Morphology of SNRs and their halos

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Supernova remnants are known to accelerate particles to relativistic energies, on account of their non-thermal emission. The observational progress from radio to gamma-ray observations reveals more and more morphological features that need to be accounted for when modeling the emission from those objects.

We use our time-dependent acceleration code RATPaC to study the formation of extended gamma-ray halos around supernova remnants and the morphological implications that arise when the high-energetic particles start to escape from the remnant.

We performed spherically symmetric 1-D simulations in which we simultaneously solve the transport equations for cosmic rays, magnetic turbulence, and the hydrodynamical flow of the thermal plasma in a volume large enough to keep all cosmic rays in the simulation. The transport equations for cosmic-rays and magnetic turbulence are coupled via the cosmic-ray gradient and the spatial diffusion coefficient of the cosmic rays, while the cosmic-ray feedback onto the shock structure can be ignored. Our simulations span 25,000 years, thus covering the free-expansion and the Sedov-Taylor phase of the remnant’s evolution.

We find strong difference in the morphology of the gamma-ray emission from supernova remnants at later stages dependent on the emission process. At early times both - the inverse-Compton and the Pion-decay morphology - are shell-like. However, as soon as the maximum-energy of the freshly accelerated particles starts to fall, the inverse-Compton morphology starts to become center-filled whereas the Pion-decay morphology keeps its shell-like structure on account of the gas-distribution. Escaping high-energy electrons start to form an emission halo around the remnant at this time.

The spectral evolution of the hadronic and leptonic gamma-ray emission is consistent with observational trends, showing a softening of the emission spectra at the highest energies once the maximum energy of the SNR starts to decrease. Escaping high-energy particles leave behind soft spectra inside the SNR.

Gamma-rays detected by current-generation instruments from the brightest Galactic SNRs contain likely emission from the “halo”. Observational features like the difference in the gamma-ray and X-ray spectral index for SN 1006 or the larger extension of the gamma-ray emission compared to the X-ray emission for RX J1713 might be explained by the fact that most high-energetic electrons reside outside the SNR where the magnetic field is lower than in the post-shock region.

There are good prospects for detecting this spectrally hard halo emission with the future Cerenkov Telescope Array, as there are for detecting variations of the gamma-ray spectral index across the interior of the remnant, which is at a level of $\Delta s \leq 0.2$ across the interior of the remnant.

Further, we find a constantly decreasing non-thermal X-ray flux that makes a detection of X-ray unlikely after the first few thousand years of the remnants evolution – consistent with the census of Galactic SNRs. The radio flux is increasing throughout the SNR's lifetime and changes from a shell-like to a more center-filled morphology later on. At the last stage, that we consider here, electron-escape becomes relevant at radio-emitting energies.