Particle escape from supernova remnants and related gamma-ray signatures

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The escape process of particles accelerated at supernova remnant (SNR) shocks is here studied with a phenomenological approach which allows to quantify its impact on the cosmic-ray spectrum observed on Earth, as well as on the gamma-ray spectral signatures emerging from these sources. We solved the particle transport inside and around the SNR shock assuming the maximum momentum of confined protons to scale as a power law in time, with a slope containing information on the evolution of turbulence with time. Under the assumption that in the spatial region immediately outside of the remnant the diffusion coefficient is suppressed with respect to the average Galactic one, we show that a significant fraction of particles are still located inside the SNR long time after their nominal release from the acceleration region. This fact results into a gamma-ray spectrum arising from hadronic collisions inside the remnant that resembles a broken power law, similar to those observed in several middle-aged SNRs. Above the break, the spectral steepening is determined by the diffusion coefficient outside of the SNR and by the time dependence of maximum energy. An interesting signature of the presence of high-energy particles still diffusing in the region outside of the SNR shock after their escape is constituted by a bump-like spectrum of the gamma-ray radiation resulting from pp collisions, which is expected to be observed as a halo of radiation surrounding the forward shock. The model of particles escape is also applied to electrons, including energy losses due to the emission in the radiation and magnetic fields of the region. Consequently, the comparison between the model prediction and broadband data allows to determine the model parameters which regulate both the energy-dependent escape process, as well as the particle propagation. We present the case of the Cygnus Loop SNR, a middle-aged SNR: interpreting the origin of its gamma radiation as hadronic, we are able to infer a lower value for the diffusion coefficient in the remnant region, the maximum energy of particles (both its time dependence and absolute value at Sedov time), and the efficiency of particle acceleration at the SNR shock. We find that the Cygnus Loop has likely not behaved as a PeVatron in the past. On the other hand, the radio data are well described as the synchrotron radiation emitted by electrons, allowing to constrain the particle acceleration slope, the strength of the background magnetic field and the electron to proton ratio. We plan to extend this study by applying the model to other interesting SNRs where multi-wavelength emission is observed, as to derive information on the particle escape from the point of view of the SNR population.