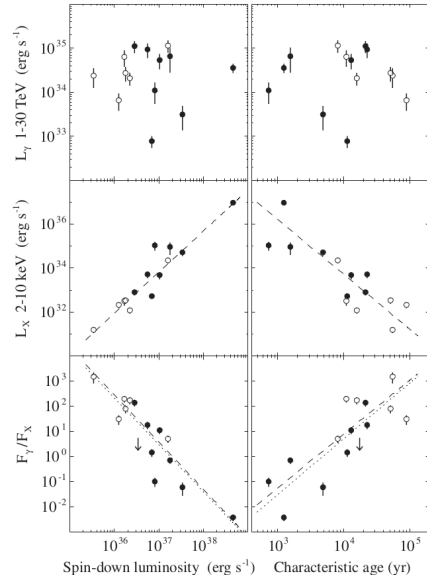
X-ray/gamma-ray correlation



- Correlations of the X-ray and gamma-ray fluxes with $\dot{E}$ and τ_c :
- $\dot{E}_{sp} = 2.7 \times 10^{35} \text{ erg s}^{-1} \Rightarrow$
 $L_X = 7.4 \times 10^{30} \text{ erg s}^{-1}$ or
 $F_X = 2.2 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$
- $\tau_c = 0.11 \text{ Myr} \Rightarrow F_\gamma/F_X \sim 1000 \Rightarrow$
 $L_\gamma = 7.4 \times 10^{33} \text{ erg s}^{-1}$

[Mattana et al. 2009 ApJ 694 12]

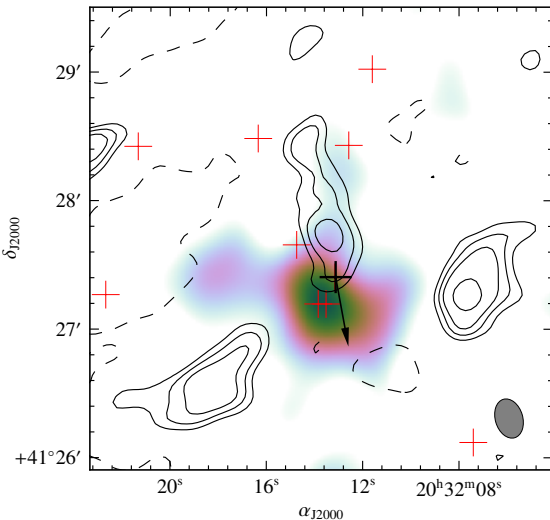
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[Mattana et al. 2009 ApJ 694 12]

Diffuse X-ray emission



The diffuse emission could be:

- Partially from the PWN itself.
- Unrelated source. Field young stars?
- e^- escaping from the shock?

Scenario

- High speed pulsar forms a shock at $\sim 1''$.
- High energy particles are accelerated and escape the shock region.
- If leptonic, they could be the responsible of the TeV source through IC in the Thomson regime off CMB and IR galactic photons with energy density $u_{\text{CMB-IR}} \sim 1 \text{ eV}$.
- Diffusion coefficient of $D \sim 10^{26} \text{ cm}^2 \text{ s}^{-1}$, $t_{\text{diff}} \sim 30 - 50 \text{ kyr}$.
- Particles are advected by the shocked flow in the opposite direction to the pulsar motion. These relativistic particles produce radio (detected) and X-ray emission (not detected yet).
- The size of the TeV source is compatible with a projected velocity of $\sim 100 \text{ km s}^{-1}$.

Conclusions

- The radio morphology strongly resembles that of a PWN.
- The positional coincidence between the pulsar and the origin of this elongated radio structure suggests a physical association.
- This is supported by the proper motion of the pulsar, opposite to the radio structure.
- The pulsar space velocity is not compatible with the Galactic rotation. Probably formed with a kick.
- The absence of diffuse X-ray emission overlapping the elongated radio structure could be explained by the low flux expected.
- The extended X-ray emission detected with *Chandra* and *Suzaku* remains unclear. (Associated with the Be stars in the field?).