AIN'T NO CRAB, PWN GOT A BRAND NEW BAG: CORRELATED RADIO AND X-RAY STRUCTURES IN PULSAR WIND NEBULAE

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Abstract

The traditional view of radio pulsar wind nebulae (PWN), encouraged by the Crab nebula's X-ray and radio morphologies, is that they are a result of the integrated history of their pulsars' wind. The radio emission should therefore be largely unaffected by recent pulsar activity, and hence minimally correlated with structures in the X-ray nebulae. Observations of several PWN, both stationary and rapidly moving, now show clear morphological relationships between structures in the radio and X-ray with radio intensity variations on the order of unity. We present high-resolution X-ray and radio images of several PWN of both types and discuss the morphological relationships between the two wavebands.

1 Introduction

The traditional model of radio pulsar wind nebulae (PWN), encouraged by the amorphous shape of the Crab radio nebula, is where the bubble blown by the pulsar acts as a bag which is filled with particles and magnetic field deposited by the wind since the pulsar's birth (for a recent review of PWN, see Kaspi, Roberts & Harding, 2004). The flow velocity of freshly injected material at the termination shock is $v_0 \sim 0.5$c. As the material expands into the nebula, the material will slow, but the nebular crossing time is still on the order of tens to a few hundreds of years, much less than the $\sim$ 1000–10,000 yr typical age of the nebula. The synchrotron cooling time of radio emitting electrons is probably much longer than the age of the nebula, while the cooling time of the X-ray emitting electrons is generally thought to be on the order of the crossing time. The long-lived radio emitting particles therefore reflect the integrated history of the pulsar wind output and should be fairly evenly distributed throughout the nebula and be largely unaffected by recent pulsar activity. This is in contrast to the relatively short-lived, X-ray emitting particles which should reflect the current pulsar wind conditions. However, high-resolution observations of both stationary (sPWN) and rapidly moving (rPWN) nebulae often show clear morphological relationships between X-ray and radio structures within the nebulae. Sometimes these are correlations and sometimes anti-correlations, but it is apparent that X-ray structures are often associated with radio intensity variations on the order of unity. These require local magnetic field variations which are related to the present day wind activity and can potentially be used to probe the structure of the pulsar wind.

2 Composite SNR with sPWN

A pulsar is born in a supernova explosion, and so the initial environment of a young PWN is that of the expanding ejecta of the progenitor star. In this environment, the young PWN undergoes accelerated expansion which generally greatly out-paces any motion of the pulsar imparted by the supernova. Hence the morphology of the PWN is not greatly effected by the displacement of the pulsar from its birth-site, and we will refer to such a nebula as a stationary PWN (sPWN). If the PWN is surrounded by a radio and/or X-ray shell caused by the supernova blast wave, then the system

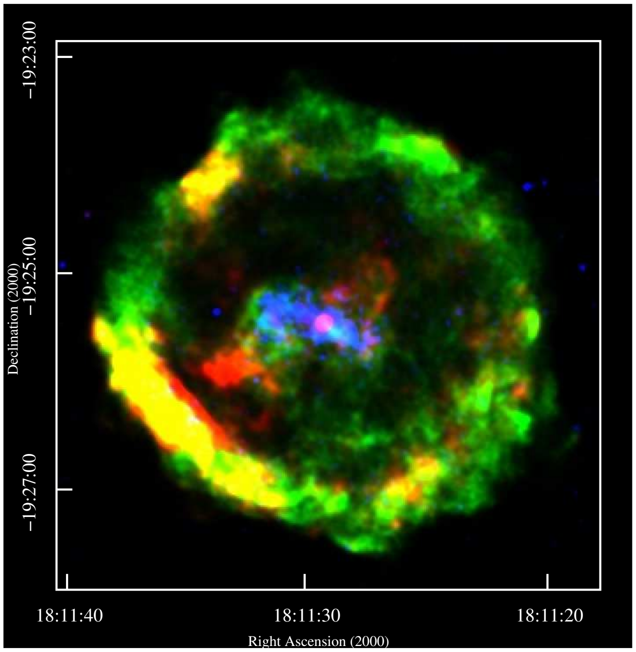

Figure 1: *Chandra* and Very Large Array (VLA) image of SNR G11.2−0.3. Red is thermal X-ray emission, green is 3.5 cm radio emission, and blue is non-thermal X-ray emission. The plus sign marks the approximate position of the pulsar. (From Roberts et al., 2003).

