Trends in Supernova Remnant Research

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Evolution stages in uniform medium (Spitzer 1968, Woltjer 1972,…)

- Ejecta-dominated
  - up to $\sim 10^3$ years
- Nonradiative Sedov blast wave
  - up to $\sim 10^4$ years
- Radiative shell
  - up to $\sim 10^{5-6}$ years
- Return to interstellar medium
Radiative remnant

1. Nonradiative Sedov-Taylor

2, 3. Shell formation

4, 5. Cool, dense shell with hot interior

$3 \times 10^{50}$ erg, 1 part./cm$^3$

RAC 1974
Crushed cloud model for SNRs

McKee & Ostriker 1977

Nonradiative shock

Hot ISM

McKee & Ostriker 1977
Duin & van der Laan (1975) showed detailed correspondence and developed model of radio from compressed IS fields and particles.
IC 443 – a molecular cloud interactor

21 cm continuum emission
Lee et al. 2008

Radio continuum
Shock CO contours
Lee et al. 2012

All molecular emission

Right Ascension (J2000)
Declination (J2000)
mJy/Beam
Early B star (B2, B3) on main sequence (8, 10 $M_\odot$) can result in a supernova that interacts with its parent molecular cloud

Molecular cloud structure

- Interclump medium $n \sim 10 \text{ cm}^{-3}$
- Clump $n \sim 10^3 \text{ cm}^{-3}$
- Dense core $n \sim 10^{5-6} \text{ cm}^{-3}$
Radiative shell/clump interaction model (RAC 99)

Applied to IC 443, W44, 3C 391

Competing model: nonradiative blast wave in intercloud region (Reach + 2005, Uchiyama + 2010)
- Column density of HI is about as expected for radiative shell in 10 cm$^{-3}$ gas

Shocked HI contours on optical image
Lee et al. 2008
both cases, the gamma-ray emission correlates strongly with the shocked gas, again arguing that the GeV and TeV emission arise from the same population of CRs. In that case, the emission is likely dominated by CRs interacting with gas close to the shock front, rather than an escaping population of CRs.

Figure 5: (left) VERITAS excess map with contours of two tracers of shocked gas, HCO$^+$ (red) and $^{12}\text{CO}$ (yellow) overlaid. (right) The Fermi-LAT counts map, with the same contours overlaid.

4. Conclusions

Deep VERITAS observations of the supernova remnant IC 443 have established that its VHE gamma-ray emission is extended over the entire surface of the remnant and traces out the shell, thus adding IC 443 to the small but growing list of VHE shell-type SNRs. The morphology is strongly correlated with the GeV morphology, suggesting that the emission is dominated by a single population of CRs across a wide range of energies. IC 443 is the first VHE shell-type SNR to clearly have significant SNR/MC interactions, and is likely the oldest and most evolved of the VHE shell-type SNRs. As such, it remains an extremely interesting laboratory in which to study the acceleration, escape, and diffusion of cosmic rays.

Acknowledgements

This research is supported by grants from the U.S. Department of Energy Office of Science, the U.S. National Science Foundation and the Smithsonian Institution, and by NSERC in Canada. We acknowledge the excellent work of the technical support staff at the Fred Lawrence Whipple Observatory and at the collaborating institutions in the construction and operation of the instrument. The VERITAS Collaboration is grateful to Trevor Weekes for his seminal contributions and leadership in the field of VHE gamma-ray astrophysics, which made this study possible.

References

source integration radius. Gamma-ray emission above 200 GeV fills the northern lobe of the SNR, tracing out the SNR/MC interaction regions and the shell along much of its length. The emission is strongest where the maser emission is brightest, but the entire remnant appears to be accelerating particles.

Figure 1: Excess map for the field including IC 443, with the color scale indicating counts integrated within a radius of 0.09° about each point. White contours indicate the radio shell and black contours indicate the significance of the VERITAS observations at the 3, 6, and 9 $\sigma$ levels. Locations of maser emission are marked in red, while the location of a likely pulsar wind nebula is marked in green.