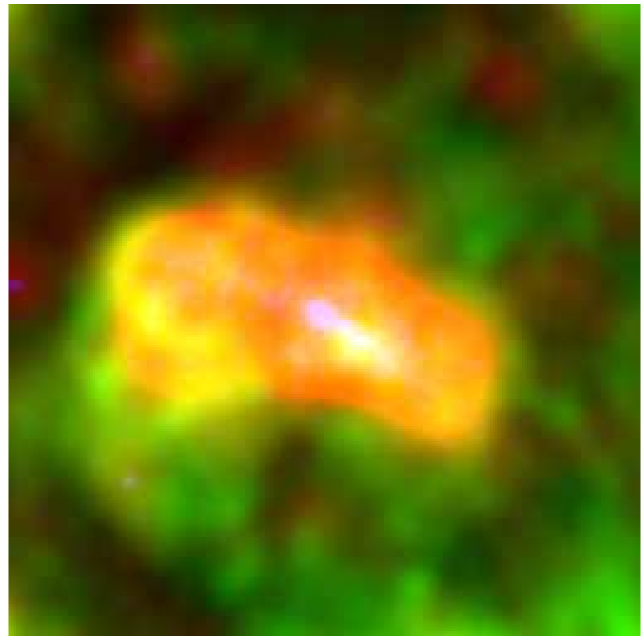

Figure 2: Close-up *Chandra* and VLA image of G11.2−0.3. The red is highly smoothed non-thermal X-rays, the green and blue as in Fig. 1.

is referred to as a composite supernova remnant (SNR) and there are observational indications of the expanding ejecta's properties.

2.1 SNR G11.2−0.3

SNR G11.2−0.3 is probably the result of the historical guest star of 386 A.D. (Clark & Stephenson, 1977). The well determined age (Tam & Roberts, 2003), highly spherical morphology of the SNR shell and the likelihood of nearly constant energy injection by the pulsar (indicated by its current long spin-down timescale) make it a particularly simple system to study (Kaspi et al., 2001). Figure 1 shows the relationship between the thermal X-ray emission (red), the non-thermal X-ray emission (blue) and the radio emission (green). Note the separation between the shell and the central PWN, and the thermal emission outside the radio PWN. In this system, the SNR reverse shock has probably not begun to interact with the PWN.

Figure 2 shows a close-up of the PWN, but this time the red is a highly smoothed image of the non-thermal X-ray emission to emphasize the fainter emission. The X-ray nebula has bright, narrow components on top of a broad faint component which mostly fills the radio nebula. The radio appears to outline the X-ray nebula with an edge brightened appearance except for a coincidence with the bright X-ray "spot" region to the southeast of the pulsar (Roberts et al., 2003). In a modified Kennel & Coroniti (1984) picture, the fresh particles may be injected in a narrow jet and remain fairly well collimated out to the nebular edge. The region of rapid bulk motion of X-ray emitting particles may be at a lower pressure than the surrounding regions, resulting in a lower magnetic field and particle density. Hence, the radio emission is suppressed. If there is significant cooling of the X-ray emitting particles in the flow, then the brightest X-ray emission may come from the rapid flow region. It also might be the case that the post termination shock magnetic field never reaches equipartition and grows out to the forward shock, which would also cause an edge brightening effect in the radio.

2.2 PSR B1509−58

The PWN around the $\sim$ 1000 yr old pulsar PSR B1509−58 in the SNR G320.4−1.2 has an unusually complicated morphology. Perhaps the most remarkable feature of the X-ray PWN is the long, bright, jet-like flow (see Fig. 3). Comparison with the radio emission shows a strong anti-correlation of the bright X-ray

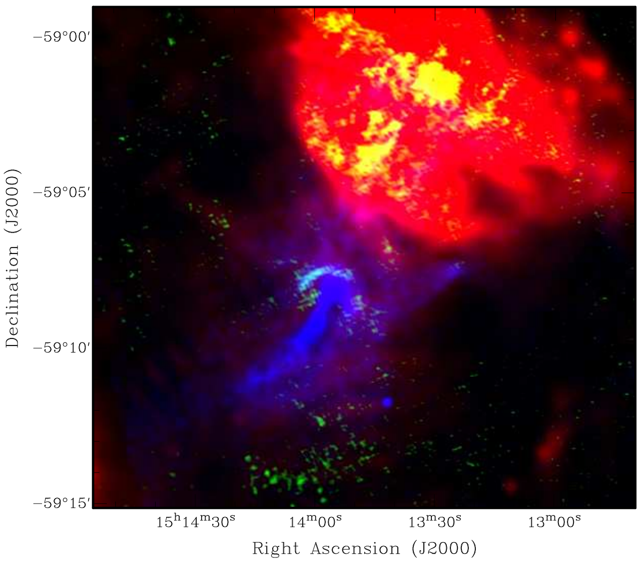

Figure 3: *Chandra* and Australia Telescope Compact Array (ATCA) image of the PWN around PSR B1509−58 and a portion of SNR G320.4−1.2. Red is 20 cm radio, blue is non-thermal X-ray, and green is 6 cm linear polarization intensity.

emission with the radio (Gaensler et al., 2002). Similar to G11.2−0.3, but here even more pronounced, the radio emission seems to outline a cavity containing the brightest X-ray emission.

The arc near the pulsar (Fig. 4) may be a toroidal outflow or some bow-like structure where the jet in the forward direction suddenly ends. Note that the high linear polarization denotes a region of highly structured magnetic field.