To study the spectrum of the remnant, we integrate all counts within an 0.3° radius around a point near its center, 06 16 52.8 +22 33 00, as well as selecting out three regions of radius 0.13° that sample different environmental conditions. Those three regions are (1) centered on the brightest maser emission, (2) covering the dim, extended maser emission along the southeast, and (3) in the north, where the shell is interacting with swept-up material and no molecular clouds are observed. The resulting spectra are shown in Figure 2, and results of power-law fits to the spectra are summarized in Table 1. The bin width is 0.2 decades, and optimized for the brighter regions, resulting in relatively poor statistics per bin in the dimmest region. All three regions, as well as the whole SNR, have power-law indices near $\gamma \approx 3$, consistent with previous studies in this energy range [14, 15]. This is unusually soft for SNRs but observed in some other SNRs interacting with molecular clouds (eg, W44 [16]). There is no clear evidence for variation in the spectral index across the remnant; note that all regions agree at the two-sigma level or better, and the statistical error on the northern region remains quite large. However, the poor reduced $c^2$ of Region 1 indicates that a simple power law does not provide a good description of the spectrum in that region, possibly indicating a break or cut-off is present.

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2Mass
Blue, J band, ionic emission from shocks
Red, K band, H$_2$ emission from shocks

Rho et al. 2001
Filament in NGC 6334
0.1 pc width
~ 10 pc long
Massive star forming region

350 \( \mu \) dust emission   Andre + 2016
Models for “mixed morphology” remnants (IC 443, W44,…)

Crushed cloud model
- X-rays indicate current shock velocity
- Mostly nonradiative shock
- Ages 10³’ s of years

White & Long 1991

Radiative shell model
- X-rays from earlier phase and left in interior
- Mostly radiative shock
- Ages 10⁴’ s of years

Chevalier 1999, Shelton, Cox…
Pulsar wind in SN ejecta: the Crab

Shell driven by the pulsar bubble in freely expanding ejecta is accelerated and subject to Rayleigh-Taylor instability

Assuming a normal SN energy, SNR shock is at large radius
Inner and outer interaction

- Forward shock
- Reverse shock
- Shock in ejecta
- Pulsar wind termination shock

\[ R_p \sim t^{6/5} \]

Blondin, RAC, Frierson 01
3C 58

X-ray photon index based on
KC 84 MHD model

Slane et al. 04  (also Reynolds 03)
Diffusion/Advection Model (Tang+RAC 12)

- Analytical and Monte Carlo models
- Reflecting outer boundary tends to flatten outer index profile
- Diffusion length < observed filament length

3C 58
John Blondin, RAC

Swept up shell

Shocked pulsar wind

Uniform ejecta

Time = 2.56374

Time = 5.88478
Shocked region driven by the supernova RAC, Blondin + 92
Forward shock
Reverse shock
Shock in ejecta
Pulsar wind termination shock

\( R_p \sim t^{6/5} \)

Blondin, RAC, Frierson 01
Continued interaction with uniform ejecta

Interaction with $\rho \sim r^{-7}$ medium
Post-blowout phase

2-dimensional

3-dimensional
The approximate condition for the blow-out to occur is that the deposited pulsar spin down energy be greater than the SN energy $E_{SN}$.

- If $E_{SN}$ is $10^{51}$ erg, an initial pulsar period in the msec range is needed. May apply to magnetar model for superluminous supernovae (Chen + 16).

- If $E_{SN}$ is $10^{50}$ erg, the period can be $3 \times$ higher.
If Crab were a normal $10^{51}$ erg supernova, would expect to see external signs

**Constraints on the Crab**
- Abundances suggest $8-10 \, M_\odot$ progenitor
- Velocity, age, radius, mass of the nebula

**Most consistent with a low energy ($\sim 10^{50}$ erg) supernova**
- Acceleration, mass, cooling shock

(Yang + RAC 15)
After > 40 years, many mysteries still persist and new ones have come along
Shocked MHD flow model
Toroidal magnetic field
Advective flow of particles, with B field

Kennel & Coroniti 84