3 RPWN associated with γ-ray sources

RPWN are formed after the pulsar has moved significantly from its birthplace and are often found outside their associated SNR. Hence, they are usually surrounded by the ISM, and their motion is probably supersonic causing a bow-shock to form. Also, since they are on average older than sPWN, they tend to have lower spin-down energies. Despite this, they are often found to be coincident with unidentified γ-ray sources. Two apparent rPWN are shown in Fig. 5 (Braje et al., 2002) and 6 (Roberts et al., 1999). The X-ray emission again seems collimated while the radio emission forms a sheath around it. The polarized emission seems to outline the nebula (although the data isn't completely clear). More detailed radio polarization studies could clarify the magnetic field structure. The current structure might hint that the radio emitting particles may not be accelerated near the pulsar but instead at the nebular/interstellar matter boundary.

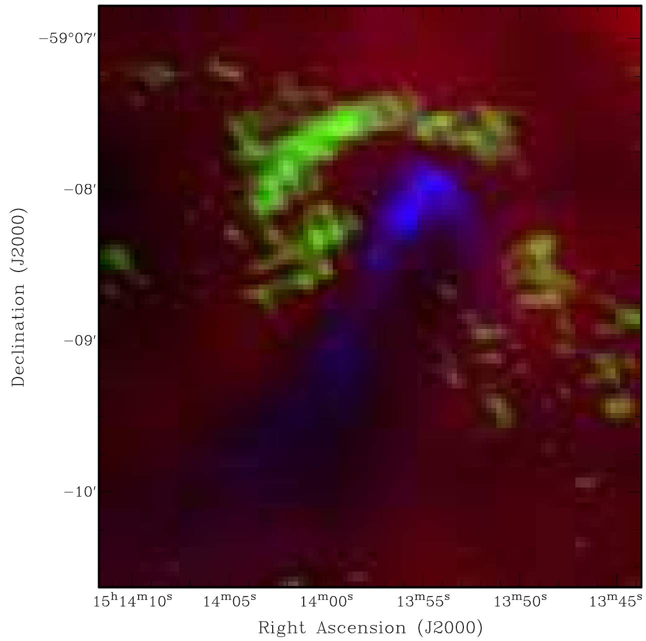

Figure 4: Close-up of region near PSR B1509−58. Colors same as in Fig. 3.

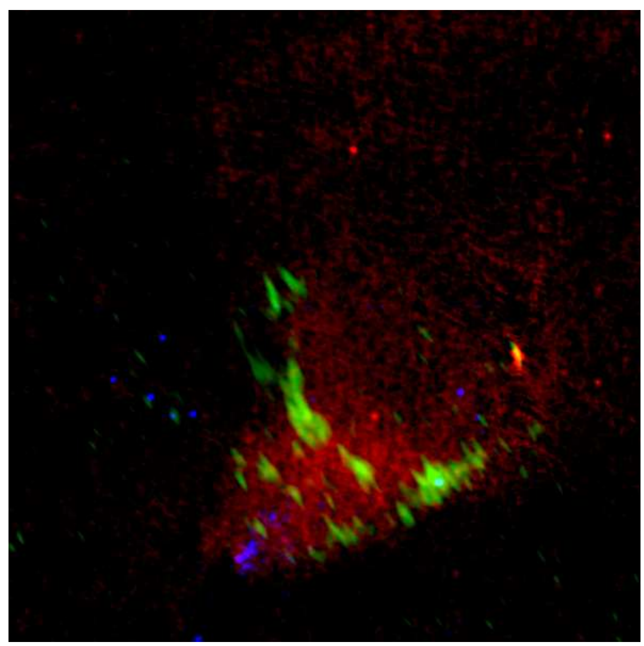

Figure 5: *Chandra* and VLA image of the nebula in the *EGRET* source GeV J1809−2327. Red is 20 cm radio continuum, green is 6 cm polarization, blue is non-thermal X-ray.

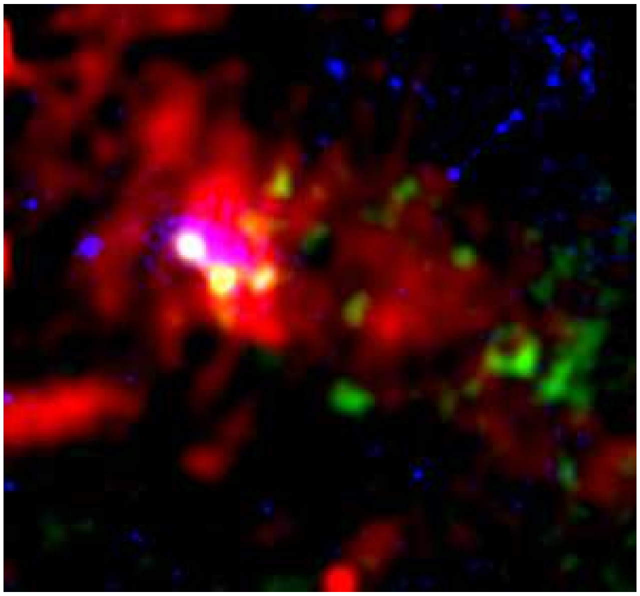

Figure 6: *XMM-Newton* and ATCA image of Rabbit nebula and lower wing of the Kookaburra radio complex in GeV J1417−6100. Red is 20 cm radio continuum, green is 20 cm linear polarization, blue is non-thermal X-ray.

Acknowledgments

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